METALS AND FABRICATION

ARC WELDING 3

Advanced Arc Welding Information Book
Learner’s Guide
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Coded welding

Weekly schedule
In this section we will look at the following.

Weekly schedule
- Week 1 – regulations (AS 1796 Item 2)
- Week 2 – safety (AS 1796 Item 1)
- Week 3 – terms and symbols (AS 1796 Item 3)
- Week 4 – elements in steel (AS 1796 Item 4)
- Week 5 – heat treatment (AS 1796 Item 5)
- Week 6 – weld testing (AS 1796 Item 6)

Test A
- Week 7 – weld joint preparation (AS 1796 Item 7)
- Week 8 – welding procedures (AS 1796 Item 8)
- Week 9 – metal cutting and gouging (AS 1796 Item 9)
- Week 10 – electrical terms (AS 1796 Item 10)
- Week 11 – arc conditions (AS 1796 Item 11)
- Week 12 – MMAW and electrodes (AS 1796 Item 12)

Test B
- Course review
- Competency mapping
Week 1 – regulations (AS 1796 Item 2)

1. Codes and Standards
   1.1 Identify the SAA Standard given below:
      AS 1796:2001, AS/NZS 1554, AS 1210, AS 1674
   1.2 Briefly describe the reasons (or purpose) for each Standard.

2. Regulations and Acts
   2.1 What is the difference between a code (or Standard) and an Act or regulation?
   2.2 List three Acts or regulations.
   2.3 List four government departments that may be involved with code of practice in the welding industry.

3. WorkSafe WA
   3.1 Occupational Safety and Health Act:
      ■ intention
      ■ employer’s responsibilities
      ■ employee’s responsibilities.

Week 2 – safety (AS 1796 Item 1)

1. Describe each of the following hazards associated with welding.
   1.1 Electric shock: primary, secondary, cables, HF.
   1.2 Fire and explosions: hazardous locations (definitions), site work, containers, fire extinguishers, assistant’s role.
   1.3 Fumes and ventilation: confined space, flux coatings, surface and metal coatings, alloys.
   1.4 Cylinders: storage handling, identification.
   1.5 Scaffolds: staging, kickboards, rails.
   1.6 Skin/eyes: radiation, arc, heat, sparks, slag, protection.
   1.7 X-rays/gamma rays: sources, weld examination, precautions.
   1.8 First aid: electric shock, burns, injury, coma.

Assignment

- List major welding hazards.
- List possible causes of these hazards.
- Describe effects on welders' health.
- Describe methods of prevention of injury from these hazards.
Week 3 – terms and symbols (AS 1796 Item 3)
1. Weld symbols
   1.1 Identify the SAA Standard.
   1.2 Interpret weld symbols and welding symbols.
2. Welding terms:
   2.1 butt and fillet welds
   2.2 refer AS/NZS 1554.

Week 4 – elements in steel (AS 1796 Item 4)
1. Typical steel analysis.
2. Elements in steel and their effects (physical and mechanical properties).
3. Consumables – matching to parent metal (see also section 12).

Week 5 – heat treatment (AS 1796 Item 5)
1. Iron/carbon diagram: upper and lower critical temp; heat treatments.
3. Mechanical properties: strength, hardness, ductility, fatigue (related to heat treatment).
5. Heating methods: gas, electric, fuel oil
6. Temperature measurement.

Assignment
- Describe the main heat treatment methods.
- Temperatures and time involved.
- Phase changes that occur.
- Cooling rates.
- Changes in mechanical properties as a result.

Week 6 – weld testing (AS 1796 Item 6)
1. Describe the need for weld testing.
2. List and describe weld tests used in the fabrication industry:
   a) destructive (workshop/laboratory)
   b) non-destructive.
3. List and describe:
   a) external weld defects
   b) internal weld defects.
Test A

Section 1 to 6

Week 7 – weld joint preparation (AS 1796 Item 7)
1. Edge preparations (sketch, dimension) AS 1554:
   a) open and closed square
   b) single and double bevel
   c) single and double V
   d) single and double U
   e) transitions.
3. Reasons for pre and post cleaning (methods).
4. Backing bars, backing strips, back purging, back gouging.
5. Alignment, fit-up and temporary support (methods), jigs.

Week 8 – welding procedures (AS 1796 Item 8)
1. Define:
   ■ welding procedure specification
   ■ welding procedure qualification.
   1.1 List the steps required to qualify a welding procedure:
   ■ make up a procedure
   ■ prepare test sample
   ■ weld test sample
   ■ evaluate test sample
   ■ modify procedure
   ■ prove results and record
   ■ gain approval (authority).
2. Variables on a welding procedure.
3. Completion of welding procedures.

Assignment
- List twelve (12) items that should appear on a welding procedure.
- Make up a welding procedure for a single V butt weld on a 20 mm thick steel plate in the 1G position.
- Welding process is MMAW.
Week 9 – metal cutting and gouging (AS 1796 Item 9)
1. Flame cutting (manual and machine).
2. Plasma cutting.
3. Gouging (arc air and flame).
4. Mechanical edge preparation (guillotine, shears, nibbler, machining, grinding).
5. List uses and applications.

Assignment
- Given the common elements found in plain mild steel (iron, carbon, manganese, silicon, sulphur, phosphorus, chromium, nickel), describe the purpose of these elements and their effect on the mechanical properties and also the weldability as the amounts are increased.

Week 10 – electrical terms (AS 1796 Item 10)
1. Define terms: voltage, amperage, resistance, arc voltage, OCV, alternating and direct current, square wave.
2. List OCV for AC and DC machines.
3. Describe requirements: cables, joiners, work connections, machine terminals.
4. Welding machines:
   - AC transformer
   - DC generator
   - AC/DC rectifiers
   - DC inverters (constant voltage and constant current form)
   - current control methods.
5. High frequency uses and safety.
6. Welding machine comparisons and applications – advantages and limitations of each type.

Week 11 – arc conditions (AS 1796 Item 11)
1. Compare the effects of welding variables on arc stability and completed welds.
2. Current type and polarity, voltage, amperage, arc length, travel speed, electrode angles (approach and travel), flux type.
3. Discuss ‘arc blow’ (causes, effects and remedies).
4. Discuss effects of arc conditions and stability on slag control.
Week 12 – MMAW and electrodes (AS 1796 Item 12)

MMAW process
1. List factors that influence electrode selection.
2. Interpret electrode classification systems (AS/NZS 4855).
3. Name the common types of electrode coatings used:
   3.1 functions of flux coatings, characteristics, applications.
Test B

Section 7 to 12

Week 13 – welding alloy steels (AS 1796 Item 13)
1. Reasons for using alloy steels.
2. Describe and define:
   2.1 low alloy steel
   2.2 high alloy steel.
3. List uses of alloy steel.
4. List common alloying elements used, describe effects on properties and weldability:
   4.1 manganese, chromium, nickel, molybdenum, copper, silicon, vanadium.
5. Weldability of low alloy steels:
   5.1 carbon equivalent
   5.2 hardenability
   5.3 welding techniques and procedures.

Week 14 – welding non-ferrous metals (AS 1796 Item 14)
1. List common non-ferrous metals.
2. Describe how metal properties affect weldability:
   2.1 melting point
   2.2 refractory oxides
   2.3 thermal conductivity
   2.4 electrical conductivity
   2.5 expansion rate
   2.6 hot shortness
   2.7 colour change
   2.8 gas solubility.
3. Discuss cutting methods:
   3.1 mechanical, air arc plasma.
Week 15–17 – welding processes GMAW, GTAW, SAW and electroslag (AS 1796 Item 15,16,18)

1. Describe principles of operation.
2. Describe applications.
3. List advantages and disadvantages.
4. List equipment required and describe characteristics and functions of component parts.
5. Discuss variables:
   5.1 current, polarity, volts, amps, travel rate, shielding medium (flux-gas), GTAW electrodes, GMAW metal transfer modes, consumables, and stick-out.
6. Discuss possible faults.
7. Discuss safety considerations.

Week 18 – oxy-acetylene welding processes (AS 1796 Item 17)

1. Describe principles of operation.
2. Describe applications.
3. List advantages and disadvantages.
4. List equipment required.
   4.1 oxygen and acetylene description, production, storage and handling
   4.2 consumables (AS 1167.1 and 2).
5. Discuss flame settings.
6. Discuss possible faults.
7. Discuss safety considerations.

Course review (provided by your lecturer)

- Test C
- Section 13 to 18.
Chapter 1 – Distortion

Introduction

Welding has proven to be a highly successful and reliable method of joining metals and other materials. Joints that are as strong and reliable as the parent metal itself are easily produced. The major problem associated with welding is ‘distortion’. Distortion tends to occur in all weldments, and to completely eliminate distortion is extremely difficult. The challenge for the welding operator is to reduce distortion to a minimum, or at worst, to keep it to within acceptable limits.

There are many factors that cause, or influence, the amount of distortion which will occur in a weldment due to welding. The welding operator needs to understand these factors if he/she is to successfully control distortion.

In this chapter we will look at the following.

- What causes distortion?
  - the heat input
    - the amount of welding
    - the number of runs or passes
    - diameter of electrode
    - the amperage used
    - the polarity
    - the welding process
    - the welding position
  - amount of restraint
  - internal stresses in the parent metal (residual stress)
  - properties of the parent metal

- Types of distortion due to welding
  - longitudinal distortion
  - transverse distortion
  - angular distortion
  - warping, bowing or buckling

- Methods of minimising distortion
  - control of heat input
  - use of restraint
  - other methods of control
• Contra-heating
  o advantages of the process
  o principles of flame straightening
  o cooling procedure
  o application to plates
  o precautions to be observed.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>distortion</td>
<td>the overall movement of parts being welded, from the position they occupy before welding to the position they occupy after welding</td>
</tr>
</tbody>
</table>
What causes distortion?

The major reason for distortion in arc welding is the fact that when the weld metal is deposited, it is molten and therefore fully expanded. The molten weld metal will solidify and can only exert contraction forces as it cools. This shrinkage force then acts on the parts to cause movement.

The other cause of distortion is expansion and contraction, which always accompanies changes in the temperature of metals. As metals are heated they expand, and then cool as they contract. Furthermore, the amount metals expand and contract per 1 °C change in temperature is particular to each metal and does not change. The amount which a metal expands or contracts per 1 °C change in temperature, is known as the coefficient of linear expansion.

The coefficient of linear expansion of steel is 0.000012. This means that if a piece of steel is heated uniformly, it will increase its length by .000012 of its original length for each °C that it is heated.

For example: A piece of steel bar 1 m long (1000 mm) is heated 100 °C. How much expansion will occur?

\[
\text{Expansion} = \text{original length} \times \text{increase in temperature} \times \text{coefficient of expansion}
\]

\[
1000 \times 100 \times .000012
\]

Expansion = 1.2 mm

Three things should be noted.

- This expansion can not be prevented, however it may be directed in a different direction.
- It will contract the same amount for a decrease in temperature of one degree, as it will expand for an increase in temperature of one degree.
- The forces due to expansion and contraction are exceptionally high – enough to bend or break the material itself.

The expansion forces exerted by steel at low temperatures are extremely high. However when steel is heated to high temperatures it becomes softer, weaker and plastic. In this plastic condition it is not capable of exerting as much force as when it was cold. As expansion continues with increasing temperature, the metal in this plastic condition yields and changes its shape. As the steel cools it becomes progressively stronger and less plastic. It can exert progressively more force as the temperature falls. This leads to the common statement that shrinkage forces are greater than expansion forces.

An illustration of the above can be seen in the following example.

If a bar of steel at room temperature is heated uniformly throughout, it will expand uniformly in all directions as represented by the dotted lines in Fig 1.1 (a). Since the bar is unrestrained, it will contract uniformly to its original dimensions when allowed to return to room temperature.
If the bar of steel is placed in a vice before heating, as illustrated in Fig 1.1 (b), lateral expansion cannot take place. The same amount of volume expansion must occur, but expansion along the bar’s horizontal axis is prevented; hence abnormal expansion takes place in thickness and width. When the heat is removed and the deformed bar returns to room temperature, it will still tend to contract or shrink uniformly in all directions. Thus, the shape after cooling is as shown in Fig 1.1 (c). The bar is now shorter, thicker, and wider. It has been permanently deformed or distorted.
In welding, the situation described is created by the concentrated nature of the heat source, which causes local expansion and contraction as the weld progresses. Local expansion and contraction takes place in the parent metal adjacent to the weld. The colder, surrounding mass of metal acts to restrict movement from these forces, as did the vice in the example, and creates distortion.

It can be seen from the example that the major factors causing distortion are:

- expansion and contraction due to temperatures changes
- uneven expansion and contraction due to restraint
- contraction forces having a greater effect than expansion forces, due to the plasticity of the metal at elevated temperatures.

**Thermal conductivity**

Metals that conduct heat well are also good conductors of electricity. Copper and aluminium are good conductors and so need more heat to counteract the loss when heat is conducted away from the weld area. On the other hand, stainless steel is a poor conductor; heat is accumulated and retained at the weld area without much loss.

A copper work lead should be used in preference to using strips of mild steel when an extension to the welder’s work lead is unavoidable. The mild steel is not a good conductor and causes more resistance in the circuit, making the machine hot and electrically less efficient.

Additionally, there are various other factors that will influence how much or what type of distortion takes place. In practical terms, these additional factors affecting distortion can be grouped as:

- the heat input
- the amount of restraint
- the internal stresses in the parent metal
- the properties of the parent metal
- deposited weld metal properties.

**The heat input**

This depends on the:

- amount of welding
- number of runs or passes
- diameter of the electrode
- amperage used
- polarity
- welding process
- welding position.
The amount of welding

It is obvious that the greater the amount of welding, the greater will be the heat input and the amount of metal exerting contractional forces. Consequently, the greater the amount of distortion which will occur. The size and length of welds must comply with design requirements, as over-welding increases distortion and costs.

The type of preparation also affects the amount of welding; some preparations require more weld deposit than others. Comparing butt preparations in plate of the same thickness, (Fig 1.2) the double-U requires the least filler, with double-V, single-U and single-V following in that order.

![Fig 1.2 – Comparison of weld volumes](image)

It can be seen from Fig 1.2 that a single-V butt weld contains approximately twice as much weld metal as a double-V butt. Additionally with double sided preparations, the shrinkage forces are balanced on each side of the plate, further reducing distortion.

The number of runs or passes

Fewer passes with large electrodes are preferable to a greater number of passes with small electrodes. The shrinkage forces from each pass tend to be cumulative, thereby increasing the shrinkage with each successive run.

In single V-butt preparation with a gap, the first run exerts practically a transverse pull. The second run exerts shrinkage at the top of the bead (face of the weld), but the shrinkage is restricted at its base. The first run acts as a fulcrum or hinge, and bending takes place (distortion).

![Fig 1.3 – Distortion in a single V-butt weld](image)
As the welding continues, each subsequent run or layer contracts at the top and is restricted to some extent at the bottom. As further runs or layers of weld metal are deposited, lesser movement will occur as the member is becoming more rigid, but distortion will occur to some degree as long as the welding operation continues. Consequently, the more runs or layers put down in a given size butt or fillet joint, the greater the movement of the parts being welded (ie the greater the distortion).

**The diameter of the electrode**

From these factors, it should also be clear that a large electrode used within the correct current range and speed range will deposit a given weld size with less heat input than a smaller electrode using the correct current, but travelling at a slow speed, and possibly requiring more weld runs.

**The amperage used**

If high amperages are used for a particular size of electrode, the amount of heat produced is increased. This in turn melts and upsets more of the parent metal, thus creating greater distortion upon cooling. Ideally, enough heat to ensure complete fusion (without excessive melting of the base metal) is what’s required.

**The polarity**

When DC machines are used, particularly in conjunction with large diameter electrodes, it is common practice to select electrode positive polarity (+ve). Higher amperages are required to ensure complete fusion, but the heat input is reduced by the increased travel speed, and higher deposition rate, when the electrode polarity is positive.

**The welding process**

By their nature, the various welding processes add more or less heat to the weld zone, and thus produce differing levels of distortion. Consider the heating effects of welding processes such as:

- oxy-acetylene; manual metal arc
- submerged arc
- gas-metal-arc (spray and dip transfer)
- flux-cored
- gas tungsten arc.

Processes with higher deposition rates and lower heat inputs will produce the lowest levels of distortion.

**The welding position**

Positional welding normally slows down the welding speed and requires the use of multi-pass techniques. Since these two factors tend to increase heat input, welding should be carried out in the flat position wherever possible.
Amount of restraint

When a weld is made, the weld metal and adjacent parent metal are very hot and in a plastic state until cooling is well advanced. If the parent metal is firmly held in position during cooling, the plastic metal will stretch or yield under the action of the contraction stresses and distortion will be reduced. Welding jigs and fixtures are used to control distortion in this way.

Internal stresses in the parent metal (residual stress)

Stresses are usually present in the components of a weldment. They are caused by previous metal working processes such as thermal cutting, guillotining, rolling, pressing etc. These stresses may combine with, or oppose, the shrinkage forces due to welding, and thus increase or decrease the amount of distortion.

Properties of the parent metal

If metal had a zero coefficient of linear expansion, then distortion would not occur. From this it follows that as a metal’s coefficient of linear expansion increases, the amount of distortion will also increase.

In practice we see that stainless steel distorts considerably more than structural steel, because its coefficient of linear expansion is approximately one and a half times that of structural steel, and its thermal conductivity is half that of structural steel.

Consider the three most commonly fabricated metals.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Coefficient of linear expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.000012</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.000026</td>
</tr>
<tr>
<td>Austenitic stainless steel</td>
<td>0.000017</td>
</tr>
</tbody>
</table>

If we looked at the aforementioned coefficients of expansion, the immediate impression would be that distortion would be twice as great in aluminium as it is in steel. This however is not the case. The level of distortion found in steel fabrications and aluminium fabrications is fairly similar, because the higher thermal conductivity of aluminium results in more uniform expansion and contraction. By far the greatest levels of distortion are found in stainless steel fabrications.

It must be kept in mind that distortion is a product of uneven expansion and contraction. Aluminium has the highest level of thermal conductivity. Because heat is conducted more rapidly away from the weld zone, expansion and contraction are more uniform throughout the weldment. This, coupled with the lower strength of aluminium, enables it to yield more readily to absorb shrinkage stresses. This results in lower levels of distortion than may be expected.

Stainless steel on the other hand is a poor conductor of heat. This, coupled with a relatively high coefficient of thermal expansion, causes considerable distortion due to localised, uneven expansion and contraction in the weldment.
Types of distortion due to welding

Distortion can be considered to act in four different ways, which are:

- longitudinal distortion
- transverse distortion
- angular distortion
- warping or buckling (a combination of the other types of distortion).

Longitudinal distortion

Contraction forces acting along the line of the weld will pull the ends of the weld towards each other. This creates what is commonly termed ‘longitudinal distortion’ (Fig 1.4).

![Fig 1.4 – Longitudinal distortion]
Transverse distortion

Contraction forces acting across the line of the weld will pull the sections of parent metal towards each other, thus creating what is commonly termed ‘transverse distortion’ (Fig 1.5).

As a simple example, consider a double-V butt weld. When the first run is made, the contracting weld metal draws the edges of the plate together. The weld metal, as deposited, is in a fully expanded state. It contracts as it cools, drawing the plate edges together (Fig 1.5). This example also indicates angular distortion.

Fig 1.5 – Transverse distortion
Angular distortion

Transverse contraction forces across the weld face cause the section of parent metal to rotate about a longitudinal axis lying along the root of the joint, thus creating an angular change in the position of the parent metal (Fig 1.6).
Methods of minimising distortion

Decisions with respect to distortion control always begin with an appraisal of the particular job, and the ways in which distortion is likely to occur. With reference to the causes already discussed, the methods of minimising distortion can be arranged as:

- control of heat input
- use of restraint
- other methods of control.

Control of heat input

- Choose a welding process capable of making narrow, high speed welds, wherever possible.
- Minimise the number of runs by correct edge preparation.
- Use the largest size electrode, consistent with the job application.
- Avoid over-welding by keeping reinforcement to a minimum level, and by maintaining strict control of joint fit-up.
- Use of backstep or sequence welding techniques to avoid localised heat build-up.
- Use chill bars.
- Minimise the number of passes.
- Use intermittent welding as and whenever specified.
Use of restraint

The greatest distortion generally occurs when the parent metal is free to follow the shrinkage of the weld metal, and the least distortion occurs where little movement of the parent metal can take place.

Restraint may be defined as any force that opposes the contraction forces which produce distortion. Methods commonly used include:

- clamps
- jigs and fixtures
- back-to-back assembly
- tack welds
- strong backs
- sequence welding.

Fig 1.11 – Clamping back-to-back

Fig 1.12 – Sequence of welding fillet welds on either side of a vertical member
Other methods of control

Balanced welding

When welding is balanced, heat input is also balanced, eliminating transverse angular distortion and thus controlling distortion.

![Balanced welds](image1)

Fig 1.13 – Balanced welds

Pre-setting parts

Allowance is made for parts to move into the required position.

![Pre-setting](image2)

Fig 1.14 – Pre-setting

Cambering

Parts are pre-cambered to allow for movement into the required position.

![Pre-cambering](image3)

Fig 1.15 – Pre-cambering
Design of weldment around the neutral axis

Welds may be placed on either side of the neutral axis, to balance shrinkage forces. The methods of distortion control just described can be applied to minimise distortion either prior to welding (pre-setting, pre-cambering) or during welding (sequence welding, chill bars, clamping, intermittent welding, use of jigs and fixtures).

Although distortion can be corrected after welding, it is difficult, expensive, and undesirable. Distortion can be corrected in the following ways:

- hammering or forging – suitable for light sections only
- pressing – suitable for larger and heavier sections
- contra-heating – this involves localised heating, as a means of employing shrinkage forces to pull the component to the desired shape.
Contra-heating

Although contra-heating can be used for correction of distortion, it is more commonly used for two other industrial applications, which are:

- flame straightening of steel sections
- cambering of steel sections.

In many instances a skilful person, with the help of an oxy-fuel set and some simple mechanical aides, can perform the same operations as large and costly bending/pressing machines. Fig 1.17 shows an example of the amount of movement that can be obtained with the use of the flame bending technique.

Fig 1.17 – Two beams that were fabricated in the normal manner, and then cambered, by the controlled use of the oxy-fuel flame
Advantages of the process

- The portability of the oxy-fuel flame means that the work may be carried out on site. Thus heavy, bulky objects do not need to be returned to the workshop for pressing.
- Many objects are just too large or complex to make mechanical methods an economic proposition, thus leaving oxy-fuel heating the only suitable alternative.
- The oxy-fuel flame can be directed into inaccessible locations that might otherwise require dismantling or removal of the section.
- Low equipment cost and simple operation.

Principles of flame straightening

A complete understanding of the principles involved in the use of the oxy-fuel flame for bending or straightening structural steel is required before the process can be applied successfully. Lack of understanding of these principles can lead to damage and distortion of the metal; particularly by the incorrect application of heat and/or overheating.

The process of bending or straightening structural steel sections is based on controlling the resulting expansion and contraction of the metal due to the application of intense localised heat. It must be noted that a high temperature is not required for the process; the temperature should not exceed 600 °C. What is needed is rapid heat input, and therefore large heating torches are generally required.

When intense heat is applied to a local area, the surrounding cold metal acts to resist expansion. Therefore, most expansion will occur in the direction of least resistance. On cooling, however, contraction will occur equally in all directions, resulting in the heated area becoming slightly shorter. This can be used to produce noticeable movement at the ends of structural members, particularly in the case of long narrow sections. If the above principle is thoroughly understood, with experience the tradesperson will develop an understanding of exactly where and how much heat is required to bend a member the desired amount, in the desired direction.

It must be remembered that the principle relies on applying the heat quickly, and does not require a high temperature. In some instances it may be found to be advantageous or necessary to assist the process with mechanical aides such as jacks, clamps and wedges etc. For example in the case of heavy members, where unsupported weight would act against the desired direction of movement during expansion and contraction.
Bent member

Deformed area to be flame straightened

Intense heat applied in the correct wedge-shaped pattern

Abnormal expansion occurs here

Expansion resisted in these directions by cold surrounding metal

Upon cooling, contraction occurs equally in all directions

Movement occurs in these areas because of contraction here

Final result of carefully planned and executed heating pattern

Fig 1.18 – Sequence of events in flame straightening heating pattern
In almost all applications involving structural sections, a wedge-shaped heating pattern is required. The proportions of the wedge are shown in Fig 1.19.

![Fig 1.19 – Proportion of the heating wedge](image)

This wedge-shaped area should be marked out on the member for the operator’s guidance. The apex of the wedge should commence at the root of the member and extend across its full width. This wedge-shaped heating pattern must be maintained, regardless of the cross-sectional shape of the member being heated. Examples of the application of the wedge-shaped heating pattern to various structural sections and their resultant direction of movement is shown in Fig 1.20 (a), (b) and (c).

![Fig 1.20 (a)](image)
Fig 1.20 – Application of the heat wedge to structural sections (a), (b) and (c)
Cooling procedure

As the process relies on the metal surrounding the heat wedge to be kept as cool as possible, where more than one wedge is required the metal must be allowed to cool between heats. It will be desirable in most cases to speed up the cooling rate by water quenching. Quenching the heated steel will not cause any undesirable change in properties, provided the temperature in the first place is kept below the lower critical range (600 °C maximum for plain carbon steel). Fig 1.21 shows a suitable quenching spray using water and compressed air.

![Cooling procedure diagram]

The advantage of the atomised spray is that the fine spray produced is rapidly converted to steam on contact with the heated steel, and the heat quickly evaporates – leaving the metal dry.

Application to plates

The principles described can be employed successfully to straighten distorted or buckled plates. Local buckling should be tackled by spot heating on the convex side of the buckle, as in Fig 1.22.

![Application to plates diagram]
Buckles that extend to the end of the plate can be removed by employing the wedge-shaped pattern as in Fig 1.23.

Fig 1.23 – Use of the heat wedge to correct buckles extending to the edges of plates

Precautions to be observed

- Members under stress from external loads should be treated carefully, as this stress may cause pronounced buckling or even failure at the heated zone.
- Care must be taken with welded components, as any residual stresses caused by welding will tend to be relieved when heated. This may add to, or subtract from, the normal movement gained from contraction in the heated zone.
- The process should not be carried out on material other than mild steel, without full knowledge of any change in the properties of the metal that may result.
- Due to the size of the heating equipment required, the allowable draw-off rate for single cylinders of acetylene is likely to be exceeded in prolonged work. In such cases, consideration should be given to manifolding several cylinders together.
- It is worth noting again that the maximum temperature of the steel must be restricted to 600 °C, particularly when water quenching, so as to avoid any undesirable change in the properties of the metal.
Chapter 2 – Welding safety

Introduction

The various welding processes used in the metal fabrication and welding industries are often divided into categories, depending on whether the source used to generate the heat required for melting of the parent metal and fusion is a combustible gas or an electric source.

The various methods used to shield the weld from the atmospheric gases and their undesirable effects on the molten weld pool and surrounding hot parent metal are often used to further define the welding processes. For example, the oxy-fuel gas process relies on a flame to provide heat and shielding, where resistance welding relies on high current for resistance heating but does not have a visible heat source and does not require shielding.

The arc welding processes use a visible electric arc to provide heat and have some form of shielding to protect the arc zone from atmospheric contamination.

To be effective, any welding process basically requires the application of three basic operations:

- **heat or energy source** – needed for melting parent and filler material and fusion
- **atmospheric shielding** – to prevent oxygen and nitrogen in the atmosphere from contaminating the weld and weld zone
- **filler metal** – to provide the required fill and weld build-up.

The above factors will be looked at in our more detailed examination of the various welding processes; however the most important thing to be considered before any welding or cutting operations are carried out is the safety of the welding operator and those around them. A clean, tidy workplace, free from clutter and debris and combustible materials is also an essential requirement for the safety of all welding personnel.
In this chapter we will look at the following.

- **Personal safety**
  - electric shock
  - fumes
    - control of fumes
  - radiation
  - fire and explosion
  - burns
  - noise

- **Special hazards**
  - confined spaces/hazardous locations
  - cutting or welding near hazardous locations
  - working on tanks and containers
  - cylinder colours
  - working on scaffolds

- **First aid for welders.**
Personal safety

To achieve safe working conditions in industry, all personnel should be able to recognise potential hazards that apply to their particular occupation and then take the appropriate preventative measures.

As a worker within the general metal fabrication industry, the welder can be subjected to all of the safety hazards associated with this industry. They may be injured through incorrect lifting practices, falling or tripping, or incorrect use of hand tools and machines.

Additionally, others working in the vicinity of welding operations are at risk from hazards such as fumes, radiation, flying slag, fire or explosions. They too must be protected if their safety and health is not to be put at risk.

The major hazards associated with any welding operations are:

- electric shock
- fumes
- radiation
- fire and explosion
- burns
- noise.

Electric shock

Electrical principles and requirements for arc welding machines will be discussed in later sections, however at this stage it is necessary to clarify some basic electrical terms.

- **Voltage** is the force which makes current flow. Voltage is essentially electrical pressure.
- **Current** is a measure of the amount of electrons flowing and is expressed in amperes.
- **Open circuit voltage** is the voltage between welding terminals when the machine is switched on but welding is not in progress.
- **Resistance** is the hindrance of a conductor to the passage of current.
- **Conductor** is a material that permits the easy flow of electricity.
- **Insulator** is a material that will not convey an electric current.

The effects of electric shock on a welding operator may simply be a slight tingling sensation when the body is exposed to low voltage and electric current. A more severe exposure may cause pain and muscle contractions and superficial burns at the entry site.

If the electrical force (voltage) is sufficient to cause high current flow, then the welder may have symptoms ranging from slight to severe muscle contractions and burns. If the current path is through vital internal body organs such as the heart, then death from cardiac arrest may occur.
Chapter 2 – Welding safety

The prevention of electric shock from welding equipment relies on three major principles.

1. The voltages at the output terminals of a welding machine are kept low enough to prevent easy passage of lethal current through the body.
2. Electrical resistance in any potential circuit is kept low. Current will take the path of least resistance, however effective insulation will prevent or inhibit current flow.
3. Voltage and current path are confined to the welding circuit.

Welding power sources

Some of the arc welding power sources that are commercially available are capable of supplying a wide range of welding current that enables the machine to be used for different applications. The power source must have a front label that clearly describes the characteristics of the machine in terms of the input voltage and output voltages at no load (or open circuit voltage) and output current and duty cycle. The output voltages at typical load currents should also be shown on the label. Open circuit voltage should be in the 35–80 V range for AC, and 32–110 V range for DC.

Typical voltages under load or (arc voltage) may be anywhere in the 16–40 V range, depending on the welding process. The gas tungsten arc welding process for example tends to load up the power source more than other processes and will operate successfully at 16 V or above. Solid wire processes such as submerged arc welding or gas metal arc welding may operate over a wider range between 16–40 V. The manual metal arc welding process however generally needs to have a power source that is able to deliver a safe OCV that enables easy arc starting and a minimum 24 V under load to successfully run most of the covered electrodes.

Power sources generally operate over a maximum output voltage range that is restricted by law and complies with the requirements of Australian Standard® AS1674.

To maximise the safety of the welding operator and reduce the risk of electric shock or electrocution, the OCV of arc welding power sources is restricted to:

- Maximum OCV for DC machines – 110 V
- Maximum OCV for AC machines – 80 V

Even with these limitations, severe electric shock is still possible. In fact welders have been known to have been electrocuted when using a power source with an OCV as low as 45 V.

Input voltage or anything on the primary connection side of the welding machine can be a source of potentially fatal electrical shock in a welding circuit. Only licensed electrical trades people are allowed to work on the 240 V or 415 V input or any internal circuits of a welding machine. Make sure the input lead insulation is not damaged, and that all input connections are tight and secured.

Welding output voltage and current occurs between the output terminals. The output circuit of a welding machine is not generally connected to the frame or earth of the welding machine.

Between the output connections and any cables, work clamps or a torch connected to them should be treated as live when the welder is turned on. All connections should be tight and all insulation should be secure and properly maintained.
Welding power sources can also supply power for ancillary devices such as hot boxes, or supply voltages and control circuit voltages for remote devices and wire feeders.

The voltages used for these devices can vary up to a dangerous 110 V. Typically, a safe voltage such as 24 or 32 V is now used. Individual manufacturers may also provide auxiliary power at other voltages.

High frequency type outputs tend to increase the risk of insulation breakdown or electrocution because they assist current to flow.

Factors determining the severity of electric shock

- The amount of current passing through the body
  - A current flow of less than 0.04 amperes can cause tingling or pain.
  - A current flow above 0.05 amperes can cause muscle contraction and stop a human heart.

- The duration of the current flow
  - A longer current flow time increases the risk.

- The amount of voltage present in the circuit
  - Increased voltage will result in greater current flow, but even quite low voltages can be dangerous.

- The current path
  - If the current path is via vital organs, then the risk of serious injury is much greater.

- The state of health of the person receiving the shock
  - A weak or sick person would be more susceptible.

- The phase of the heart cycle at the instant the shock occurs.

The body's electrical resistance

The body is a good conductor because of its water content, but dry skin acts as an insulator that naturally resists the flow of current. Moist skin in contact areas, and contact over large areas, increases the chance of electric shock. Dry protective clothing, gloves and footwear increase insulation and resistance, thereby reducing the possibility of electric shock.

- Normal dry skin has a resistance of approximately 100 000 Ohms and if exposed to 80 volts will allow 0.0008 Amps to flow using the rule $A = \frac{v}{r}$ or $80/100\,000$.

- Wet skin has a resistance of approximately 500 Ohms and if exposed to 80 volts will allow 0.16 Amps to flow using the rule $A = \frac{v}{r}$ or $80/500$.

- Wet skin and a short current path with resistance of 250 Ohms and if exposed to 50 volts will allow 0.2 Amps to flow using the rule $A = \frac{v}{r}$ or $50/250$. 
Figure 2 has been removed. It was reproduced from page 29 of AS 1674.2-2007.

Fig 2.1 – Transformer type welding circuit

Avoiding electric shock
The following practices are highly recommended.

- Input electrical supply circuits (primary) should be kept as short as possible and be serviced only by electrical tradespersons.
- Welding equipment should be in good repair and fully insulated.
- Work return contact points should be close to the site of welding and be carefully selected. All connections should be clean and tight.
- Machines should be switched OFF and unplugged when changing leads or carrying out any maintenance.
- When the machine is to be left without any welding taking place, electrode stubs should be removed and the machine should be turned off.
- The welding circuit should be isolated by a circuit breaker when it is not actually being used for welding or for changing of electrodes. Alternatively, a VRD (voltage reduction device) should be fitted to the welding machine.
- Avoid any moisture and keep everything dry. Remember, sweating decreases body insulation, therefore be extra careful when involved in welding under hot conditions.
- Dry insulating material such as wooden boards or rubber mats should be used in confined spaces.
- Dry gloves in good repair should be worn when handling any welding circuit or equipment, particularly when changing electrodes.
- Footwear should be insulating, dry and in good condition.

**Fumes**

Studies in safety and health in welding suggest the main adverse health risk for welders is working in confined spaces for extended periods of time. Investigators have found a higher incidence of respiratory ailments in this group. Welders are known to have higher incidence of bronchitis and emphysema.

Further studies found that although arc welding produces visible, infra-red and ultraviolet light that increases in intensity with current and this radiation represents risk to welders, particulate fumes represent the greatest health risk to welders.

**Sources of fumes**

Fumes are produced in all welding and cutting operations. Fumes may be a mixture of:

- any by-products of a combustion process (carbon dioxide or carbon monoxide or any other gases)
- any chemical reaction between atmospheric gases such as nitrogen or oxygen in the vicinity of the electric arc (nitrogen dioxide, ozone)
- arc shielding gases such as carbon dioxide, argon, helium or the various gas mixtures
- vaporised materials or elements such as iron, manganese, nickel, zinc, chromium or cadmium from the parent metal, metal coatings, or welding consumables
- airborne particles from metal working, grinding, welding or fluxes that are small enough to be inhaled.
Chapter 2 – Welding safety

Effects of fumes

Research suggests that the buildup of any welding fumes in a well-ventilated workshop is normally at low levels and tends to pose no great health risk. However, given that most workshops are not effectively ventilated, any concentration of fumes from highly toxic metals, even in low concentrations, may also cause health problems with respect to the upper respiratory tract, lungs, blood, liver, kidneys, and central nervous system. The welder may also be deprived of the basic oxygen level needed to maintain good health.

Certain constituents found in welding fumes are recognised as being particularly dangerous, even in very low concentrations. Welding operators should be aware of the dangers associated with working with metals such as beryllium, cadmium, zinc, and lead.

Table 2.1 gives an indication of the toxicity of some of the fumes more commonly encountered by welding operators.

<table>
<thead>
<tr>
<th>Metal fumes</th>
<th>Effect</th>
<th>Fume source</th>
<th>Ventilation recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminium (Al)</td>
<td>irritation to eyes, nose and throat chronic bronchitis</td>
<td>parent metal</td>
<td>local exhaust</td>
</tr>
<tr>
<td>antimony (Sb)</td>
<td>irritation to eyes, skin, nose and throat, and lungs heart damage stomach upsets</td>
<td>alloys</td>
<td>local exhaust</td>
</tr>
<tr>
<td>arsenic (As)</td>
<td>dermatitis stomach upsets headache nasal infections cancer internal organ damage</td>
<td>alloys</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>barium (Ba)</td>
<td>dust disease stomach and circulatory system problems</td>
<td>some inner shield wires</td>
<td>local exhaust</td>
</tr>
<tr>
<td>beryllium (Be)</td>
<td>carcinogen, highly toxic, quick acting poison eye damage respiratory failure chronic illness</td>
<td>alloys</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>boron (B)</td>
<td>irritant to eyes, skin, respiratory system</td>
<td>alloys</td>
<td>local exhaust</td>
</tr>
<tr>
<td>cadmium (Cd)</td>
<td>highly toxic, carcinogen heart, lung and kidney damage</td>
<td>alloys surface coating</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>Metal fumes</td>
<td>Effect</td>
<td>Fume source</td>
<td>Ventilation recommended</td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
<td>-------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>chromium (Cr)</td>
<td>carcinogen, toxic to lung and skin&lt;br&gt;nasal irritation</td>
<td>alloys</td>
<td>local exhaust</td>
</tr>
<tr>
<td>copper (Cu)</td>
<td>irritant to nose and throat&lt;br&gt;metal fume fever&lt;br&gt;stomach upsets</td>
<td>parent metal&lt;br&gt;alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>cobalt (Co)</td>
<td>irritant to eyes, skin, respiratory and circulatory system</td>
<td>alloy</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>iron (Fe)</td>
<td>benign siderosis&lt;br&gt;possible carcinogen</td>
<td>parent metal</td>
<td>general ventilation</td>
</tr>
<tr>
<td>lead (Pb)</td>
<td>fatigue, insomnia, headache&lt;br&gt;muscle aches and pain, stomach upsets&lt;br&gt;brain, nerve and kidney damage&lt;br&gt;high blood pressure</td>
<td>parent metal&lt;br&gt;coatings</td>
<td>local exhaust&lt;br&gt;aux. air supply</td>
</tr>
<tr>
<td>lithium (Li)</td>
<td>irritant to eyes, skin, respiratory system</td>
<td>alloy</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>magnesium (Mg)</td>
<td>irritant to eyes, skin, respiratory system&lt;br&gt;metal fume fever</td>
<td>parent metal&lt;br&gt;alloy</td>
<td>general ventilation</td>
</tr>
<tr>
<td>manganese (Mn)</td>
<td>toxic, chronic damage to brain and nervous system&lt;br&gt;irritant to eyes, throat, skin, respiratory system</td>
<td>alloy</td>
<td>local exhaust&lt;br&gt;aux. air supply</td>
</tr>
<tr>
<td>mercury (Hg)</td>
<td>chronic damage to brain, bones and teeth&lt;br&gt;nausea&lt;br&gt;irritant to skin and respiratory system</td>
<td>parent metal&lt;br&gt;alloy</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>molybdenum (Mo)</td>
<td>mild irritant to eyes and respiratory system</td>
<td>alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>Metal fumes</td>
<td>Effect</td>
<td>Fume source</td>
<td>Ventilation recommended</td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
<td>-------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>nickel (Ni)</td>
<td>skin and respiratory irritation and mutations cancers heart, lung, kidney damage</td>
<td>parent metal alloy</td>
<td>local exhaust aux. air supply</td>
</tr>
<tr>
<td>silver (Ag)</td>
<td>metal fume fever major irritant to eye, skin, respiratory system</td>
<td>parent metal alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>thorium (Th)</td>
<td>cancer irritant to respiratory system (radioactivity is absorbed by body)</td>
<td>parent metal alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>tin (Tn)</td>
<td>benign stenosis of lungs (seen on x-ray)</td>
<td>parent metal solders alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>titanium (Ti)</td>
<td>irritant to eyes, skin, respiratory system</td>
<td>parent metal alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>tungsten</td>
<td>hard metal disease</td>
<td>parent metal alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>vanadium (V)</td>
<td>irritant to skin, eyes, respiratory system green tongue bronchitis chemical pneumonia</td>
<td>alloy</td>
<td>local exhaust aux. air supply</td>
</tr>
<tr>
<td>zirconium</td>
<td>cancer irritant to respiratory system (radioactivity is absorbed by body)</td>
<td>parent metal alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>zinc (Zn)</td>
<td>metal fume fever irritant to eyes, skin and respiratory system</td>
<td>parent metal alloy</td>
<td>local exhaust</td>
</tr>
<tr>
<td>Gases</td>
<td>non-toxic effect</td>
<td>Fume source</td>
<td>Ventilation recommended</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>acetylene (C₂H₂)</td>
<td>not-toxic, mild anaesthetic, depressant effect</td>
<td>fuel gas</td>
<td>general ventilation</td>
</tr>
<tr>
<td></td>
<td>displacement of oxygen in atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>argon (Ar)</td>
<td>non-toxic</td>
<td>inert gas</td>
<td>general ventilation</td>
</tr>
<tr>
<td></td>
<td>displaces oxygen in atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>carbon dioxide (CO₂)</td>
<td>non-toxic</td>
<td>combustion by product</td>
<td>local exhaust aux. air supply</td>
</tr>
<tr>
<td></td>
<td>displaces oxygen in atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>carbon monoxide (CO)</td>
<td>displaces oxygen in atmosphere attaches to blood and prevents oxygen being absorbed, may lead to coma and death</td>
<td>combustion by product</td>
<td>local exhaust aux. air supply</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>helium (He)</td>
<td>non-toxic</td>
<td>inert gas</td>
<td>general ventilation</td>
</tr>
<tr>
<td></td>
<td>displaces oxygen in atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nitrogen</td>
<td>nitrogen is non-toxic but will displace oxygen in atmosphere</td>
<td>inert gas</td>
<td>general ventilation</td>
</tr>
<tr>
<td></td>
<td>nitrogen oxides can cause respiratory problems</td>
<td>action of arc on atmospheric gas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>nitrogen dioxide is toxic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oxygen (O₂)</td>
<td>supports combustion, can cause burning to skin, throat and lung lining</td>
<td>oxidising gas</td>
<td>general ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ozone (O₃)</td>
<td>irritant to eyes, skin, respiratory system problems or failure, headache, bronchitis, fatigue</td>
<td>arc welding zone</td>
<td>local exhaust</td>
</tr>
<tr>
<td>phosgene (COCl₂)</td>
<td>highly toxic, severe irritant to eyes, respiratory system problems or failure</td>
<td>chlorinated hydrocarbons exposed to UV</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>phosphine (PH₃)</td>
<td>severe irritant to eyes, respiratory and digestive system, fits, headache, coma</td>
<td>phosphate paint exposed to UV</td>
<td>isolation box, fresh air supply</td>
</tr>
<tr>
<td>stubine</td>
<td>damage to blood and then vital organs (brain), may be fatal</td>
<td>cutting brass/ bronze alloys</td>
<td>isolation box, fresh air supply</td>
</tr>
</tbody>
</table>
### Table 2.1 – Toxicity of fumes; metals, toxics and solvents

<table>
<thead>
<tr>
<th>Toxics</th>
<th>Effect</th>
<th>Fume source</th>
<th>Ventilation recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>calcium carbonate</td>
<td>irritant to eyes, skin, respiratory system</td>
<td>welding flux</td>
<td>local exhaust</td>
</tr>
<tr>
<td>fluorides</td>
<td>irritant to eyes, skin, respiratory system</td>
<td>hydrogen-controlled rods, welding fluxes</td>
<td>local exhaust</td>
</tr>
<tr>
<td>titanium oxide</td>
<td>irritant to eyes, skin, respiratory system</td>
<td>welding flux</td>
<td>local exhaust</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solvents</th>
<th>Effect</th>
<th>Fume source</th>
<th>Ventilation recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>alcohols</td>
<td>blindness, skin irritant, brain and liver damage</td>
<td>methanol-based cleaner</td>
<td>local exhaust</td>
</tr>
<tr>
<td>basic hydrocarbons</td>
<td>irritant to skin, brain damage</td>
<td>white spirits, kerosene etc</td>
<td>local exhaust</td>
</tr>
<tr>
<td>TCEs</td>
<td>irritant to eyes, skin, respiratory system</td>
<td>welding flux</td>
<td>local exhaust</td>
</tr>
</tbody>
</table>

An isolation box is a sealed chamber into which the job is placed. Access is via gloves built into the wall of the chamber.

### Control of fumes

To ensure that the concentration of fumes and exposure to fumes are within safe limits, various controls can be applied.

- **Substitution**
  
  Where practicable, a less dangerous material, consumable, process or procedure can be substituted.

- **Limiting the period of exposure**
  
  Limiting the time any one welder is exposed to excessive fume concentration is not the most desirable method, but in some cases may be the only practical solution.
- **Work methods**
  Good housekeeping and work practices can avoid the unnecessary generation of fume and exposure to it; for example, removing surface contaminants from parent material prior to welding or cutting. It should be noted that certain degreasing agents such as the chlorinated hydrocarbons decompose under heat and ultraviolet radiation to give off toxic fumes.

- **Ventilation**
  This is the most common method of control and can be achieved by various means.

**Types of ventilation**

- **Natural ventilation**
  In the greater majority of workshops and open sites, the natural flow of air is sufficient to disperse fume concentrations.

![Fig 2.2 – Natural ventilation](image)

- **General ventilation**
  This method is often used where the workshop does not have adequate natural ventilation. Fumes rise and are dispersed into the atmosphere, generally through ceiling exhaust fans.

![Fig 2.3 – General ventilation](image)
- **Local exhaust ventilation**
  This method collects the fume at its source and directs it away from the work area. The suction inlet should be as close as possible to the source of the fume. There are various types of local exhaust systems, each offering certain advantages and suited to certain applications.

![Fig 2.4 – Dedicated welding booth](image)

- **Local dispersion ventilation**
  In some cases, suitable ventilation can be obtained locally by fans which deflect and disperse the fumes away from the welder.

![Fig 2.5 – Local dispersion ventilation](image)

**Personal respiratory protection**
In special situations where general or local ventilation systems are not effective or convenient in reducing fume levels, personal respiratory protection by one of the following methods (complying with AS/NZS 1716) is required.

- **Hose mask respiration method**, which is a full-face piece fitted with a length of relatively large bore air hose, drawing from a clean source by the normal breathing action of the wearer.
- **Airline respiration** which may comprise a full-face piece, half-face piece, hood or helmet type. Clean air is supplied at a suitable pressure from a remote source.
- **Self-contained breathing apparatus** using a cylinder of compressed air. This equipment is not dependent on an air compress which may be subject to failure, and is recommended for use in confined spaces.
- **Dust respirator** which may consist of a full-face, or half-face mask, fitted with the correct filter cartridge.
Radiation

Types of radiation

Three types of radiation are emitted by the arc welding processes: visible radiation, infra-red radiation and ultraviolet radiation. Low levels of these radiation types are also emitted from the flame and materials in gas welding and cutting.

Visible radiation

Exposure to high intensity visible radiation may result in ‘dazzle’, with temporary loss of vision and fatigue. There may be permanent damage to the eyes over the long-term.

Infra-red radiation

Infra-red radiation acts in the same manner as exposure to surface heat, producing burns. Permanent damage is unlikely unless exposure is severe, but the heat adds to discomfort. Repeated exposure to infra-red radiation and burns can cause skin cancers and damage the unprotected structure of the eye, such as the iris, the lens and the retina. In severe cases of repeated exposure to luminous infra-red, eye cataracts can develop.

Fig 2.6 – Personal respirators

These provide protection only against fume particles and not against gases.
Chapter 2 – Welding safety

Ultraviolet radiation

Ultraviolet (UV) radiation is the most common and powerful radiation hazard in welding. This radiation type attacks the subsurface layers of exposed skin and eyes.

Brief ultraviolet radiation exposure to unprotected skin can produce inflammation symptoms similar to sunburn. Longer exposure times or more intense radiation levels can produce severe burns and blistering skin that may require hospitalisation and/or result in permanent damage to the skin.

The eye is particularly sensitive to UV rays and even brief exposure to unprotected eyes can result in a condition known as ‘arc eye’ or ‘welding flash’. This is accompanied by pain, watering of eyes, and photophobia (intolerance to light).

Prolonged exposure to ultraviolet light can cause permanent damage to eyes and exposed skin in the form of impaired vision, cataracts and damaged skin or skin cancer. The symptoms of radiation burns or ‘arc eye’ develop over time and sometimes do not appear until several hours after the exposure. These symptoms may last several days in severe cases but generally subside, leaving no permanent or residual damage.

The amount of ultraviolet radiation emitted from the arc depends on several factors such as the welding process type, the type of electrode, the amperage and the arc length.

Welding processes such as gas tungsten arc and gas metal arc welding in particular, emit powerful ultraviolet radiation because of their high current densities and open arc characteristics.

The GMAW and GTAW welding processes therefore require the welder to take greater care and precautions against exposure to radiation. The use of a welding lens one shade darker than those recommended for MMAW is also recommended (refer to Table 2.2).

Protection from radiation

Personal protection

Protection is needed for both the eyes and skin. For arc welding, a suitable welding helmet or face shield, fitted with the recommended filter lens for the job in hand, is necessary.

Recommended filters for manual metal arc welding are given in Table 2.2.

<table>
<thead>
<tr>
<th>Recommended filters for MMAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Up to 100</td>
</tr>
<tr>
<td>100–200</td>
</tr>
<tr>
<td>200–300</td>
</tr>
<tr>
<td>300–400</td>
</tr>
<tr>
<td>Over 400</td>
</tr>
</tbody>
</table>

Table 2.2 – Recommended filters for MMAW as per AS/NZS 1338.1:1992
Oxy-acetylene or fuel gas welding, heating and cutting flames give off infra-red and ultraviolet rays. Although the rays are not as concentrated as those of the arc, they have a similar effect on the eyes over a long period of time.

As with arc welding, the oxy-welding processes require operators to protect their eyes from damage that can be caused by injurious rays, sparks and flying scale.

For gas welding and cutting, the use of protective goggles fitted with the recommended filter is essential.

The correct type and shade of lens must be used at all times: refer to Table 2.3.

<table>
<thead>
<tr>
<th>Description of operation</th>
<th>Type of work</th>
<th>AS/NZS 1338.1: 1992 Shade No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxy-cutting and gouging, flame descaling, silver brazing, fusion welding zinc die cast, braze welding light gauge copper pipe and steel sheet</td>
<td>light and general cutting</td>
<td>4</td>
</tr>
<tr>
<td>Fusion welding of copper and its alloys, nickel and alloys, medium thickness steel plate Braze welding of heavy steel, cold cast iron, hard facing</td>
<td>general</td>
<td>5</td>
</tr>
<tr>
<td>Fusion welding heavy steel, heavy and hot cast iron Braze welding hot cast iron and cast steel</td>
<td>heavy work</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2.3 – Recommended filters for OAW as per AS/NZS 1338.1:1992

**General welding safety**

All personnel working with or near welders should wear safety spectacles complying with the requirements of AS/NZS 1336. Safety spectacles fitted with glass lenses not less than 3 mm thick, or plastic lenses not less than 2 mm thick (incorporating a shade filter of up to 2.5), are highly desirable to give protection from stray welding flashes.

In order to protect the skin from radiation, it is essential that suitable clothing is worn to cover all areas that could be exposed to radiation. Woollen materials have much greater resistance to ultraviolet radiation than synthetic and plain cotton materials, which can rapidly deteriorate or rot when exposed to strong ultraviolet radiation. Leather aprons, sleeves, jackets and gloves are usually required in welding processes where strong radiation is emitted (refer to Fig 2.7).

It is most important to realise that all three radiation types can be reflected from shiny surfaces – such as the underside of galvanised roofs, plates, or painted screens.
Where reflection is likely, for example in welding on highly reflective metals such as aluminium or stainless steel, protection for the eyes and skin against indirect radiation is required.

All welding processes require the operator to protect him/herself from the radiated heat and rays associated with the process. Perhaps the most efficient way of doing this is by the wearing of protective clothing. The use of all protective clothing is dictated by the nature of the work and the comfort of the operator.

Ideally, dress for the operator should consist of the following items.

Always take care to check clothing for frayed edges, torn areas and open pockets where sparks can lodge and start burning. Work clothes should also be free of oil or grease. This may be difficult in some workshops, but a spare pair of clean overalls could be left at work specifically for welding operations.
Personal safety for oxy-fuel gas operators

- Be neat and clean about your work.
- Keep your equipment in good condition.
- Wear your eye protection when using a blowpipe. It protects your eyes from sparks, from flying slag, and from the strong light and harmful rays from the flame. It also helps you to see your work better.
- Wear the proper gloves, apron, shoes, and any other protective clothing provided.
- Watch out for sparks landing on your sleeves, cuffs and open pockets.
- Never use oxygen to dust clothing or work.
- Never use matches to light a blowpipe. Use a flint lighter or pilot light.
- Clear all inflammable material at least 10 m away from where you are welding or cutting.
- Keep flame, sparks and hot metal away from cylinders and tubing.
- When working on any metal giving off poisonous fumes, use proper ventilation or wear a suitable respirator.

Protection of others

Adequate protection should be provided for all personnel within about 12 m of an open arc or gas flame. Suitable screens, either fixed or portable, are desirable. These screens and surrounding walls or partitions should have a matt finish and dull colours in order to reduce reflection.

Fire and explosion

Flame cutting and welding operations are a major cause of industrial explosions and fires. Each year losses can amount to several million dollars, and loss of life or severe injury resulting from explosions or fire. The safety requirements depend largely upon the processes being used and the location of the work being carried out. Protection against fire and explosion should comply with statutory regulations covering prevention and comply with the requirements of AS 1674.

Sources of fire

Even though the temperature of the arc or flame of welding or cutting is more than sufficient to cause combustion of many materials, a direct flame or electric arc is rarely the cause of an actual fire. Any materials such as wood, wood-based products, paper, synthetic materials, oil and grease soaked materials with a low ignition temperature that are in the immediate vicinity of any cutting or welding operations will certainly easily ignite. However, ignition will most likely occur by contact with hot metal sparks, electrode stubs and spatter.

Any type of flammable or combustible materials should be cleared away from any welding or cutting areas for a distance of at least 10 m, as hot particles lodged amongst them may produce smouldering and fire at a later stage.

When considering the area affected by cutting and welding sparks, account should be taken of the process and the job situation. Cutting and gouging can produce high velocity particles travelling long distances, and hot particles falling from a high workstation will travel further than normal, as illustrated in Fig 2.8.
Fire prevention
- Don’t let rubbish pile up in your work area. Remove it as it comes in.
- Throw oily, greasy, or paint-stained rags into special bins and remove them as soon as possible.
- Keep areas around stored timber or other combustible material free from weeds and scrub.
- Store all flammable liquids and explosives in isolated areas and do not smoke near them. Use only non-sparking tools to open the containers of these materials.
- Don’t let material that can burn stay in the near vicinity of welding and flame cutting operations.
- Don’t walk or wheel materials over flexible electric cables. You could accidentally cut the wire, causing sparking and a fire.

Causes of explosion
The risk of explosion is always present when welding or cutting, as these processes may project hot sparks into an atmosphere containing flammable gases, liquids or solids. Non-volatile oils or solids (which do not produce flammable gases at atmospheric temperatures) may produce flammable or explosive gases when exposed to heat and oxygen from welding or cutting. Drums, fuel tanks and other containers pose a particular hazard to the safety of the welding operator, and no cutting or welding should be carried out on them until all precautions have been carried out and the job has been made safe.
Fire and explosion become greater hazards in situations where flammable gases and liquids are present. In the ordinary workshop, welders should be aware of normal fire precautions.

**Prevention of fire and explosion**
- Maintain clean and tidy work areas, free from accumulations of combustible materials.
- Check that work introduced for cutting or welding does not constitute a fire or explosion hazard.
- Ensure that screens, welding aids and building fittings are not constructed from flammable materials.
- Ensure that personal clothing is sound and made from the most suitable materials.
- Store flammable substances and gases in a safe area or separate building.
- Be aware of fire extinguisher locations and how to operate each type.
- Avoid oxygen enrichment of clothing or work space, as may be caused by leaking oxygen valves.

**Burns**

Because welding and cutting is associated with intense heat, the welder is always in danger of receiving painful burns.

Burns are classified in terms of their extent and depth. The extent of a burn is described by calculating the burned area as a percentage of total skin area.

Depth of a burn is described by degree.
- A ‘superficial burn’ produces reddening of the skin (1st degree).
- An ‘intermediate burn’ produces blistering (2nd degree).
- A ‘severe burn’ extends below the surface of the skin and causes injury to underlying tissues (3rd degree).

In welding and cutting operations, burns result from:
- ultraviolet and infra-red radiation
- contact with slag, sparks and hot particles
- contact with hot work or heat radiated from work
- electrical leakage, in particular, leakage from high frequency devices
- fire and explosions.

**Protection from burns**
- Use tongs to handle hot metal and mark ‘hot’ work.
- Make provision for disposal of hot metal and electrode stubs.
- Wear all necessary protective clothing.
- Protective clothing must be non-flammable and free from oil, grease, tears and fraying.
Noise

In the metal fabrication and welding industry, noise of all types has been a constant problem. Noise occurs at various frequencies (tones) and intensity. Noise is measured in terms of sound pressure levels in decibels – dB (A).

Hazardous noise is any excessive continuous noise that inhibits normal conversation. Excessive noise that is either high in level or continuous over a long period can result in permanent damage to hearing. Use noise control methods and wear personal hearing protection.

Special hazards

There are special work situations which present increased hazards to the safety and health of the welding operator. These are:

- confined spaces
- hazardous locations
- working on tanks and containers.

Confined spaces

Working in confined spaces usually entails difficult entry/exit and/or cramped conditions. The workplace is often poorly ventilated and the welder is often completely surrounded by a conductor which forms part of the welding circuit. Under these circumstances, the welding operator is at increased risk from the following.

A build-up of fumes

The possibility of a build-up of dangerous fumes in a confined space due to the use of welding processes in restricted air movement must be allowed for and adequate ventilation must be provided.

- Exhaust fans must be used.
- Additional supplementary air supply may be required.

Electric shock

The possibility of an electric shock is greater because the welder can easily make contact with the job and awkward and enclosed workplaces often lead to higher levels of perspiration.

- The welder should keep themselves dry as possible and use all necessary protective clothing to prevent electrocution.
- An all-insulated electrode holder shall be used.
- High-frequency attachments shall not be used.
- Portable electric lamps exceeding 32 V supply shall not be used. Electronic leakage breaker (ELB) devices are acceptable.
- Provision must be made close to the work for power to be switched off by an assistant when:
  - the welder is not prepared for welding
  - the electrode is being changed
  - the welder leaves the job.
Confined space regulations
The following regulations are specified as mandatory when working in a confined space.

- Environment atmosphere tested permit to work must be obtained.
- Adequate ventilation must be provided.
- A lifeline must be attached.
- A semi-skilled operator who is trained in rescue and resuscitation must be stationed at the manhole to monitor the workspace at all times, to adjust oxy-acetylene gear and the welding machine whilst continually observing the welder.
- All leads and hoses are to be kept clear of the floor, dampness and falling metal sparks. Circular vessels must be prevented from rolling.
- General tidiness and care is essential, equipment should not be allowed to contact hot work or sharp objects.
- Oxy-cutting equipment should not be left inside the confined space when not in use, and it should always be lit by the assistant outside and then passed to the welder.
- Oxygen should never be used for dusting down or any purpose other than the oxy-flame.

Fig 2.9 – Precautions for cutting or welding in confined spaces
Hazardous locations

Although many workplaces may be described as hazardous, a ‘hazardous location’ is defined as an area where any flammable liquids, solids, dusts, fibres or gases may be present so as to pose a fire or explosion hazard.

Hazardous locations may be classified into four main groups (some examples are provided below).

1. Typical locations in which flammable or combustible liquids are manufactured, used, handled or stored, or where vapours may be present. For example:
   - refineries, fuel stores
   - dry cleaning plants
   - spray painting premises
   - varnish and paint manufacturing plants.

2. Typical locations in which combustible dust is thrown into suspension in the air and quantities may be sufficient to produce explosive mixtures. For example:
   - sections of flour mills
   - grain elevators
   - coal pulverising plant.

3. Typical locations in which easily ignitable fibres are produced, handled, used or stored. For example:
   - cotton or cotton seed mills
   - wood working plant
   - sections of clothing factories.

4. Any location or part of a ship.

Cutting or welding in or near hazardous locations

If at all possible, the work shall be removed from the hazardous location and carried out in a safe location.

Cutting or welding in/or adjacent to hazardous locations shall not take place until the following conditions have been established.

- It is impractical to move the work to a safe area.
- The production of any hazardous or explosive substance has ceased or been excluded from the precise location.
- The location has been tested and found to be free from flammable substances.
- A hot-work permit has been obtained (see Appendix 2).
- Authorisation has been obtained from the responsible officer.
In general terms, the welder’s responsibility with respect to hazardous locations can be expressed as follows.

- Always examine the possibility of removing the work to a safe area.
- Always examine work areas for possible hazards.
- Seek authorisation before proceeding with cutting or welding whenever any doubt exists.
- Work must be carried out in accordance with the provisions of the hot-work permit.
- Be aware of the location of any firefighting equipment.
- Be vigilant in the provision and maintenance of any safety screens, doors or barriers required to ensure safety.
- Be vigilant in the possible entrapment or catching of any sparks, offcuts or electrode butts as provided for in the safety arrangements.
- Always check behind walls, partitions, bulkheads etc, to ensure safety in adjoining areas.

A fire watch must be maintained for a minimum of one hour after any cutting and welding operations have ceased.

**Working on tanks and containers**

**Responsibility for work**

When approaching a job on tanks or containers, the welder should display the same caution as when working in hazardous locations. If there is any possibility that the container may have held petrol, oil or any volatile liquid, special precautions are necessary.

Sight and smell are not reliable indicators of the presence of flammable gases, as some substances may only release these gases when heated. Doubtful cases should be referred to a qualified person for testing, and subsequent work carried out by experienced welders.

**Recommended practice**

Where steam is available, this may be used to remove materials which are easily volatile. Washing with strong soda solution or detergents will remove heavier oils.

Chlorinated hydrocarbon solvents must **not** be used for cleaning prior to welding.
Even after thorough cleansing, the container should (whenever possible) be filled with water before any cutting or welding operation is performed. In practically every case, it will be found possible to place the container in such a position that it can be filled with water to within a short distance from the point where cutting or welding is to be done.

In doing this, however, care must be taken to ensure that there is a vent or opening to provide for the release of heated air from the container. Where it is not possible to fill the container with water, carbon dioxide or nitrogen may be used for added protection. If possible, periodic examination of the air contents of the vessel should be made by means of a detector of combustible gases, where such an instrument is available.

![Fig 2.10 – Preparation of tanks for welding](image)

**Radiography**

Radiographic examination of welds using x-rays or gamma rays to penetrate welded joints and project onto film is now fairly common practice. Often this quality assurance function has to be carried out in the workshop at various project stages.

The ionizing radiation emitted from either the x-ray or gamma ray source units is invisible and can be extremely harmful to any part of the human body. Strict control measures must be followed whenever these operations are to be carried out, to prevent any person being exposed to harmful radiation.

All staff must be made aware of the danger involved and the safety procedures that should be followed. The following precautions should be observed.

- Whenever practical, radiographic testing should be carried out when most staff are not in the immediate area (e.g. overnight).
- Equipment or exposure containers must be secured and kept locked at all times.
- Radiographic equipment must not be tampered with or operated by unauthorised personnel.
Operators of radiographic equipment must be licensed and authorised by NATA or similar.

The radiographic operations or the work area should be isolated by barriers designed to exclude any unauthorised personnel. Warning signs should be erected around the restricted area.

Any personnel working in the area must wear film badges or dosimeters that are to be monitored on a regular basis.

Gas cylinders

Oxygen cylinders

An oxygen cylinder is a hollow container of sufficient wall thickness and strength to withstand much more than the filling pressure (safety factor). Into this container a cylinder valve is screwed, to which a regulator may be attached. Oxygen cylinders are painted black and have right-hand threads.

Oxygen gas is compressed and forced into the cylinder to produce a pressure to a maximum of 17 5000 kPa at 15 °C. One size of cylinder (G) commonly used will hold in excess of 8.9 m³ (8900 litres) of gas under pressure. Because oxygen cylinders are therefore very dangerous, they are fitted with bursting discs that are designed to vent off any excessive increases in cylinder pressure.
Acetylene cylinders

An acetylene cylinder is rather different from an oxygen cylinder. The cylinder is not hollow, because acetylene is extremely unstable when compressed in a free area. The cylinder is filled with a porous material saturated with liquid acetone.

The outside shell of the container is not required to be very strong, as the pressures involved are not very high. Fusible plugs that melt at 100 °C are provided in acetylene cylinders to vent off acetylene should any overheating occur (increased temperature would increase pressure).

Acetylene cylinders are painted claret and have left-hand threads.

Liquefied petroleum gas cylinders (LPG)

LPG cylinders are hollow containers of the required mechanical strength in which the gas is stored under pressure sufficient to maintain the gas in its liquid form. This is a valuable feature of the gas, for it is possible to store more fuel in liquid form than is possible in gaseous form. LPG in liquid form occupies only 1/270th of the space it occupies as a gas.

The pressure in the container depends upon the type of gas and the temperature. For propane, the pressure varies from 650 kPa at 25 °C to 1180 at 38 °C.

LPG cylinders are fitted with a pressure relief valve to vent off gas, should any overheating occur.

LPG cylinders are painted silver/aluminium and have left-hand threads.
Cylinder safety and handling

General safety

- Keep all empty or full cylinders in separated (e.g., fuel gas, oxidising gas, inert gas) locked and secure storage areas, away from radiators, furnaces, other sources of heat and electrical circuits and direct rays of the sun.
- Close valves of empty cylinders.
- Never tamper with or alter cylinder numbers, marking or colour coding.
- Never try to refill a cylinder or try to mix gases in a cylinder.
- Never use a cylinder or its contents for other than its intended purpose.
- Keep oil and grease away from cylinders. Keep them clean!
- Make sure cylinders are upright and secure and protect cylinder valves from bumps, falls, falling objects and from weather.
- Never allow anyone to strike an arc or tap any electric arc against any cylinder.
- Never draw oxygen or acetylene from cylinders except through properly attached pressure regulators.
- If valves cannot be opened by hand, do not use a hammer or wrench, notify the supplier.
- Never use cylinders as supports or rollers.
- Always remove regulators before moving cylinders, be sure valves are tightly closed before removing regulator.
- Open all cylinder valves slowly. Never open a cylinder valve more than 1½ (one and a half) turns.

Oxygen cylinders

- Always call oxygen ‘oxygen’ not ‘air’.
- Never use oxygen in pneumatic tools, oil pre-heating burners, blowing out pipes or tanks, or anywhere as a substitute for compressed air or other gases.
- Any hydrocarbon (oil, paint, grease etc) can form an explosive compound when subjected to oxygen under pressure. Never use oil on oxygen/fuel gas equipment.

Acetylene cylinders

- Always call acetylene ‘acetylene’ not ‘gas’.
- Always keep acetylene cylinders upright when in use to avoid loss of acetone.
- If an acetylene cylinder valve leaks from or around the spindle, close the valve and tighten the glands. If this fails, or if the fusible plug is leaking, remove the cylinder to the open air, far away from possible sources of ignition. Tag the cylinder properly to explain the trouble and notify the supplier immediately.
- If the acetylene cylinder is on fire or seriously heated, either accidentally or through severe flashbacks, if possible:
  1. shut valve
  2. take the cylinder into the open air
  3. cool with copious supply of water.
If an acetylene cylinder is on fire, and cooling is being applied to allow the fire to burn, call fire authorities and evacuate all personnel. Any gas leak that cannot be shut off is more dangerous, because there is a high risk of explosion.

**Cylinder colours**

<table>
<thead>
<tr>
<th>Type of gas</th>
<th>Colour of cylinders</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetylene</td>
<td>claret</td>
<td>cutting and welding</td>
</tr>
<tr>
<td>air</td>
<td>dark admiral grey with black neck</td>
<td>powder cutting</td>
</tr>
<tr>
<td>argon</td>
<td>peacock blue</td>
<td>GTAW and GMAW aluminium welding</td>
</tr>
<tr>
<td>carbon dioxide with 5% or more argon</td>
<td>peacock blue with French grey neck</td>
<td>GMAW steel welding</td>
</tr>
<tr>
<td>carbon dioxide</td>
<td>French grey (green-grey)</td>
<td>GMAW steel welding</td>
</tr>
<tr>
<td>LPG</td>
<td>aluminium</td>
<td>cutting and heating</td>
</tr>
<tr>
<td>hydrogen</td>
<td>signal red</td>
<td>cutting under water</td>
</tr>
<tr>
<td>oxygen</td>
<td>black</td>
<td>cutting and welding</td>
</tr>
<tr>
<td>nitrogen</td>
<td>dark admiral grey</td>
<td>powder cutting</td>
</tr>
<tr>
<td>helium</td>
<td>middle brown</td>
<td>GMAW aluminium welding</td>
</tr>
</tbody>
</table>

Table 2.4 – Colour code for identification of industrial compressed gas cylinders

Labels affixed to the shoulder identify the gas contents of cylinders (Fig 2.13). The properties of the gases contained in cylinders can be determined by the colour of the identification label, ie:

- **red** – flammable gas
- **yellow** – oxidising gas
- **green** – inert gas
- **red and white** – poisonous gas.
Working on scaffolds

Welders working at height should be aware of the special hazards involved; such as falling from height, working with heat or hot material, sparks and spatter and the risk of electrocution and fire. Special safety precautions are required and welders should have sufficient knowledge of scaffold construction and use to enable them to work safely at height.

Because of the increased danger, it is recommended that any person welding or cutting at height should have an assistant and should not be asked to work alone. Any welding or cutting being carried out above hand-held height (1.8 m) should be carried out on platforms or scaffolding erected specifically for the purpose. Working from temporary supports such as ladders, trestles or old oil drums is not permitted.

For welding and cutting operations, the immediate area under and around any scaffolding should be isolated with barriers and warning signs. Attention should be taken to ensure that sparks and spatter do not fall or travel onto combustible material below. Stub ends and offcuts should be caught in a steel container rather than be allowed to fall.

According to AS/NZS 4576 – Guidelines for scaffolding and AS/NZS 1576.1 – Scaffolding – General requirements, anyone working at a height above 2 m must be provided with suitable platforms or scaffolding. Platforms or scaffolding are subject to regulations and should only be erected by suitably trained or qualified personnel.

Fig 2.14 – Mobile scaffolding
The use of mobile platforms of up to 4 m height is allowed, provided they comply with the guidelines given below.

- Where a person or object can fall more than 2 m, the scaffold must be fenced. Typical fencing should consist of handrails/guard rails and these should be set at 900–1100 mm in height with a mid rail at 400–600 mm. Kick boards of 150 mm height are to be fitted at platform level.

- Where a person is working up to 4 m and cannot fall, or cause objects to fall, no qualifications are required to erect scaffolding but the scaffold must be erected to manufacturers’ specifications and the base must be firm and secure.

- Where a person or object can fall more than 4 m, the scaffold must be erected by a person holding the basic level of scaffolding certificate of competency.

- Scaffolding erected for working at heights above 8 m must be erected and maintained by a ticketed scaffold.

Any scaffolding must have suitable safe access/egress. A ladder is suitable, provided it is set at the recommended height-to-base distance ratio of 4:1 and is securely attached to the scaffold.

Whenever a person can fall over 2 m, the use of a fall arrest system is recommended. Equipment or heavy tools that can fall over two metres should be secured using lanyards and small items and tools should be kept in carry bags designed for the purpose.

The use of fibre or nylon ropes is not permitted near any cutting or welding.

<table>
<thead>
<tr>
<th>Question</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is the supporting surface hard and flat?</td>
<td>A soft or uneven supporting surface will cause instability and may lead to the collapse of the scaffold.</td>
</tr>
<tr>
<td>Is the area of operation free of floor penetrations, powerlines and other hazards?</td>
<td>It may be necessary to clearly limit the operational area of a mobile scaffold by erecting barricades or implementing other forms of control in order to isolate the scaffold from hazards.</td>
</tr>
<tr>
<td>Are the castor wheel locks in working order?</td>
<td>A mobile scaffold should not be left unattended or worked from while the castors are in a free-running condition. Castors with inoperative or missing wheel locks should be replaced.</td>
</tr>
</tbody>
</table>

Table 2.5 – Checklist for lightweight aluminium mobile scaffolds

Any toxic material that is used in a workshop must be accompanied by a Material Safety Data Sheet (MSDS), and these should be held in a secure but accessible location. A sample MSDS for chromium, which is a common alloying material, is shown following.
Material safety data sheet (MSDS) for CHROMIUM

1 PRODUCT IDENTIFICATION

PRODUCT NAME: CHROMIUM
FORMULA: CR
FORMULA WT: 52.00
CAS NO.: 7440-47-3
NIOSH/RTECS NO.: CB420000
PRODUCT CODES: 4961
EFFECTIVE: 09/10/86
REVISION #03

PRECAUTIONARY LABELLING: BAKER SAF-T-DATA™ SYSTEM

HEALTH - 0 NONE
FLAMMABILITY - 0 NONE
REACTION - 0 NONE
CONTACT - 0 NONE

HAZARD RATINGS ARE 0 TO 4 (0 = NO HAZARD; 4 = EXTREME HAZARD).

LABORATORY PROTECTIVE EQUIPMENT
SAFETY GLASSES; LAB COAT

PRECAUTIONARY LABEL STATEMENTS
DURING USE AVOID CONTACT WITH EYES, SKIN, CLOTHING. WASH THOROUGHLY AFTER HANDLING. WHEN NOT IN USE KEEP IN TIGHTLY CLOSED CONTAINER.

SAF-T-DATA™ STORAGE COLOUR CODE: ORANGE (GENERAL STORAGE)

2 HAZARDOUS COMPONENTS

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>%</th>
<th>CAS NO.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHROMIUM</td>
<td>90-100</td>
<td>7440-47-3</td>
</tr>
</tbody>
</table>
Chapter 2 – Welding safety

3 PHYSICAL DATA

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point</td>
<td>2200 °C (3992 °F)</td>
</tr>
<tr>
<td>Melting Point</td>
<td>1900 °C (3452 °F)</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>7.14</td>
</tr>
<tr>
<td>Solubility (H₂O)</td>
<td>NEGLIGIBLE (LESS THAN 0.1%)</td>
</tr>
<tr>
<td>Vapor Density (Air=1)</td>
<td>N/A</td>
</tr>
<tr>
<td>Evaporation Rate</td>
<td>N/A</td>
</tr>
<tr>
<td>Appearance and Odour</td>
<td>STEEL GREY TO SILVER PELLETS</td>
</tr>
</tbody>
</table>

4 FIRE AND EXPLOSION HAZARD DATA

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash Point (Closed Cup)</td>
<td>N/A</td>
</tr>
<tr>
<td>Flammable Limits</td>
<td>UPPER - N/A % LOWER - N/A %</td>
</tr>
<tr>
<td>Fire Extinguishing Media</td>
<td>USE WATER SPRAY, ALCOHOL FOAM, DRY CHEMICAL OR CARBON DIOXIDE.</td>
</tr>
<tr>
<td>Special Firefighting Procedures</td>
<td>FIREFIGHTERS SHOULD WEAR PROPER PROTECTIVE EQUIPMENT AND SELF-CONTAINED BREATHING APPARATUS WITH FULL FACE PIECE OPERATED IN POSITIVE PRESSURE MODE. MOVE CONTAINERS FROM FIRE AREA IF IT CAN BE DONE WITHOUT RISK. USE WATER TO KEEP FIRE-EXPOSED CONTAINERS COOL.</td>
</tr>
<tr>
<td>Unusual Fire &amp; Explosion Hazards</td>
<td>CAN BE AN EXPLOSION HAZARD, ESPECIALLY WHEN HEATED.</td>
</tr>
</tbody>
</table>

5 HEALTH HAZARD DATA

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold Limit Value (TLV/TWA)</td>
<td>0.5 MG/M3 (PPM)</td>
</tr>
<tr>
<td>Permissible Exposure Limit (PEL)</td>
<td>1 MG/M3 (PPM)</td>
</tr>
<tr>
<td>Carcinogenicity</td>
<td>NTP: YES IARC: YES Z LIST: NO OSHA REG: NO</td>
</tr>
</tbody>
</table>

Note: While the specific compounds cannot be identified, there is evidence that certain chromium compounds cause cancer in humans and experimental animals. Chromium is widely distributed in air, water, soil and food. Trivalent chromium may be an essential trace ingredient in the human diet. All chromium compounds are regulated by the EPA, but no specific data is available to link trivalent chromium to cancer. Prudent judgement dictates that exposure should be minimised as much as possible.

EFFECTS OF OVER EXPOSURE

CONTACT WITH SKIN OR EYES MAY CAUSE SEVERE IRRITATION OR BURNS.

DUST MAY ULCERATE MUCOUS MEMBRANES. EXCESSIVE INHALATION OF DUST IS IRRITATING AND MAY BE SEVERELY DAMAGING TO RESPIRATORY PASSAGES AND/OR LUNGS. INGESTION MAY RESULT IN SEVERE INTESTINAL IRRITATION WITH BURNS TO MOUTH.

NOTE: PRODUCT IS A SOLID MASS; HOWEVER, WARNINGS ARE BASED ON INHALATION DUST, MIST OR FUME EMISSIONS THAT ARE POSSIBLE DURING MANUFACTURING OR CHEMICAL REACTIONS.

TARGET ORGANS
RESPIRATORY SYSTEM
MEDICAL CONDITIONS GENERALLY AGGRAVATED BY EXPOSURE NONE IDENTIFIED

ROUTES OF ENTRY
INGESTION, INHALATION

EMERGENCY AND FIRST AID PROCEDURES

INGESTION: IF SWALLOWED AND THE PERSON IS CONSCIOUS, IMMEDIATELY GIVE LARGE AMOUNTS OF WATER. GET MEDICAL ATTENTION.

INHALATION: IF A PERSON BREAThes IN LARGE AMOUNTS, MOVE THE EXPOSED PERSON TO FRESH AIR. GET MEDICAL ATTENTION.

EYE CONTACT: IMMEDIATELY FLUSH WITH PLENTY OF WATER FOR AT LEAST 15 MINUTES. GET MEDICAL ATTENTION.

SKIN CONTACT: IMMEDIATELY WASH WITH PLENTY OF SOAP AND WATER FOR AT LEAST 15 MINUTES.

6 REACTIVITY DATA

STABILITY: STABLE
HAZARDOUS POLYMERISATION: WILL NOT OCCUR
CONDITIONS TO AVOID: FLAME
INCOMPATIBILITIES: CARBONATES, STRONG BASES, MINERAL ACIDS

7 SPILL AND DISPOSAL PROCEDURES

STEPS TO BE TAKEN IN THE EVENT OF A SPILL OR DISCHARGE
WEAR SUITABLE PROTECTIVE CLOTHING. CAREFULLY SWEEP UP AND REMOVE.

DISPOSAL PROCEDURE
DISPOSE IN ACCORDANCE WITH ALL APPLICABLE FEDERAL, STATE AND LOCAL ENVIRONMENTAL REGULATIONS.

EPA HAZARDOUS WASTE NUMBER: D007 (EP TOXIC WASTE)
<table>
<thead>
<tr>
<th>8</th>
<th>PROTECTIVE EQUIPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VENTILATION: USE ADEQUATE GENERAL OR LOCAL EXHAUST VENTILATION TO KEEP FUME OR DUST LEVELS AS LOW AS POSSIBLE.</td>
</tr>
<tr>
<td></td>
<td>RESPIRATORY PROTECTION: A RESPIRATOR WITH DUST/MIST FILTER IS RECOMMENDED. IF AIRBORNE CONCENTRATION EXCEEDS TLV, A SELF-CONTAINED BREATHING APPARATUS IS ADVISED.</td>
</tr>
<tr>
<td></td>
<td>EYE/SKIN PROTECTION: SAFETY GLASSES WITH SIDE SHIELDS, PROPER GLOVES ARE RECOMMENDED.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9</th>
<th>STORAGE AND HANDLING PRECAUTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAF-T-DATA™ STORAGE COLOUR CODE: ORANGE (GENERAL STORAGE)</td>
</tr>
<tr>
<td></td>
<td>SPECIAL PRECAUTIONS</td>
</tr>
<tr>
<td></td>
<td>KEEP CONTAINER TIGHTLY CLOSED. SUITABLE FOR ANY GENERAL CHEMICAL STORAGE AREA.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10</th>
<th>TRANSPORTATION DATA AND ADDITIONAL INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DOMESTIC (DOT)</td>
</tr>
<tr>
<td></td>
<td>PROPER SHIPPING NAME: CHROMIUM</td>
</tr>
<tr>
<td></td>
<td>HAZARD CLASS: ORM-E</td>
</tr>
<tr>
<td></td>
<td>LABELS: NONE</td>
</tr>
<tr>
<td></td>
<td>REPORTABLE QUANTITY: 1 LBS</td>
</tr>
<tr>
<td></td>
<td>INTERNATIONAL (IMO)</td>
</tr>
<tr>
<td></td>
<td>PROPER SHIPPING NAME: CHEMICALS, NOS (NON-REGULATED)</td>
</tr>
</tbody>
</table>

Reference: West Virginia Toxics Release Inventory Database Search
www.gis.wvdep.org/tir/cheminfo/msds452.text
First aid for welders

Basic objectives
In the event that a person is injured or suddenly becomes ill, efficient first aid should be carried out as quickly as possible, preferably by trained first aid officers. This action, if taken before medical help is available and often at a critical stage, can save lives, reduce the severity or worsening of the injury and limit discomfort.

Essential emergency action
- Ensure that there is no danger to the patient or rescuer.
- Get the casualty out of any danger zone, without endangering anyone.
- Give first aid to the casualty.

For all but minor injury, arrange for medical assistance. If there is little risk in moving the casualty, arrange for transport (and for care during transport) to a physician, hospital or nurse. If there is any risk of further injury posed by moving the patient, he/she should not be moved and qualified medical help should be sought.

First aid for some common welder injuries

Welding flash (arc eye)
This is eye injury caused by exposure to infra-red or ultraviolet rays.
- In mild cases, irrigate or flush the eyes, add eye-drops and shade the eyes.
- In severe cases, loosely pad both eyes and get the casualty quickly to a doctor.

Particles in the eyes
- Cover BOTH eyes of the victim and take the patient as quickly as possible to a doctor.
- In the case of chemical burns (eg from acids, alkalis or similar liquids), remove the chemicals from the eyes by washing at once with large amounts of running water and flush continuously for up to 20 minutes.
- Seek urgent medical advice.

Burns – to hands and body

Minor burns
Minor burns should be immediately cooled under cold running water, then covered with sterile dressing material. Avoid the use of ointment or powder as these may interfere with any subsequent medical treatment.

Major burns
Since urgent action is essential, cool the area with running water, cover and get the casualty to hospital as quickly as possible. Keep the casualty covered with a light blanket or other suitable material. Care must be taken to ensure that dressings, blankets etc. will not stick to the wound.
Electric shocks
Electric shock usually does not kill at once, but may stun the victim and stop his or her breathing. Delay in rescue and resuscitation may be fatal.

Rescue
Immediately switch off the electricity where practicable and then pull or push the patient clear. If the electricity cannot be switched off immediately, remember that the patient is electrified until released and take precautions against receiving electrical shock yourself. The patient must be pulled or pushed away from the conductor using any type of dry insulating material, such as wood, rope, clothing, rubber or plastic. Do not use metal or anything moist. In some cases, it may be easier to remove the conductor from the patient. Where necessary, take care that the patient does not sustain injury by falling.

Resuscitation
After rescue, if the patient is not breathing, commence artificial respiration immediately and continue without interruption for hours if necessary. When assistance is available, send for a doctor and an ambulance.

Artificial respiration and cardiac massage
The need for artificial respiration is evident if the patient is not breathing, and must begin immediately. At the same time, a check on the patient’s carotid pulse will establish the need for cardiac massage. If no pulse can be felt, cardiac massage should proceed – together with artificial respiration.

Severe bleeding
Apply direct pressure to the wound by placing a large dressing over the wound and holding it in position with a firm bandage. If the dressing becomes saturated with blood, do not remove it, but apply another. This will aid clotting. In an emergency, if a dressing is not readily available, firmly press the sides of the wound together with the fingers or hand. Elevate the injured part to decrease the blood flow to the wound. Seek medical attention immediately.

Fractures
Do not move the patient, but immobilise the person and the fractured limb by use of pillows, blankets or other suitable materials. Bleeding should be controlled if present and the patient kept warm until qualified medical help arrives.

Inhalation of toxic or intensively irritating gas or fumes
Remove the casualty out of the danger zone at once and into fresh air. Place the casualty in a comfortable position and keep him or her warm. The casualty should be taken to (or seen by) a physician as quickly as possible. Where it is at all possible, the gas or fume involved should be identified to assist the physician with treatment.
Further information on subjects discussed in this chapter can be gained by consulting the following:

- WTIA Technical note 7 – Health and safety in welding
- AS 1319 – Safety signs for the occupational environment
- AS/NZS 1336 – Recommended practices for occupational eye protection
- AS/NZS 1337 – Eye protectors for industrial applications
- AS/NZS 1338 – Filters for eye protectors
- AS 1470 – Health and safety at work – Principles and practices
- AS 1674 – Safety in welding & allied processes – Fire precautions
- AS 1674 – Safety in welding & allied processes – Electrical
- AS/NZS 1715 – Selection, use and maintenance of respiratory protective devices
- AS/NZS 1716 – Respiratory protective devices
- AS/NZS 2210 – Occupational protective footwear
- AS 2613 – Safety devices for gas cylinders
- AS/NZS 2865 – Safe working in a confined space.
Chapter 3 – Codes and regulations

Introduction

The previous section on safety makes reference to various standards or codes related to safety in the workplace. Standards or codes and specifications are often used to lay down minimum specifications or performance requirements for goods or service.

Standards and specifications related to welding or fabrication are used to control the quality of the finished product, methods of manufacture and standards of workmanship in the fabrication and many other industries.

This standardisation of work methods makes for greater efficiency and uniformity. Without the use of standards and codes, designers, engineers and fabricators would apply their own ideas as to how the work was to be designed and constructed and inspection procedures would be difficult to carry out. Without some sort of work code or standard being specified, the customer would not be able to define or verify the quality of the finished product by other than visual means. In metal fabrication and welding in particular, this could encourage sub-standard work. Contractors may be tempted to under-quote and cut corners to get the job completed on schedule.

Most code books in the welding industry are a book of rules and standard procedures laid down for carrying out work in a safe, organised and efficient manner.

Codes or standards are a recommendation of a minimum set of rules, or specifications that should be followed. They are not law or enforceable unless they are specified or adopted by a third party.

Typical third parties may be simply an internal QA/QC section. The client will often specify the adoption and use of codes or standards in the purchasing contract. External parties may be government or other bodies, sections or departments.

Typical government departments that may become involved include:

- WorkSafe WA
- utility bodies such as the electricity, gas and water departments
- minerals or mines departments
- road, rail or water transport departments
- building or construction departments
- local shires or councils.
In this chapter we will look at the following.

- Who produces standards
  - application of standards
  - Australian Standard®
    - titles and types of certificates
- Acts, regulations, codes of practice and guidance notes
  - occupational safety and health laws.
Who produces standards?

Standards may be produced by:

- standards organisations whose sole or major function is to produce standards, for example:
  - Standards Association of Australia (SAA)
  - British Standards (BS)
  - American National Standards Institute (ANSI)

- insurance companies, for example:
  - Lloyds of London
  - Det Norske Veritas (DNV).

Additionally, the customer may develop a set of specifications of their own. This is common for larger projects using specific processes such as manufacturing plant, gas processing plants or fuel refineries. For example, the American Petroleum Institute (API) issues standards for use in the petroleum industry.

Advantages of the use of codes include:

- standardisation and uniformity of product
- uniform reference for engineers, supervisors, welders
- simplifies inspection procedures
- ensures a minimum standard of the finished product
- protects the customer from inferior workmanship
- removes the onus from the welder or foreperson
- ensures public safety and safe working conditions and practices
- a good reference
- available in times of dispute
- lowers costs.

Problems associated with the use of code books include:

- expensive
- new clauses are frequently needed
- become outdated
- terminology is sometimes difficult for the average tradesperson
- not always readily available
- reference to other codes is frequently needed
- sometimes applied badly.
Chapter 3 – Codes and regulations

Application of standards

Correct application of standards is an essential factor in their use. To this end, probably the most important clause in any standard is the ‘scope clause’. The scope clause is usually the first clause of any standard and as the name suggests, states the scope of the code, ie it states exactly to what the code is to be applied. For example, the following extract from a scope clause is taken from AS/NZS 2980 – Qualification of welders for fusion welding of steels.

1.1 SCOPE. This standard defines the qualification test of welders for the welding of steels to the requirements of a welding procedure specification. It provides a set of technical rules for a systematic qualification test of the welder and enables such qualifications to be uniformly accepted independently of the type of product, location and examiner/examining body.

This standard does not deal with the certification of welders, this subject being covered by AS/NZS 1796.

Further to this, some codes will also include an ‘application clause’ which gives further guidance in the use of the standard. The following extract from an application clause is also taken from AS 2980.

1.2 APPLICATION. The qualification tests prescribed in this Standard are intended to provide a method to qualify welders for the welding of steel structures; however, they may also be suitable for the qualification of welders for other applications, by agreement between the principal and the fabricator. These tests are not intended to be used as a guide for welding during actual construction. The latter should be performed in accordance with the requirements of a welding procedure specification (WPS) produced for the purpose.

Section 2 deals specifically with qualifications for welders using hand held equipment, while Section 3 deals with qualifications for welders using non-hand held equipment.

Where a welder fails the specified tests, their performance can be used as a basis for establishing the value to be gained by further training.

When reading the scope clause, it is important to note the limitations that apply to the application of the code. For example, the scope clause of AS/NZS 1554.1 states that ‘the code is “limited” to the welding of steel parent metal with a specified minimum yield strength not exceeding 500 MPa.’

Anything outside this, or outside of the other limitations stated, is clearly outside the scope of this code and another code should be applied.

‘Should’ and ‘shall’

- The words ‘should’ and ‘shall’ are frequently used throughout standards.
- Where the word ‘shall’ is used, it indicates that the statement is mandatory.
- Where the word ‘should’ is used, it indicates a recommendation.
Australian Standard®

Standards Australia is the body responsible for producing Australian Standard® documents.

Australian standards are easily recognised by their cover. The cover is usually yellow in colour (sometimes blue when they are joint Australia/New Zealand, or joint Australia/ISO Standards).

The cover always contains:

- the Standard number and edition
- the words ‘Australian Standard®’
- the title
- the Standards Australia logo.

The following example is of the cover of AS 1228—2006.

Fig 3.1 – Typical cover of an Australian Standard® document
Chapter 3 – Codes and regulations

Common standards for fabrication

This section looks at the various codes or standards that may apply to the fabrication and erection of steel buildings.

A building is not just fabricated and erected as per somebody’s idea. Although it may be up to one person to come up with the shape and size, certain rules and guidelines are given that the building must adhere to.

The guidelines are usually presented or referred to as the ‘codes and specifications’. The fabricator is required to manufacture the building in relation to these guidelines.

Some of the main codes that relate to building and fabrication or construction that a fabricator has to be aware of are provided here. A brief description of some of the main relevant points of these codes that you should study is provided.

Remember, there are a lot of codes or standards that are used in the metal fabrication industry.

For example


Five of the most commonly applied codes used in the fabrication industry in Australia are:

- **AS 4100** – Steel structures
- **AS/NZS 1554.1** – Structural steel welding – Welding of steel structures
- **AS 1210** – Pressure vessels
- **AS 1796** – Certification of welders and welding supervisors
- **AS/NZS 2980** – Qualification of arc welders for welding of steels.

Students should make use of college library or class resource sets (if provided) to become familiar with these codes.

**AS 4100 – Steel structures**

This covers the minimum requirements for design, fabrication, erection and modification of steelwork in structures. The code applies to buildings, structures and cranes constructed from steel.

**Section 1**

Covers scope, terms and definitions.

**Section 2**

The material used in construction must comply with the requirements of the structural steel codes AS/NZS 3678, AS/NZS 3679, AS1163, AS/NZS 1594, AS/NZS 3679.1 and AS/NZS 3679.2, or their equivalent.

Bolts, nuts and washers must also conform to the specified standards.

All welds should be performed in accordance with the recommendations of AS/NZS 1554.
Section 14
Relates to fabrication and recommends methods for cutting and welding should comply with AS/NZS1554.1. Methods of holing are described and most holes other than those used on base plates should be bolt diameter plus two millimetres. Flame-cut holes are not permitted. Bolting standards and methods are defined and joint types can be either bolt bearing or friction grip type. General workmanship is defined.

Section 15
Covers erection procedures such as delivery, storage and handling, straightness and alignment, joint assembly and tensioning methods.

The tolerances for location of anchor or holding down bolts and grouting are also covered.

AS/NZS 1554.1 – Structural steel welding
This specifies materials of construction, weld preparations and weld qualities, qualification of welding procedures and welding personnel and fabrication and inspection requirements for welds related to the fusion welding of steelwork in structures made up of combinations of steel plate, sheet or sections, including hollow sections and built-up sections, or castings and forgings.

Section 1
Covers scope, terms and definitions.

An important aspect of section one is the welding processes allowable such as:

- manual metal-arc welding (MMAW)
- submerged arc welding (SAW)
- gas metal-arc welding (GMAW or MIG), including pulsed mode
- gas tungsten-arc welding (GTAW or TIG)
- flux-cored arc welding (FCAW)
- electroslag (including consumable guide) welding (ESW)
- electrogas welding (EGW).
The standard is limited to the welding of steel parent material with a specified minimum yield strength not exceeding 500 MPa. The Standard applies to the welding of steelwork in structures complying with AS 3990, AS 4100, AS/NZS 4600 or NZS 3404.1. Where welded joints in these structures are governed by dynamic loading conditions, the Standard applies only to those welded joints that comply with the fatigue provisions of AS 3990, AS 4100 or NZS 3404.1, as limited by Item (ii) below, or the directly equivalent fatigue provisions of other application Standards.

Welded joints complying with the above requirements are those that are —

(i) not subject to fatigue conditions; or

(ii) subject to fatigue conditions, where—

(A) the stress range in the welded joint complies with the permissible stress range of stress categories C, D, E or F of AS 3990, or weld categories lower than or equal to detail category 112 of AS 4100 or NZS 3404.1; or

(B) the stress range in the welded joint is not more than 80% of the permissible stress range of stress category B of AS 3990.

Arc stud welding is dealt with in AS/NZS 1554.2.

In addition to the abovementioned structures, AS/NZS 1554.1 applies to the welding of cranes, hoists and other dynamically loaded structures; the welding of road and pedestrian bridges; and the welding of steelwork in applications other than structural.

The Standard does not apply to the welding of structures by the following processes:

- oxy-acetylene welding (OAW)
- resistance welding (RW)
- friction welding (FW)
- thermit welding (TW).

It also does not apply to the welding of pressure vessels and pressure piping, or railway bridges. The Standard does not cover the design of welded connections or permissible stresses in welds, nor the production, rectification, or repair of castings.

This text has been removed. It was reproduced from 1.6 ‘Weld categories’ on page 7 of AS/NZS 1554.1:2004.
The major differences between these two joint types are the allowable levels of imperfection and thereby, two levels of inspection. This is reflected in Table 7.2 of the Standard and Appendix F of the Standard.

**Section 2**

Specifies permitted materials and these are mainly low carbon/manganese structural steels. These may have a minimum yield strength up to but not exceeding 500 MPa. See AS/NZS 3678 and AS/NZS 3679.1.
Section 3
Describes recommended welded connections such as butt, fillet welds, plug and slot welds. Terms and definitions and parts of butt and fillet welds are also shown in this section.

There is a distinction made between ‘complete penetration butt welds’ and ‘incomplete penetration butt welds’.

Note the design throat thickness allowance for the various types of weld and configurations.

Section 4

Table 5.12.2 explains how a welder may qualify for various welds when welding on selected text pieces, eg 6G pipe test.

This text has been removed. It was reproduced from Section 2, 2.3.1 ‘Electrodes and filler wires’ on page 9 of AS/NZS 1554.1:2004.

This text has been removed. It was reproduced from Section 4, 4.2 ‘Methods for qualifying a welding procedure’ on pages 20 and 21 of AS/NZS 1554.1:2004.
Section 5

Describes the level of workmanship allowable for aspects such as thermal cutting, edge preparation, assembly and alignment. Pre-heat and interpass temperature recommendations are made based on carbon equivalent, joint configuration and heat input. There are details for tacking, control of distortion and weld repairs.

A brief summary is as follows.

All surfaces to be welded shall be clean, smooth and free from imperfections and foreign matter. Plates to be butt welded shall not be out of alignment by more than 10% of the plate thickness, or 3 mm, whichever is the lesser. Where the separation of plates forming a fillet weld is 1.5 mm or greater, the size of the fillet weld shall be increased by the amount of the separation. The separation between plates to be butt welded and any backing material shall not exceed 1.5 mm. Where pre-heating is required, the plates shall be brought to the pre-heat temperature prior to tacking. The joint must be brought to temperature for a minimum distance on each side of the joint at least equal to the plate thickness, with a minimum distance of 75 mm.

Welding processes requiring an external gas shield shall not be carried out in a draft or wind greater than 10 km/h, unless suitably protected. The minimum length of tack welds shall be not less than four times the thickness of the thicker part, or 40 mm, whichever is the lesser. The width of the weld face shall be the largest dimension of the weld, ie exceed both the depth and the width.

This graphic has been removed. It was reproduced from Figure 6.6 on page 55 of AS/NZS1554.1:2004.

Fig 3.2 – Depth to width ratio

Peening may be carried out, except on the root run or surface layer of the weld. Where correction of distortion by flame heating is carried out, the maximum temperature of steels shall not exceed 600 °C.

Any grinding shall blend smoothly into the surface of the parent metal without abrupt changes in contour. The depth of any grinding shall not extend below the surface of the parent metal by more than:

- 0.5 mm for material less than 10 mm thick
- for material 10 mm and over in thickness – 0.07 times the nominal thickness, or 3 mm, whichever is the lesser.
Temporary welds and attachments shall not be allowed on the tension flanges of beams and girders etc. Stray arc strikes are to be avoided. Slag shall be cleaned from all welds and the welds shall not be painted until inspection has been completed.

Where welds are to be dressed flush, the surfaces shall be finished so as to:

a) not reduce the thickness of the thinner base metal or weld metal by more than 0.8 mm, or 5% of thickness, whichever is lesser; or

b) not leave reinforcement greater than 0.8 mm.

Section 6
Covers the quality of welds. Note the different various levels of imperfections allowable for the GP and SP categories.

Section 7
Describes the methods of weld inspection that are to be used once welding is completed. Note that all completed welds must be visually inspected.

Other methods of weld inspection that may be used to supplement visual are:

- dye penetrant inspection
- magnetic particle inspection
- ultrasonic inspection
- radiographic inspection.

AS 1210 – Pressure vessels
This Standard sets out requirements for the materials, design, construction, testing, inspection, certification and installation of unfired pressure vessels constructed in ferrous or non-ferrous metals by welding, brazing, casting or forging and include the application of non-integral fittings required for safe and proper functioning of an unfired pressure vessel.

The purpose of this Standard is to establish uniform safe requirements for the materials, design, construction, testing, inspection, certification and installation of unfired pressure vessels.

Users are advised that pressure vessels must comply with the requirements of the Inspecting Authority in the State or Territory where the vessel is to be installed or used. However this Standard is usually used as the basis for the requirements for vessels in all States and Territories of the Commonwealth.

AS 1210 applies to unfired pressure vessels only. Boilers are covered by other codes.
Class of vessel

Pressure vessels under AS 1210 are designated as:

- class 1
- class 2A or 2B
- class 3.

The class into which the vessel will fall depends on many factors such as:

- volume
- working pressure
- location
- nature of contents
- operation and maintenance.

Examples of vessels under AS 1210 are:

- air receivers
- heat exchangers
- transport vessels for hazardous materials
- cryogenic vessels
- vessels containing lethal materials.

Qualification of welding personnel

General – Each welder shall have a ‘specific welder qualification’ in accordance with Clause 5.2.1 of the Standard to show they are qualified to make those welds they will be required to make on the vessel, in accordance with AS/NZS 3992:1998.

Methods of qualification

(a) Welding a test piece which simulates the production weld and examining and testing the test piece in accordance with Clause 9.5.

Where the option in Clause 9.5.1(a) is taken to approve a welder by non-destructive examination methods, the parent material for the test piece may be from Group A1 or A2 materials welded using the pre-heat and consumables of the required welding procedure. This option is only permitted for the parent material specification listing in Table 9.1.

(b) Presentation of documentary evidence of having satisfactorily welded a production joint which has complied with the appropriate requirements of the pressure equipment Standard for radiographic or ultrasonic testing within the previous six months.

(c) Presentation of documentary evidence of having welded the test piece of a qualified welding procedure within the last six months.

(d) Holding an appropriate certificate specified in AS 1796 (for Australia), or the NZIW Welding Supervisor’s Certificate or the NZIW Certificate in Welding Engineering (for New Zealand) which shall qualify the welder within the range covered by that certificate provided that welder has made production welds complying with this Standard within the previous six months.
(e) Part of the first production weld or a complete pipe weld carried out by a welder to an approved welding procedure is shown by either radiographic or ultrasonic examination to comply with the pressure equipment Standard.

(f) The length of weld examined in a production weld or test piece shall be at least 300 mm, or the circumference of a pipe weld, whichever is less.

Welders qualified in accordance with the above are permitted to undertake production welding within the limits of the essential variables listed in Table 9.1 using welding procedures documented in accordance with the requirements of this Standard.

**Extent of approval of welder qualification**

A welder qualified to an approved welding procedure in accordance with any method as laid down in Clause 9.2 shall be requalified when the essential variables of additional production welds exceed the requirements laid down in Table 9.1 for the items as listed.

**AS 1796 Certification of welders and welding supervisors**

This Standard specifies the requirements necessary for the granting of certificates to persons engaged in the operation of various welding processes used in the manufacture of pressure equipment such as boilers, pressure vessels and associated piping as defined in AS/NZS 1200, as well as other applications requiring a prescribed standard in the theory and practice of welding. Certification in welding is related primarily to basic welding techniques and processes and not to the parent metal of the joint.

Welder certification should not be confused with welder qualification. The requirements for welder qualifications are specified in the appropriate application Standards.

**Welder certification**

Certifies the ability of a welder to weld to a particular standard using a particular process. Welder certification is portable and stays with the welder under AS 1796.

A welder’s certificate shall remain valid indefinitely, provided that the examining authority does not cancel the certificate because either:

a) there is evidence of serious deterioration in the quality of the welder’s work, or

b) the welder is incapable of maintaining the necessary standard.

**Welder qualification**

Welder qualification qualifies a welder to carry out a given welding procedure, i.e. to weld a given joint type in a given position using given process and consumables. Welder qualification does not attest to a welder having attained a certain level of skill as does certification. Welder qualification is not portable and will usually lapse if the welder has not carried out the welding procedure in the last six months.

**Titles and types of certificates**

The titles and types of AS 1796 certificates shall be as follows.

- **Certificate No 1** Manual metal-arc welding (MMAW) of butt welds in carbon steel plate and carbon steel pipe over 600 mm outside diameter (single V welded from both sides).

- **Certificate No1E** Manual metal-arc welding (MMAW) of butt welds in carbon steel plate and carbon steel pipe over 270 mm outside diameter (single V welded from one side only).
- **Certificate No 2** Manual metal-arc welding (MMAW) of butt welds in carbon steel pipe (single V welded from one side only).
- **Certificate No 3** Manual metal-arc welding (MMAW) of butt welds using hydrogen-controlled electrodes in alloy steel plate and alloy steel pipe over 600 mm outside diameter (single V welded from both sides).
- **Certificate No 3E** Manual metal-arc welding (MMAW) of butt welds using hydrogen-controlled electrodes in alloy steel plate and alloy steel pipe over 270 mm outside diameter (single V welded from one side only).
- **Certificate No 4** Manual metal-arc welding (MMAW) of butt welds using hydrogen-controlled electrodes in alloy steel pipe (single V welded from one side only).
- **Certificate No 5** Gas tungsten-arc welding (GTAW) root run and manual metal-arc welding (MMAW) of butt welds using hydrogen-controlled electrodes in alloy steel pipe (single V welded from one side only).
- **Certificate No 6** Gas welding (GW) (single V welded from one side only).
- **Certificate No 7** Gas tungsten-arc welding (GTAW) (single V welded from one side only).
- **Certificate No 8G** Gas metal-arc welding (GMAW) of plate and pipe.
- **Certificate No 8F** Flux-cored arc welding (FCAW) of plate and pipe.
- **Certificate No 9** Automatic welding.
- **Certificate No 10** Welding supervisor.

The suffix ‘E’ indicates that a candidate elected to make a full penetration single-sided butt weld on plate.

**Test pieces**
The test pieces for the qualification tests are either pipe and/or plate, depending upon the certificate being examined. All details of test pieces including number, types, size and preparation details are given in Section 2 of the code, as are details of consumables and general conduct of the test.

**Assessment**
Upon completion, the test pieces are examined visually and those which pass visual examination undergo further radiographic or destructive examination to determine compliance with code requirements.

To gain certification to AS 1796, a candidate must:
- meet the pre-examination requirements
- pass a theory examination according to the syllabus set out in AS 1796
- pass one of the practical tests.
AS/NZS 2980 – Qualification of arc welders for welding of steels

This Standard specifies requirements for qualification tests which are specially devised to determine the ability of a welder, using consumable electrode arc welding processes, to produce sound welds in steels.

This Standard does not deal with the certification of welders, this subject being covered by AS 1796.

Application

The qualification tests prescribed in this Standard are not intended to be used as a guide for welding during actual construction. The latter should be performed in accordance with the requirements of a procedure specification produced for the purpose.

Section 2 deals specifically with qualifications for welders using hand-held equipment, while Section 3 deals with qualifications for welders using non-hand-held equipment.

Where a welder fails the specified tests, their performance can be used as a basis for establishing the value to be gained by further training.

Qualification of a welder to AS/NZS 2980 gives reasonable assurance that the operator can carry out the range of joints qualified by conduct of the test. Tests under this Standard apply to carbon steel plate and pipe.

Acceptance criteria

Test welds are made, visually examined and destructively tested according to the criteria set out in Appendix A of the Standard. Alternatively, radiographic examination may be carried out.

Period of effectiveness

The welder’s qualification as specified in this Standard shall be considered as remaining in effect indefinitely unless:

(a) there is some specific reason to question a welder’s ability; or
(b) the welder changes employer.
Acts, regulations, codes of practice and guidance notes

The previous chapter on safety makes reference to some rules and regulations related to cutting and welding in hazardous locations, working in confined space and with scaffolding.

There are a number of Acts (or laws) and types of legislation used to govern occupational safety and health practice and rules in Western Australia.

In addition to the broad duties established by an Act, the legislation is supported by a further tier of statute, commonly referred to as regulations, together with a lower tier of non-statutory codes of practice and guidance notes.

An Act is declared by government after debate in the parliament. Once an Act appears in the government gazette, it becomes law and can be enforced by various authorities. Sometimes severe penalties such as heavy fines or imprisonment can be applied to anyone or any corporation who fail to abide with the provisions within an Act.

Typical Acts that may be applied to the fabrication and welding industry are:

- Occupational Safety and Health Act
- Factories and Shops Act
- Construction and Safety Act
- Machinery and Safety Act.

Regulations are support documents or laws or rules that help to clarify or redefine certain parts of an Act. Regulations are easier to make and change and they can be used by authorities to help to enforce the laws.

Occupational Health, Safety and Welfare Regulations

The Occupational Safety and Health Regulations (1996) have the effect of spelling out specific requirements of the legislation.

Regulations may prescribe minimum standards and have a general application, or they may define specific requirements related to a particular hazard or particular type of work. They may also allow the licensing or granting of approvals and certificates etc.

If a regulation exists about a risk, you must comply with the regulation before any code of practice or guidance note.

If an Australian Standard®, or part of a Standard is referred to in a regulation, the Standard or relevant part of the Standard must be complied with.

If there is no regulation about a risk but there is a code of practice or guidance note, you must either do what the code of practice or guidance note says, or adopt and follow another way that gives the same level of protection against the risk.

Codes of practice are documents that provide guidelines and help towards the practical application of laws or rules.

Typical codes of practice mentioned in this text may be:

- safe working on roofs
- manual handling
- noise control.
A code of practice is defined in the Act as a document prepared for the purpose of providing practical advice on preventative strategies and a practical means of achieving any code, standard, rule, provision or specification relating to occupational safety and health in Western Australia.

A code of practice may contain explanatory information. The preventative strategies outlined do not represent the only acceptable means of achieving a certain standard.

A code of practice does not have the same legal force as a regulation and is not sufficient reason, of itself, for prosecution under the Act.

If there is no regulation or code of practice about the risk, you must choose an appropriate way and take reasonable precautions and exercise proper diligence to ensure you meet your obligations.

Codes of practice should be followed, unless there is another solution which achieves the same or better result and can be used to support prosecution for non-compliance.

**Guidance notes** provide helpful and useful information. Typical guidance notes mentioned in this text may be:

- general duty of care
- election of safety and health representatives
- notification of accidents
- resolution of safety and health issues in the workplace.

**Occupational safety and health laws**

Western Australia has occupational safety, health and welfare legislation that shifts the responsibility for making each workplace safe back to employers and employees.

Safety and health in Western Australian workplaces is regulated by the *Occupational Safety and Health Act 1984* and the Occupational Safety and Health Regulations 1996, supported by codes of practice and guidance notes.

The *Occupational Safety and Health Act 1984* provides for the promotion, co-ordination, administration and enforcement of occupational safety and health in Western Australia.

The Act places certain duties on employers, employees, self-employed people, manufacturers, designers, importers and suppliers. It also places emphasis on the prevention of accidents and injury.

Under the Act, there are three types of instruments to help you meet your workplace safety and health obligations – regulations, Australian Standards® and codes of practice.

---

**Note**

WorkSafe is the government department solely responsible for OSH matters in Western Australia. WorkSafe may also specify the mandatory adoption of codes or standards.
Objectives of the Health, Safety and Welfare Act 1986

- To promote and secure safety, health and welfare at work.
- To assist persons to work against hazards.
- To assist in securing safe and hygienic work environments.
- To reduce or eliminate and control the hazards at work.
- To foster co-operation and consultation.
- To provide policies and laws related to occupational safety, health and welfare.
- To provide education and awareness of matters related to OSH.

Responsibilities and duties of employers

All employers have a general duty of care and are expected to ensure that employees are not exposed to hazards while they are working.

In order to make the workplace safe, every employer needs to:

- provide and maintain workplaces, plant and systems of work that do not expose employees to hazards
- provide information and training and supervision so that employees are not exposed to hazards
- consult and cooperate with OSH representatives
- provide adequate personal protective equipment
- make arrangements for the safe use and handling of dangerous substances
- report all accidents.

Responsibilities and duties of employees

All employees are expected to cooperate with their employers, observe safety and health provisions and to take care to protect themselves and others from injury.

In order to make the workplace safe, every employee needs to:

- look after themselves at work and ensure the workplace is safe and healthy. Be careful!
- co-operate with employer
- follow instructions
- use protective equipment issued by the company
- not be affected by drugs or such at work
- attend safety education and training sessions
- report to supervisor (instructor) any workplace hazards or injury.

Consultation between employers/employees

The OSH Act requires open communication and consultation between employers and employees in the workplace and a speedy resolution of issues and disputes.
Chapter 3 – Codes and regulations

Safety and health representatives/committees

Safety and health committees should be made up of safety and health representatives elected for the purpose by the employees and persons nominated by the employer.

Safety and health representatives should liaise between the employer and employees. They should keep informed on safety and health matters and attend committee meetings. They should need to inspect the workplace and report hazards to the employer and investigate any accidents.

Further information on subjects discussed in this chapter can be gained by consulting the following:

- WTIA Technical Note 7 – ‘Safety and health in welding’
- AS 1101.3 – Graphical symbols for general engineering
- AS/NZS 1554.1:2004 Structural steel welding – Welding of steel structures
- AS/NZS 1554.2:2003 Structural steel welding – Stud welding (steel studs to steel)
- AS/NZS 1554.3:2002 Structural steel welding – Welding of reinforcing steel
- AS/NZS 1554.4:2004 Structural steel welding – Welding of high strength quenched and tempered steels
- AS/NZS 1554.5:2004 Structural steel welding – Welding of steel structures subject to high levels of fatigue loading
- AS/NZS 1554.6:1994 Structural steel welding – Welding stainless steels for structural purposes
- AS/NZS 1554.7:2006 Structural steel welding – Welding of sheet steel structures
- AS 1210 – Unfired pressure vessels
- AS 1228 – Pressure equipment – Boilers
- AS 1796 – Certification of welders and welding supervisors
- AS 2214 – Certification of welding supervisors
- AS/NZS 2980 – Qualification of welders for fusion welding of steels
- AS 2812 – Welding, brazing and cutting of metals – Glossary of terms
- AS 4100 – Steel structures
- AS/NZS 4854 – Welding consumables – Covered electrodes for manual metal arc welding of stainless and heat-resisting steels – Classification
- AS/NZS 4855 – Welding consumables – Covered electrodes for manual metal arc welding of non-alloy and fine grain steels – Classification
- AS/NZS 4856 – Welding consumables – Covered electrodes for manual metal arc welding of creep-resisting steels – Classification
- AS/NZS 4857 – Welding consumables – Covered electrodes for manual metal arc welding of high-strength steels – Classification.
Chapter 4–Welding terms and symbols

Introduction

AS 2812:2005 Welding, brazing and cutting metals – Glossary of terms sets out and defines basic terms that may be used for describing various welding processes and principles. The information contained herein is a guide to interpretation of these terms and is by no means exhaustive in covering all the information contained in the code. The purpose of this code is to try to standardise terms and thus help to avoid confusion.

In this chapter we will look at the following.

- Common welding processes
- Types of welds
- Welding symbols
  - basic symbols
  - supplementary symbols
  - location of symbols.
Common welding processes

The common welding processes are defined as follows:

- **OAW**  oxy-acetylene welding
- **EGW**  electrogas welding
- **ESW**  electroslag welding including consumable guide
- **FCAW**  flux-cored arc welding
  (C or M)  (C indicates carbon dioxide shielding, M indicates mixed gas shielding)
- **FCAW**  flux-cored arc welding
  (N)  (N indicates no gas shield)
- **GMAW**  gas metal arc welding
- **GTAW**  gas tungsten arc welding
- **MMAW**  manual metal arc welding
- **SAW**  submerged arc welding.
Types of welds

Welds may be any one of four basic types, however welds may also be combined to produce compound welds.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>fillet joint</td>
</tr>
<tr>
<td>B</td>
<td>butt joint</td>
</tr>
<tr>
<td>C</td>
<td>corner joint</td>
</tr>
</tbody>
</table>
| T | T joint  
   | pad weld (surfacing)  
   | plug and/or slot weld |
| 1 | flat weld (position) |
| 2 | horizontal weld |
| 3 | vertical weld |
| 4 | overhead weld |

As the standards are reviewed, changes are made that can result in some standards being ‘out of date’ in terms of ‘position’. Examples are AS 1796, AS/NZS 1554.1 and AS/NZS 2980, which refers to the terms used in Fig 4.2 and Table 1 from AS 3545 – Welding positions.
Chapter 4 – Welding terms and symbols

1.F
Throat of weld vertical
Axis of weld horizontal

2.F
Vertical plate
Axis of weld horizontal
Horizontal plate

3.F
Axis of weld vertical
Vertical plate

4.F
Axis of weld horizontal
Horizontal plate
Vertical plate

Fig 4.1 – (a) Fillet weld terms
Test position flat

Pipe shall be rolled while welding

Test position horizontal

Pipe shall not be turned or rolled while welding

Fig 4.1 – (b) Butt weld terms

- The flat position is also referred to as the downhand position.
- The welding position ‘VERTICAL’ can be ‘VERTICAL UP’ and ‘VERTICAL DOWN’ and hence application codes make no distinction between the two.
- A fillet weld where one plate is in the flat position and one plate is in the vertical position, is commonly referred to as an H/V (horizontal/vertical) fillet.
Plug and slot welds and pad welds are not commonly used in general fabrication and will not be considered in depth in this text.
Fillet welds

**Definition** – A fillet weld is a weld approximately triangular in cross-section, lying external to the planes of the parts being joined.

The parts of a fillet weld (Fig 4.2) are as follows.

- Parent metal – the parts to be joined.
- Root – where the parts to be joined are in the closest proximity.
- Face – the exposed surface of the weld.
- Toe – where the weld face meets the parent metal.
- Depth of fusion – the degree to which the weld penetrates the parent metal.
- Leg length – the distance from the root to the toe.
- Actual throat thickness – the distance from the root to the weld face measured through the centre of the weld.
- Design throat thickness – the distance from the root to the hypotenuse of a triangle lying wholly within the weld (used for design calculations).
- Reinforcement – the distance between the design throat thickness and the actual throat thickness.

![Fig 4.2 – Parts of a fillet weld](image-url)
Fillet weld configuration

The weld configuration relates to the relationship of the plates to be joined. The joint types may be made in various positions, eg flat, vertical etc.

![Fillet weld configurations](image)

Fig 4.3 – Fillet weld configurations (a) T fillet, (b) corner fillet and (c) lap fillet

Butt welds

A butt weld is a weld lying internal to the planes of the parts being joined. The terminology that applies to a fillet weld applies equally to butt welds, the major difference being design throat thickness which in a full penetration butt weld is equal to the plate thickness.

Butt welds can be either a ‘C’ complete penetration butt weld where fusion exists through the full thickness of the joint, or a ‘P’ part (incomplete) penetration butt weld where the depth of the weld is less than the thickness of the plates joined.

At this stage it is only intended to discuss complete penetration butt welds and even here the types of butt welds referred to will be the more common types. Additional information can be gained by referring to AS/NZS 1554.1.

<table>
<thead>
<tr>
<th>Graphic</th>
<th>Terminology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Weld root" /></td>
<td>Weld root</td>
<td>the portion of the weld where the parts to be joined are in the closest proximity to each other</td>
</tr>
<tr>
<td><img src="image" alt="Root face" /></td>
<td>Root face</td>
<td>that portion of the prepared edge of a part to be joined by a butt weld that has not been bevelled. This unbevelled section will support the first run of weld metal deposited in the groove</td>
</tr>
<tr>
<td>Graphic</td>
<td>Terminology</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td><img src="image" alt="Root gap" /></td>
<td>Root gap</td>
<td>the separation between parts to be joined by a butt weld. The gap is for the purpose of ensuring, as far as possible, complete fusion or penetration through the full thickness of metal</td>
</tr>
<tr>
<td><img src="image" alt="Angle of bevel" /></td>
<td>Angle of bevel</td>
<td>the angle of the prepared edge of a component bevelled for welding</td>
</tr>
<tr>
<td><img src="image" alt="Included angle" /></td>
<td>Included angle</td>
<td>the angle between the fusion faces of components prepared for welding</td>
</tr>
<tr>
<td><img src="image" alt="Throat thickness" /></td>
<td>Throat thickness</td>
<td>the distance from the root to the weld face measured through the centre of the weld</td>
</tr>
<tr>
<td><img src="image" alt="Design throat thickness" /></td>
<td>Design throat thickness</td>
<td>in a full penetration butt weld the design throat thickness is equal to the thickness of the thinner part joined</td>
</tr>
<tr>
<td><img src="image" alt="Reinforcement" /></td>
<td>Reinforcement</td>
<td>reinforcement in a butt weld is the term given to the metal lying outside of the planes of the parts being joined</td>
</tr>
</tbody>
</table>

Fig 4.4 – Parts of a butt weld
Welding symbols

Introduction

Designers, engineers and workshop personnel need to have a system that transfers or displays the information in a clear and precise manner to avoid confusion over information or details related to the welding of steel structures.

AS 1101.3 – Graphical symbols for general engineering part 3 – welding and non-destructive examination – This code describes symbols which provide the means of placing complete welding information on drawings. Part 3 covers the details and application of symbols related to various welding processes and non-destructive examination.

The purpose of these symbols is to provide a means of placing complete and uniform welding information on drawings. The information contained herein is a guide to interpretation of these symbols and is by no means exhaustive in covering all the information contained in the code. In fact, coverage will be limited to the more common of the symbols for butt and fillet welds.

The code makes a distinction between a welding symbol and a weld symbol:

- a welding symbol is a method that is used to present welding information on a drawing
- a weld symbol indicates or is a representative of the type of weld.

Elements of a welding symbol

Welding symbols are made up of eight basic elements, all of which may or may not be used on any given welding symbol. Every welding symbol will have at least three elements:

- a reference line
- an arrow
- either a basic symbol or design throat thickness.

These are the minimum required to make up a welding symbol.

Extra detail for welding symbols

- The reference line (drawn horizontally) is the base for the symbol, around/on which the other elements are placed.
- The arrow (at either end going up, down or cranked) indicates what the symbol refers to.
- The basic weld symbol (indicates the type of weld required).
- Dimensions and other data (provide information about the size, number and spacing of welds).
- Supplementary symbols are used in conjunction with the basic symbols and provide information about the weld to be made (eg the weld is to be made on site).
- Finish symbols describe the method of finishing welds other than by cleaning.
• A tail is placed on the arrow when reference is made to a process, procedure or specification. This reference is placed within the tail of the arrow. Where no reference is used, the tail may be omitted.
• Specification, process, or other references may be given.

These elements are placed as shown in Fig 4.5 to make the welding symbol.

Fig 4.5 – Standard location of elements of a welding symbol
Notes related to Fig 4.5

1. Notes related to the other side of the joint will appear on the top of the line.
2. Actual welded length must include any allowance for starting and stopping of the weld.
3. The tail should be omitted when information is not required.
4. Size, weld symbol, length of weld and spacing must read in that order from left to right along the reference line. Neither orientation of reference line nor location of the arrow alters this rule.
5. Where the basic symbol has a perpendicular leg (fillet, level, or ‘U’), the perpendicular is always placed to the left.
6. Arrow side and other side welds are made the same size unless otherwise dimensioned.
7. Symbols only apply between abrupt changes in direction of welding unless governed by the ‘weld all round’ symbol or otherwise dimensioned.

Basic symbols

The type of weld is shown by the basic symbol as indicated in the table (Fig 4.7).

The symbols for fillet, single and double bevel, single and double-J butt welds have a vertical line in their formation and this vertical line is always shown to the left of the symbol.

Elements of a non-destructive examination symbol

The non-destructive examination of welds can also be indicated by a system of symbols.

Fig 4.6 shows the standard method by which this information is shown.
This graphic has been removed. It was reproduced from Figure 13.1 on page 99 of AS 1101.3-2005.
Symbols maintain their basic shape irrespective of root face, root gap or the number of runs required.

Basic weld symbols are shown in the following.

These tables have been removed. They were reproduced from Figure 2.1 on page 7 of AS 1101.3-2005.

Fig 4.7 – Basic weld symbols

Supplementary symbols

This graphic has been removed. It was reproduced from Figure 2.2 on page 7 of AS 1101.3-2005.

Fig 4.8 – Supplementary symbols
Backing material

Permanent and temporary backing material is distinguished by the notation placed within the backing symbol (see Fig 4.9).

Finishing symbols

Finishing symbols are used in conjunction with contour symbols to indicate the contour and method of weld finishing. Finishing symbols are as follows.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>chipping</td>
</tr>
<tr>
<td>G</td>
<td>grinding</td>
</tr>
<tr>
<td>M</td>
<td>machining</td>
</tr>
<tr>
<td>R</td>
<td>rolling</td>
</tr>
<tr>
<td>P</td>
<td>peening</td>
</tr>
</tbody>
</table>

Contour symbols may be used without finishing symbols.
Process symbols
Where the use of a definite welding process is required, this is indicated by placing a process symbol in the tail of the arrow. Some common process symbols are as follows.

<table>
<thead>
<tr>
<th>FG</th>
<th>flame gouging</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCAW</td>
<td>flux-cored arc welding</td>
</tr>
<tr>
<td>GMAW</td>
<td>gas metal arc welding</td>
</tr>
<tr>
<td>MMAW</td>
<td>manual metal arc welding</td>
</tr>
<tr>
<td>OAW</td>
<td>oxy-acetylene welding</td>
</tr>
<tr>
<td>PAC</td>
<td>plasma arc cutting</td>
</tr>
<tr>
<td>SAW</td>
<td>submerged</td>
</tr>
<tr>
<td>RSW</td>
<td>resistance spot welding</td>
</tr>
</tbody>
</table>

Examples of the use of process symbols are shown below.

Fig 4.11 – Process indication

Location of symbols
The basic symbol is placed on the reference line, its position depending upon where the weld is to be made (see Figs 4.12 (a), (b) and (c)).
The weld all-round symbol is placed at the junction of the arrow and the reference line.

![Fig 4.13 – Weld all-round symbol](image)

The flag of the site weld symbol always points away from the arrow.

![Fig 4.14 – Flag of the site weld](image)

Welds where complete penetration from one side is required must be indicated by placing the symbol on the reference line opposite the basic symbol, or alternatively by placing the letters CP in the tail of the arrow.

![Fig 4.15 – Complete penetration](image)

The backing run symbol is placed on the reference line opposite the basic symbol.

![Fig 4.16 – The backing run symbol](image)

The backing material symbol is placed on the reference line opposite the basic symbol.

![Fig 4.17 – The backing material symbol](image)

Where compound welds are required, one symbol for each weld must be shown. The first operation shall be on the reference line, each sequential operation is placed progressively outward.

![Fig 4.18 – Compound weld symbol](image)
Cranked arrow
Where it is required that one member of a joint is to have preparation applied, eg a bevel, the arrow must point to that part with a definite crank (see Fig 4.19).

Fig 4.19 – Crank in arrow symbol

Multiple reference lines
The code makes provision for the use of multiple reference lines. Additional reference lines may be used in the following ways.

a) To indicate a sequence of operations. The first operation is shown on the reference line nearest the arrow. Subsequent operations are shown sequentially on other reference lines (see Fig 4.20).

Fig 4.20 – Indication of sequence of operation
b) To show data supplementary to welding symbol information included on the reference line nearest the arrow (see Fig 4.21).

![This graphic has been removed. It was reproduced from Figure 2.29 on page 27 of AS 1101.1-2005.]

Fig 4.21 – Multiple reference lines

c) To show supplementary symbols relating to a particular operation (see Fig 4.22).

![This graphic has been removed. It was reproduced from Figure 2.30 on page 28 of AS 1101.1-2005.]

Fig 4.22 – Supplementary symbols
Size and spacing data
Irrespective of which way the arrow is pointing, the sequence of data from left to right is always as follows.

Design throat thickness
Depth of preparation or size

(S) (D) V

Length of weld
Pitch (c/c spacing) of welds

L - P

Basic symbol

This sequence will appear either above or below the reference line, depending on whether the weld is to be made on the other side or the arrow side of the joint.

Where required, the following symbols are placed in the following order either side of the reference line.

Finish symbol
Contour symbol

Preparation angle
Root gap

Basic symbol

This sequence is reversed for welds to be made on the arrow side of the joint.
Extent of welding denoted by symbols

Except where the weld all-round symbol is used, symbols apply between abrupt changes in the direction of welding, or to the extent of dimension lines or hatching (see Fig 4.25).

![Fig 4.25 – (a), (b) and (c) Extent of welding](image)

**Intermittent fillet welds**

- The length of a weld is shown immediately to the right of the basic symbol.
- The pitch of intermittent fillet welds is shown immediately to the right of the length, the two being separated by a dash.
- For chain intermittent fillet welds, the fillet symbol shall be shown on both sides of the reference line, the two placed opposite each other.
- For staggered intermittent fillet welds, the fillet symbol is placed on both sides of the reference line, but the two are staggered as shown in Fig 4.26.
- If required by actual length of the joint, a weld's increment length should be altered so that the weld terminates at the end of the joint.
Fillet and single bevel

Single bevel fillet over site weld all around

Double bevel with backing run

Backing run
Fig 4.26 – (a) Intermittent, (b) intermittent chain and (c) intermittent staggered chain
Chapter 4 – Welding terms and symbols

Fig 4.27 – Welding symbol examples
Chapter 5 – Welding plain carbon steel

Introduction
In this chapter we will look at the following.

- What is steel?
- Classification and availability of plain carbon steels
- Properties of metals
  - mechanical properties
- Mechanical tests
  - tensile testing
  - impact tests
  - hardness tests
  - fatigue tests.
What is steel?

Steel is an alloy of iron and carbon, in which the carbon content is within the range of 0.05–1.7%.

Elements in steel

The approximate composition of mild steel is as follows:

- iron (Fe)
- carbon (C) 0.1–0.3%
- phosphorous (Ph) 0.05% max
- silicon (Si) 0.35% max
- sulphur (S) 0.06% max
- manganese (Mn) 0.8–1.0% max.

Iron

Pure iron is a metal that is magnetic and has mechanical properties similar to those of copper. The tensile strength of iron is 139 MPa, which means pure iron is too weak and too soft for most engineering and structural applications.

Iron in its pure form is not readily available in nature. Its raw form of iron oxide (ore) is processed in a blast furnace. The oxides are reduced by the heat produced by combustion of a fuel which is typically coke. Other impurities are removed by adding limestone (which acts as a fluxing agent) and the blast furnace lining itself.

Carbon

Carbon has the greatest effect of any element when alloyed with iron. Adding carbon to pure iron or increasing the carbon content of low carbon steel will:

- increase tensile strength
- increase hardness
- increase hardenability
- increase toughness
- decrease ductility
- decrease malleability
- decrease weldability
- lower the melting point.

Even small amounts of carbon will bring about significant improvements in the mechanical and physical properties of steel.

Once the carbon content of steel exceeds 0.3%, the steel becomes ‘hardenable’, i.e., it has the ability to be hardened by heat treatment. Heat treatment is an important process and can be used to bring about significant changes in the mechanical properties of steels. For example, a high carbon steel in the soft state may be cut with a hacksaw, but following heat treatment it may be so hard that the only practical method of cutting is by grinding.
Apart from carbon, which is used to control the mechanical properties of steel, the other elements present are either impurities such as sulphur or phosphorus, or are added for such functions as de-oxidation or grain refinement. Complete removal of phosphorous and sulphur during the manufacture of steel is expensive and unnecessary, provided the level of each is below the above maximum percentages. The effect of these elements on plain carbon steel is as follows.

**Phosphorous**
Phosphorous forms iron phosphates, which cause cold shortness (a lack of ductility at normal temperatures). Phosphorous must be kept below 0.05%.

**Silicon**
Silicon is used mainly as a de-oxidiser in the steelmaking process. Silicon has no significant effect on improving the mechanical properties of steel. In excessive amounts, it tends to cause grain boundary weakness.

**Sulphur**
Sulphur causes hot shortness in steel. In plain carbon steels, sulphur is kept below 0.06%. Sulphur has been used as an alloy in free machining steels, however the modern trend is to use lead to improve machinability in steels.

**Manganese**
Although carbon/manganese steels (1.0–1.8% Mn) make use of manganese to improve hardness and tensile strength, lower amounts of manganese (0.8–1.0% Mn) are used in mild steels:
- as a grain refiner
- as a de-oxidiser
- to counteract the effect of sulphur in promoting hot shortness.

**Groups of steels**
Steels may be divided into two main groups, as follows.
- **Plain carbon steels** – Where the element used to improve mechanical properties is carbon.
- **Alloy steels** – Where elements other than carbon are used to improve mechanical properties.

Alloy steels will be discussed in a later chapter of this text.

**Plain carbon steels**
Plain carbon steels are divided into three groups, which are:
- low carbon steel
- medium carbon steel
- high carbon steel.
Low carbon steel

Low carbon steel is an iron/carbon alloy where the percentage of carbon is within the range of 0.05–0.30%. Low carbon steel is non-hardenable by heat treatment and therefore is essentially unaffected by welding. This makes low carbon steel the ideal choice for general fabrication purposes where high strength is not a prime requirement, but ease of fabrication and welding are.

Medium carbon steel

Medium carbon steel contains carbon in the range of 0.30–0.50%. Medium carbon steels are hardenable and exhibit improved mechanical properties over low carbon steel when they are heat treated.

High carbon steel

High carbon steel contains carbon in the range of 0.50–1.70%. High carbon steels are generally selected for use where hardness is a prime requirement and components made from this material are usually heat treated during manufacture.

Once these alloys exceed 1.70% carbon, they cease being called steels and are referred to as ‘cast irons’.

It should be noted at this point that although plain carbon steels are economical to produce and are the most widely used, the progressive loss of ductility that accompanies increases in carbon content precludes the use of plain carbon steels for some applications. Medium and high carbon steels are commonly used where hardness is a prime requirement of the finished product. Using mainly carbon to provide this hardness results in a loss of ductility and toughness. Consequently, where toughness is a prime requirement, the use of alloy steels is preferred.

Low carbon steels are ideally weldable, however in the hardenable medium and high carbon steels, increasing carbon content leads to a progressive loss of weldability. Careful consideration must be given to welding procedures when these steels are used. Typical uses for carbon steels are shown in Table 5.1.
<table>
<thead>
<tr>
<th>Carbon class</th>
<th>Carbon range %</th>
<th>Typical uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.05–0.15</td>
<td>Chain, nails, rivets, wire, pressing steels</td>
</tr>
<tr>
<td></td>
<td>0.15–0.30</td>
<td>Structural sections and plates</td>
</tr>
<tr>
<td>Medium</td>
<td>0.30–0.50</td>
<td>Axles, gears, drop forgings, con-rods, shafts</td>
</tr>
<tr>
<td>High</td>
<td>0.50–0.60</td>
<td>Crankshafts, scraper blades</td>
</tr>
<tr>
<td></td>
<td>0.60–0.75</td>
<td>Car springs, anvils, bandsaws</td>
</tr>
<tr>
<td></td>
<td>0.75–0.90</td>
<td>Chisels, punches</td>
</tr>
<tr>
<td></td>
<td>0.90–1.00</td>
<td>Knives, shear blades, springs</td>
</tr>
<tr>
<td></td>
<td>1.00–1.10</td>
<td>Milling cutters, dies, taps</td>
</tr>
<tr>
<td></td>
<td>1.10–1.20</td>
<td>Lathe and woodworking tools</td>
</tr>
<tr>
<td></td>
<td>1.20–1.30</td>
<td>Files, reamers</td>
</tr>
<tr>
<td></td>
<td>1.30–1.40</td>
<td>Dies for wire drawing</td>
</tr>
<tr>
<td></td>
<td>1.40–1.50</td>
<td>Metal cutting saws</td>
</tr>
<tr>
<td>Cast irons</td>
<td>Above 1.70</td>
<td>Machine base</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Castings</td>
</tr>
</tbody>
</table>

Table 5.1 – Uses of carbon steels

The difference between the C% and the CE is due to micro-additions of other elements. The WR grades are micro-alloyed with other elements; principally chromium, nickel and copper. Grade 200 is available only in plate, strip and floorplate up to 12 mm thick.
Chapter 5 – Welding plain carbon steel

Classification and availability of plain carbon steels

Plain carbon steels, are manufactured in Australia by OneSteel Pty Ltd as:

- plate and slab (to AS/NZS 3678)
- structural steel sections (to AS/NZS 3679)
- coil, strip and sheet (to AS/NZS 1594).

Low carbon steels are classified by yield strength. These low strength steels exhibit a noticeable yield point. When the yield point is reached they may continue to deform for a short time, with no increase in load. This is in contrast to higher strength steels, which exhibit no noticeable yield point. High strength steels are classified according to their ultimate tensile strength.

Classification system

Steels classified by yield strength are covered under AS/NZS 3678 and AS/NZS 3679 and are specified by Australian Standard® number, nominal minimum yield stress (eg 250/350 MPa), a treatment type suffix (/1 OR /2) and an optional ‘WR’ prefix where appropriate for weather-resistant (weathering) steels.

eg

AS/NZS 3678 – 250
AS/NZS 3679 – WR 350/1

Additional to this, where the material must possess specified minimum impact properties a suffix such as ‘L’ is used. ‘L’ indicates that the material has been low temperature impact tested. Additionally, the suffix ‘L’ is followed by a number, which indicates the temperature at which the test is conducted, at or below 0 °C.

eg

WR 350/1 L0 – indicates that an impact test has been conducted at 0 °C.
350 L15 – indicates that a low temperature impact test has been conducted at -15 °C.

The grades of steel plates available under AS/NZS 3678/3679 are given in Table 5.2.

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This table has been removed. It was reproduced from Table 1 on page 9 of AS/NZS 3678:1996 and Table 1 on page 12 of AS/NZS 3679.1:1996.

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Table 5.2 – Steel grades to AS/NZS 3678 and AS/NZS 3679
Weldability of plain carbon steels

Weldability refers to the ease with which metals can be welded. Weldability is determined by three major factors, which are:

- the quality required for the finished weld
- the ease of making the weld using a given weld process
- cost factors.

Welding low carbon steels

Low carbon steel is considered to be easily welded as it is simple and easy to weld. Because the material is not hardenable, a sound weld usually results.

As the material thickness or carbon content (or equivalent) increases, however, hardenability and welding problems increase. Consequently weldability decreases in medium and high carbon steels or thicker sections. This is the result of the potential formation of martensite, a brittle constituent in the grain structure, which forms when steel containing more than 0.3% carbon (or equivalent) is cooled rapidly from elevated temperatures.

In low carbon steels, there is insufficient carbon present for martensite to be formed by rapid cooling and therefore the cooling rate is not significant in this regard.

However, rapid cooling of the weld promotes the formation of undesirable crystal structures with a resultant loss of ductility and also increases shrinkage stresses. Pre-heating may be necessary on thick sections to reduce these tendencies.

Summary

- Low carbon steels are relatively ductile and are easily welded using any welding process and appropriate filler material.
- Pre-heating is normally unnecessary, except to reduce shrinkage stresses in thick sections.
- Rapid quenching (eg water quenching) should be avoided, as a loss of ductility may result.

Welding medium carbon steels

As the carbon content of the steel is increased, so is the likelihood of the formation of undesirable martensite. This means that medium carbon steels can present problems related to hardenability and loss of ductility when welding. The cooling rate must be slow enough to prevent the formation of martensite. This may be achieved by the application of pre-heat to prevent the rapid chilling of the weld zone due to heat conduction to the surrounding mass of parent metal. Alternatively, the welding variables may be manipulated to ensure that the cooling rate of the weldment is slow enough to prevent significant martensite formation.
Chapter 5 – Welding plain carbon steel

The effect of dilution and pick up

Dilution is the extent to which deposited weld metal is diluted by molten parent metal during welding. Weld metal is composed of a mixture of the filler material used and the parent metal melted by fusion.

Carbon or alloy pick-up in the weld metal from the fused base metal can result in reduced ductility of the weld metal, which in turn will increase the possibility of cracking. The amount of dilution on pick-up is obviously influenced by the degree of penetration. Therefore, care should be taken to avoid excessive fusion into the parent metal. This can be achieved by restricting the welding amperage to that which is necessary to provide good fusion. Dilution is not a problem where the carbon content is reasonably low and on medium carbon steels this is usually within safe limits, but in high carbon steels dilution needs careful control.

Summary

Medium carbon steels present the possibility of cracking in the weld itself or the heat-affected zone, due to martensite formation.

Pre-heating will be required depending on the cooling rate of the weldment and the heat input from welding. The higher the carbon content, the higher the pre-heat temperature.

The use of hydrogen-controlled electrodes and/or processes is highly advisable.

Consideration should be given to the amount of penetration and fusion into the parent metal, with the aim of minimising dilution and pick-up.

Rapid cooling of the weld zone is to be avoided.

Welding high carbon steels

In high carbon steels, martensite will form readily, even at relatively slow cooling rates. This reduces the weldability of high carbon steels. The use of a weld procedure and close control of the heat input must be exercised. In weldments which have been heat treated during manufacture, annealing may be required prior to repair welding being carried out.

All sources of hydrogen must be removed from the welding process as this may cause/contribute to underbead cracking in the heat-affected zone, adjacent to the weld. The high strength weld metal will be less ductile and joint restraint must be minimised to prevent cracking in the weld or the adjacent base metal.

Summary

- High carbon steels are extremely hardenable and slow cooling must be ensured.
- Good fit-up must be assured.
- All sources of hydrogen must be removed. Clean workpieces and hydrogen-controlled consumables are essential.
- Joint restraint and shrinkage stresses must be minimised.
- Pre-heat is usually applied and in some cases is followed by post-heating. Further post-weld heat treatment may be required.
- The use of a nickel alloy filler may be advisable.
Properties of metals

Knowledge of a material’s properties will greatly assist the tradesperson in many ways. It is important to be able to select the most suitable material for a particular application and the correct methods to be employed in using a given material, eg the correct welding method. A general knowledge of materials can be built up by recognising the individual characteristics or properties of each one.

The properties of metals can be divided into two groups:

- physical
- mechanical.

Physical properties

The physical properties of materials are those properties that are not directly related to strength and may generally be determined by methods which do not destroy the material under investigation. Among the more common physical properties are:

- colour
- mass
- grain structure
- heat and electrical conductivity
- corrosion resistance
- magnetism.

Colour

Many materials can be identified by their characteristic colour, eg rusty steel, bright aluminium and dull copper. However, care must be taken as some metals are similar in colour or may exhibit differences when scratched, polished or fractured. For example; steel may be blue when new due to mill scale, silvery when wire-brushed, or may be brown from rust.

Mass

An obvious example of mass is the comparison of components made from lead being a heavy metal and aluminium being a light metal. The mass of a material is an important consideration in modern construction, where every attempt is made to reduce mass and yet obtain maximum structural strength. In metal fabrication, where materials are often purchased according to a tonne rate, the less material that is used the lower the costs.

Grain structure

All metals have differing grain structures. It is sometimes possible to identify fractured metal by examining the grain structure exhibited on the face of the fracture. Cast and malleable iron are good examples. Cast iron has a coarse dull grey appearance, whereas malleable iron has a finer structure. Malleable cast iron also can be further classified as ‘white heart’ or ‘black heart’, the former having a silvery grain structure and the latter a dark centre surrounded by a thin silvery border. The term ‘homogeneous’ grain structure means that the grain or fibre patterns are the same throughout the piece of material.
Heat and electrical conductivity

Metals that conduct heat well are also good conductors of electricity. Copper and aluminium are good conductors and so need more heat to counteract the loss when heat is conducted away from the weld area. On the other hand, stainless steel is a poor conductor because heat is accumulated and retained at the weld area without much loss. This also contributes to local overheating and distortion.

A copper work lead should be used in preference to using strips of mild steel when an extension to the welder’s work lead is unavoidable. Mild steel is not as good a conductor and causes more resistance in the circuit, making the machine less efficient.

Corrosion resistance

The corrosion resistance of metals varies with the chemical composition and service conditions or environment in which it is placed. Temperature, moisture, air and other factors influence the selection of the most suitable material for a particular service. Metals such as copper, zinc and aluminium greatly resist natural corrosive attack. Mild steel is painted or protected by zinc rich coatings (eg galvanising) to keep corrosion to a minimum and so retaining its design strength. By alloying iron with high amounts of chromium, the material can become ‘stainless’.

Magnetism

Most ferrous material is magnetic and may be identified by holding a magnet near it. However, care should be taken as there are exceptions where some metals may confuse the unwary. Austenitic stainless steel (a ferrous metal) is non-magnetic. Carbon steels can be non-magnetic when heated and some non-ferrous alloys containing aluminium, nickel and cobalt are very magnetic although they contain no iron. It is therefore wise to use magnetism as only one of a number of tests to assist in identifying a metal.

Mechanical properties

Mechanical properties in a metal are those properties that can be observed when various loads or stresses are placed on it. The mechanical properties of metals have great influence on their selection for use whether for strength or ability, to be formed to shape or processed using commercially available methods.

Tenacity

This is a measure of a metal’s ability to withstand a smoothly applied load or direct pull before it breaks. The ultimate tensile strength of a metal is usually found by testing to enable safe working limits to be established for construction work. A wire rope is a good example of the tenacity of steel.

Ductility

A ductile material is one that can be permanently deformed, pulled, bent and drawn without failure. The deformation of a flat steel sheet into a motor car bonnet or guard is an example of the ductile nature of steel.

Brittleness

Some metals show practically no permanent distortion before failure. In other words, they fail suddenly without warning. Brittleness therefore indicates lack of ductility. Ordinary cast iron, a brittle metal, has a low resistance to shock.
Toughness
A tough metal is one that can withstand considerable stress (slowly or suddenly applied) continuously or often applied and that will deform before failure.

Hardness
Hardness is usually defined as the resistance a metal has to forcible penetration by another metal. A hard metal resists scratching or wear. It takes a combination of hardness and toughness to withstand heavy pounding.

Malleability
A material can be defined as malleable when it can be formed or worked by cold forging or hammering. Gold is the best example of a material that can be cold worked into very thin sections without hardening.
Mechanical tests

The quality of steel is usually established on the basis of tensile properties and hardness. Other tests, however, are used in finding the strength of steel under compression, shear or torsion loading. Furthermore, specimens of steel may be subjected to suddenly applied loads as in impact testing, or to many repetitions of loading as in fatigue testing. The information gained from mechanical testing is of immense value to the engineer, metallurgist, technician or tradesperson.

Mechanical testing may be classified as follows:

- tensile testing
- impact testing
- hardness testing
- fatigue testing.

A brief summary of these terms is included here. For a more detailed description of these tests, refer to chapter 7.

Tensile testing

Tensile testing is used to measure the elastic limit, yield point, ultimate tensile strength, percentage of elongation and the percentage of reduction of area.

In this type of test, a specially shaped sample of the metal is subjected to a steadily increasing load and is pulled until fracture occurs.

Explanation of terms in tensile testing

Tensile test

Strictly speaking, this term covers any test figures obtained by a tensile or pulling machine.

Elastic limit

Is expressed as the load, usually in MPa, at which the test piece ceases to behave like an elastic product, returning to its original dimensions upon release from load. Beyond this load, the steel commences to stress and deform permanently. In practical use a part stressed beyond this point will be damaged and in addition to having lost its accurate shape will be more easily damaged further by repeated working stresses.

Yield point

Is the point at which the natural resistance of the steel breaks down so that it deforms rapidly without a load increase. Once this point is reached, small additions to the load cause rapidly increasing deformation until actual breakage occurs. The yield point is close to the elastic limit and as it is a noticeable point in the test, it is usually taken as the elastic limit in commercial testing.
Ultimate tensile stress

Is the greatest pulling force that a test piece can withstand without actual breakage. This is usually expressed in MPa. Ultimate tensile stress is sometimes referred to as ‘the breaking strain’, but this is not correct. The ultimate tensile stress figures given are based upon the actual force, divided by the sectional area of the test piece.

Elongation

This is the total amount by which the test piece increases in length before actual breaking under tensile test. It is usually measured over an initial length and resultant length and expressed as a percentage of their respective lengths. It is important that the original length be stated when per cent elongation figures are given.

Reduction of area

Unless it is extremely brittle, a test piece pulls out thin before it breaks. The reduction of area expresses the difference between the area of the fracture and the original cross-sectional area of the test piece as a percentage. It is a valuable indication of the ductility of the material. Both the elongation and the reduction of area are an indication of the ductility of the steel.

Impact testing

To determine the notch brittleness of a material and its ability to withstand impact at any temperature, or suddenly applied loads, impact tests are performed on specimens prepared with a notch of precise width, depth and shape.

The two main types of impact tests are the Charpy and the Izod test. The impact test is performed by a weighted pendulum striking the notch specimen from the material being tested. The energy absorbed in breaking the specimen is recorded on a direct reading indicator. The tougher the material, the greater the amount of energy absorbed in fracturing it and the smaller will be the extent of swing of the hammer after it has been fractured.

Hardness testing

The hardness of a material is an important property in itself, but measurement of hardness will also provide a useful indicator with respect to tensile strength, ductility and impact resistance. In general, the harder of the two metals of similar composition has a higher tensile strength, lower ductility and more resistance to abrasive wear. High hardness also indicates low impact strength.

Different types of hardness test are used, not all of which involve penetration of the material surface by a ball or point. These tests are the:

- Brinell test
- Rockwell test
- Vickers hardness test.
Fatigue testing

A knowledge of tensile properties makes possible the design and fabrication of a structure that will support a steady load pulling in one direction. These properties, however, do not indicate the strength a metal will have if used in a structure where the load is applied first in one direction and then in another. When the load alternates like this, in a cycle, at one moment the force is tension and at another compression. Alternating stresses are present in such components as axles, connecting rods, transmission shafts, boiler drums and pressurised storage tanks. The stresses in these components may alternate between high tension and low tension, or between tension and compression.

Metals will fail at a lower stress under a changing load than if the load were steady. Failure under a changing load is called ‘fatigue failure’.

Fatigue failure is invariably triggered off by some surface imperfections such as inclusions near or on the surface, undercut, overlap, excessive build up, or even grinding marks. Failures start at the surface as tiny cracks which spread into the metal until failure occurs.

Fatigue tests are made by subjecting a test specimen to varying loads. Tests may be made by:

- bending the specimen alternately in one direction and then the other
- applying and removing tensile loads
- making a cycle of tension and compression by rotating a loaded specimen.
Chapter 6 – Heat treatment

Introduction

In this chapter we will look at the following.

- Grain structure
- The structure of steel
- Phases in steel
  - time temperature transformation
  - essential features of the iron/carbon diagram
  - the effect of heating and cooling
  - recrystallisation
- Effects of welding on the grain structure
  - grain growth
  - heat treatment.
Grain structure

Steel, like all metals, is composed of grains. Each of these grains is in fact a crystal of the metal or metal alloy. The size, composition and structure of these grains and the strength of the bond between the grains, determine the physical and mechanical properties of the metal.

A metal that is composed of grains which are soft and weak will itself be soft and weak. A metal that is composed of grains which are hard and brittle will itself tend to be hard and brittle.

Additionally, metals which are composed of grains that are large in size will generally display poor mechanical properties, particularly in terms of malleability and ductility. Grains form at elevated temperatures. Consequently the grain structure of a material can be changed by heat treatment and also by the heating/cooling cycle of welding. Control over changes in grain structure is important. Firstly it enables us to produce desirable properties in the metals we use and secondly to prevent the formation of undesirable grain structures due to welding.

Ideally, metals will have a grain structure which:

- is fine and regular in shape
- is of suitable composition and internal structure
- has few impurities at the grain boundaries and good bond strength.

The mechanisms involved in the formation of grains in pure iron are described below.

- As pure molten iron cools, the temperature of the metal falls until the solidification temperature of around 1500 °C is reached.
- At various points throughout the metal and generally on the outside at the cooling surface where the solidification temperature has been reached, nuclei (or seed crystals) begin to form in the molten metal as atoms cease to have the energy needed to move freely (remain fluid).
- The crystals continue to form where the temperature has fallen to the solidification temperature. The seed crystals attract additional atoms into the structure in a definite arrangement (according to temperature) and begin to grow away from the cooling source. These structures are known as dendrites. These dendrites will continue to grow in a certain direction. As growth of these dendrites continues, secondary arms begin to grow at right angles to the first and arms grow in a third direction, at right angles to the second and so on in six directions along each axis at right angles to each other until their growth is restricted by their neighbours. From this point, continuing growth is internal and will continue until there are no more free atoms to take up or the space between the arms of the dendrites is packed tight and a solid grain is formed (Fig 6.1).
If the temperature of the cooling metal falls rapidly to the solidification temperature, a large number of seed crystals will form. This means that less overall dendritic growth can occur before the dendrites meet their neighbours and a fine grain structure will result.

If cooling to the solidification temperature is slow and/or uneven, the points at which seed crystals form will be fewer and considerable growth of the dendrites will occur, resulting in a coarse grain structure.

A good illustration of this is in the solidification of a metal ingot. Keep in mind that the outer section of the ingot will fall to the solidification temperature first, due to the chilling effect of the mould into which the metal is poured.

This rapid cooling will give rise to the formation of many nuclei or seed crystals and a polycrystalline layer of a new form developing upon the inner boundaries of the chilled crystals.

The direction of growth will now be predominantly inwards towards the centre of the casting, ie in the opposite direction to which the extraction of heat is taking place.

The crystals formed are extremely elongated, having their lateral growth greatly reduced owing to early contact being made with adjacent crystals growing in the same direction. Such crystals are known as columnar crystals and may often be found in some types of weld metal deposits.
The continuation of heat loss from the mass of molten metal will reduce the internal temperature so that simultaneous freeing of the remaining molten metal will now take place. Hence a third type of crystal will begin to form.

These crystals in the centre zone of the metal do not show any preference to directional growth because they are able to grow in any direction and are therefore said to be equi-axed. They are much larger in size than the surface layer of chilled crystals, due to a slower rate of cooling.

The sectional view of the cast iron ingot (Fig 6.2) clearly shows the crystal structure of the cast pure metal.

During cooling from the molten state, the temperature will fall until the solidification temperature is reached. However the temperature will not fall below this point until solidification is complete. Once solidification is complete, the temperature will once again begin to fall. The graph shown in Fig 6.3 shows temperature plotted against time during the cooling of a molten metal.
Pure iron is allotropic in nature, this means it can have different atomic structures according to temperature. Pure iron will form into a body centred cubic (bcc) arrangement on solidification and then has a face centre cubic (fcc) arrangement from around 1400 °C down to 910 °C. It then becomes body centred cubic (bcc) again below 910 °C. This means the iron crystals will have various atomic structures according to temperature.

Adding carbon (or other additional elements) to pure iron alters the change point temperatures and the mechanisms involved. This has a complicating effect on the basic structures within the metal.

The structure of steel

Steel is an alloy of iron, carbon, manganese and silicon. Pure iron is also known as ferrite. Ferrite is soft, weak and ductile. When a small percentage of carbon such as 0.3% (as in mild steel) is added to molten iron, all of the carbon will dissolve into the iron. When slowly cooled, the iron crystals of the solidifying metal crystals will reject the carbon as they cool and try to revert to pure iron. The solidification temperature and structures will also be altered because of the effect of the carbon.

At around 1550 °C the atomic structure will form up into metal crystals in a bcc arrangement until there are no more free atoms. The carbon will be forced into the outer extremities of each metal crystal as either free carbon or carbon chemically combined with iron (iron carbide). Around 1400 °C the crystals begin to transform into an fcc arrangement which can absorb all of the carbon within its structure (up to a maximum of 1.7%).

At about 920 °C the metal crystal structure will again rearrange back into a bcc arrangement. Most of the new iron (ferrite) crystals will now reject the carbon again and the grain boundaries will become saturated with carbon. At 723 °C the remaining crystals will be forced to lock up the carbon within their structure. They do this by forming a chemical compound known as iron carbide. Iron carbide is also known as cementite which can be hard, strong and brittle.

The number of cementite crystals which form is therefore dependent upon the overall amount of carbon that is added to the iron. The iron carbide crystals occur as a layered structure within the grains of ferrite. The metal grains which have this layered structure are known as pearlite. In mild steel the structure of iron/iron carbide is supported by the ductile ferrite grains. This combination of both hard and ductile material within each grain results in a tough, strong material being formed (Fig 6.4).
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ferrite</td>
<td>a constituent of carbon steels; pure iron; magnetic and soft</td>
</tr>
<tr>
<td>cementite</td>
<td>the iron carbide constituent of steel and cast iron; very hard and brittle</td>
</tr>
<tr>
<td>pearlite</td>
<td>lamellar structure resembling mother of pearl; a compound of iron and carbon occurring in steel as a result of transformation of austenite into aggregations of ferrite and iron carbide</td>
</tr>
<tr>
<td>tensile strength</td>
<td>pertaining to forces on a body that tend to stretch, or elongate, the body</td>
</tr>
<tr>
<td>eutectoid steel</td>
<td>a steel that contains 0.83% carbon (the eutectic point); a carbon steel with 0.83% carbon is pure pearlite</td>
</tr>
<tr>
<td>austenite</td>
<td>a phase of steel in which the metal is in a solid solution; austenite is stable only above 1333 °F in plain carbon steels</td>
</tr>
</tbody>
</table>

In low carbon steel, the grains are predominantly ferrite. As the percentage of carbon is increased, the number of ferrite grains decreases and the number of pearlite grains increases, until at 0.83% carbon the steel is composed entirely of pearlite and is said to be ‘fully pearlitic’.

When the carbon content exceeds 0.83%, the additional iron carbide which forms cannot be taken in to the grains. It resides at the grain boundaries and is known as ‘free cementite’. This brittle constituent at the grain boundaries results in decreasing toughness of the steel as more free cementite is formed. Fig 6.5 summarises the changes to the grain structure which occur with increasing carbon content and shows the accompanying properties and uses.
Fig 6.5 – The relationship between carbon content, microstructure, mechanical properties and uses of plain carbon steels in the normalised condition
Chapter 6 – Heat treatment

a) Pure iron is composed wholly of ferrite and is soft, ductile and weak.

b) 0.3% C (low carbon steel) is composed of approximately 25% pearlite distributed evenly in a matrix of ferrite. The pearlite increases the tensile strength and hardness but there is a loss of ductility.

c) 0.6% C (high carbon steel) is composed of approximately 60% pearlite. There is a further increase in strength and hardness but a notable decrease in the ductility. Because of this, welding is more difficult for the material is brittle and tends to crack.

d) 0.83% C (eutectoid steel) is composed wholly of pearlite and is even more brittle and therefore difficult to weld unless close attention is paid to heat input and cooling rate.

e) 1.1% C (hypereutectoid steel) is composed mainly of pearlite but with cementite forming at the grain boundaries. These steels are extremely hard and can only be welded after the steel is heat treated to soften it.

1.7% C is the limit for steels. More cementite is present around the pearlite, thus the steel is extremely hard and brittle.

Phases in steel

Steel can also be seen to be allotropic in nature, i.e. the patterns into which the atoms of the material arrange themselves (the atomic structure) is changeable and may exist in more than one form depending on carbon content, temperature achieved, time at temperature and cooling rate.

This change in structure results in differing properties in the metal; e.g., steel at ambient temperatures is magnetic. If the steel is heated to a high temperature, the atomic structure changes and the steel becomes non-magnetic. It becomes magnetic again just prior to the melting temperature being reached.

Changes of this type are referred to as ‘phase changes’. Metallurgists make use of these phase changes to obtain desirable properties in many metals.

The two structures present in low carbon steels at ambient temperatures are ferrite and pearlite.

Other phases of steel which are important are as follows.

**Austenite** – When carbon steel is heated above the lower critical temperature (or transformation range), the ferrite/pearlite structure is dissolved into a constituent known as austenite. This transformation to austenite occurs while the steel is in the solid state. The carbon is dissolved evenly throughout the austenite and the ferrite/pearlite structure is no longer present. Austenite is non-magnetic.

In plain carbon steels, austenite can only exist at elevated temperatures above 723 °C. In some steels, austenite can exist at ambient temperatures. The two most common examples of such steels are ‘austenitic stainless steel’ and ‘austenitic manganese steel’. In these steels, the grain structure is predominantly austenite. Due to the fact that austenite is non-magnetic, these steels themselves are non-magnetic.

Because austenite can only exist in plain carbon steels at elevated temperatures, as the steel cools it reverts back to a ferrite/pearlite structure or some other phase, depending on carbon content and cooling rate.
Martensite – A hard, brittle constituent which forms in steels that are cooled rapidly from elevated temperatures. For martensite to form, the steel must contain at least 0.3% carbon, i.e., steels containing less than 0.3% carbon are not hardenable by heat treatment as martensite is not formed during cooling. Phase changes in steel as a result of heat treatment are time/temperature transformations. That is, changes are a result of time and changes in temperature.

If a hardenable steel in the austenite condition is allowed to cool slowly through the transformation range, migration of the carbon will cause a return to the ferrite/pearlite structure with which we are familiar. If the cooling rate is too rapid, there is insufficient time for the transformation to ferrite/pearlite to occur. The carbon is then trapped in a hard, needle-like structure within some of the grains. This structure is known as martensite (Fig 6.6).

The higher the carbon content and the more rapid the cooling rate, the greater the amount of martensite which will form within the ferrite/pearlite structure.

Martensite increases hardness and tensile strength in steels but also reduces ductility. Steels containing large amounts of martensite are too brittle for most applications. The steel is usually reheated to modify the internal structure of the needles within the grains. Slightly decomposing the internal structure in this way will restore some ductility to the steel.

**Time temperature transformation**

As previously mentioned, phase transformations are a product of time and changes in temperature. The phase changes which occur in carbon steels can be identified on a graph known as ‘the iron/carbon equilibrium diagram’.

A relatively simple version of this diagram showing the essential features when dealing with plain carbon steels is given in Fig 6.7.
Fig 6.7 – Iron/carbon equilibrium diagram

Essential features of the iron/carbon diagram

Lower critical temperature (LCT)
The LCT is the point at which a phase change from the ferrite/pearlite structure of steel begins to occur during heating. There is no change in the grain structure below this point. The LCT for all carbon steels is 723 °C.

Upper critical temperature (UCT)
UCT is the temperature at which the phase change from ferrite/pearlite to austenite is complete during the heating cycle. It is also the point at which austenite begins to form some other phase (usually ferrite/pearlite) during the cooling cycle. The UCT varies, depending on the carbon content of the steel. The UCT ranges from 910 °C for pure iron, to 723 °C for steel containing 0.83% carbon, to approximately 1140 °C for the steel limit of 1.7% carbon.

Eutectoid steel
Steel which contains 0.83% carbon has both an LCT and a UCT of 723 °C. Because the carbon is evenly distributed throughout the metal, no time is required for the migration of carbon, as is the case with other steels when they undergo phase changes. The change to austenite is almost immediate.

Transformation zone
The range between the LCT and the UCT is known as the transformation zone. It is between the LCT and the UCT that the transformation from one phase to another occurs.

When steel is heated, a phase change from ferrite/pearlite to austenite begins to occur at the LCT. When the UCT is reached, the change to austenite will be complete.

The phases within the transformation zone are:
- ferrite and austenite for steels below 0.83% carbon (hypoeutectoid steels)
- cementite and austenite for steels above 0.83% carbon (hypereutectoid steels).
The effect of heating and cooling

- If a hypoeutectoid steel (containing less than 0.83% carbon) is heated, no change in grain structure occurs until the LCT of 723 °C is reached, whereupon the pearlite present transforms to austenite.
- As the temperature continues to rise, the ferrite grains still present begin to dissolve into the newly formed austenite, until at the UCT all the ferrite is dissolved and the grain structure is entirely austenite.
- During the cooling of steel from high temperatures, no change in the austenite grain structure occurs until the UCT is reached. At this point, ferrite grains begin to grow as the ferrite comes out of solution in the austenite. The ferrite grains continue to form until the LCT is reached, at which point the remaining austenite transforms to pearlite. These changes can be seen in Fig 6.8.

![Fig 6.8 – Phase changes in hypoeutectoid steel due to heating and cooling](image-url)
Recrystallisation

The phase changes just described occur when steel is heated through the transformation range and subsequently cooled.

It is unlikely however that the ferrite/pearlite structure upon cooling will be identical to the ferrite/pearlite structure prior to heating. In most cases, the grain structure of the steel prior to heating will be distorted due to stress or cold working. Alternatively the grain size may be large due to the metal having undergone prolonged heating.

When steel passes through the transformation range during heating, new grains grow from the grain boundaries at close and regular intervals. These new equi-axed crystals will result in the formation of a fine grained austenite structure at the UCT. If the steel is cooled from just above the UCT, it will transform to a ferrite/pearlite structure within the new grains which have been formed being fine and regular in shape.

Summary

The phase changes in steel are summarised in Fig 6.9.
The following information explains the phase changes illustrated in Fig 6.9.

**Point 1**  Ferrite/pearlite structure in steel of approximately 0.4% C. Grain is irregular due to cold working.

**Point 2**  Heating to just below the LCT – no change in grain structure.

**Point 3**  Within the transformation zone – grain structure is ferrite and austenite, new grains growing out of old structure.

**Point 4**  Just above the UCT transformation is complete – the structure is fine-grained austenite. If cooling from this point is slow, a fine-grained ferrite/pearlite structure will result (Point 7). If cooling is rapid, a fine-grained ferrite/pearlite/martensite structure will result (Point 6).

**Point 5**  Metal is liquid at high temperature. No grains are present.

**Point 6/7**  Phase changes in steel.

**Point 8**  Temperature falls to the solidification temperature – seed crystals form, dendritic growth begins.

**Point 9/10**  Phase changes in steel.

**Point 11**  Phase changes in steel.

If the temperature continues to fall steadily from this point, the fine-grained austenite structure will transform to a fine-grained ferrite/pearlite structure (Point 7) if cooling through the transformation zone is slow. A fine-grained ferrite/pearlite/martensite structure (Point 6) will result, if cooling through the transformation zone is rapid.

If cooling from just below the solidification temperature is slow, or if the steel is held at high temperature for a prolonged period of time, grain growth will occur (Point 9).

Cooling of the steel (Point 9) will result in a coarse-grained ferrite/pearlite structure being formed if cooling through the transformation range is slow (Point 11), or a large-grained ferrite/pearlite/martensite structure if the cooling rate through the transformation range is fast (Point 10).
Effects of welding on the grain structure

When a weld is made, the weld metal is melted and some of the adjacent parent metal is heated above the lower critical temperature. As the weld metal solidifies and the heat affected zone cools, new grains are forming in these areas.

Typically, grains in the weld metal tend to be columnar, as a result of solidification progressing away from the cooler adjacent parent metal.

The metal in the heat-affected zone adjacent to the fusion line is heated to a high temperature and is slow to cool. Consequently grain growth occurs, resulting in a region of coarse grain structure immediately adjacent to the weld.

Metal that has been heated above the UCT will have undergone full transformation and adjacent to the coarse-grained region, a fully transformed fine-grained region will result, due to more rapid cooling as the distance from the weld increases.

The zone which has been heated to between the UCT and the LCT will undergo partial transformation.

Adjacent to this will be parent metal which has not been heated to a temperature high enough for any transformation to take place and therefore the grain structure will remain unchanged. This can be seen in Fig 6.10.

![Fig 6.10 – Changes in grain structure as a result of welding](image-url)
Multi-pass welds

The first pass in a multi-pass weld forms a grain structure composed of columnar crystals, similar to that of a single-pass weld. Providing the next pass is made whilst there is still heat in the weld zone, the second pass has the effect of reheating and recrystallising the first pass, thus causing a refinement of the grains. A third pass refines the second pass and so on until the weld is completed. The weld reinforcement, which is considered surplus, has a coarse grain structure, but the weld metal considered for the effective strength is composed of refined grains, see Fig 6.11.

![Fig 6.11 – Grain refinement in multi-pass welds](image)

The refinement of the grains achieved by multi-pass welds makes the weld metal stronger and tougher. However, if the weld is allowed to cool between passes, then only the surface of the previous run is refined.

Grain growth

Grain growth is the term used to describe the actual growth of some grains by the absorption of adjacent grains (Fig 6.12).

![Fig 6.12 – Grain growth](image)

Grain growth and the resultant coarse-grained structure may be caused by:

- slow cooling from the liquid to the solid state
- maintaining the metal at a high temperature for an extended period of time
- heating the metal to a temperature well above the recrystallisation temperature.
The effect of this grain growth upon the mechanical properties of the metal is reduced:

- tensile strength
- ductility
- malleability
- impact resistance
- fatigue resistance.

Grain growth is caused by prolonged heating and slow cooling. It follows, therefore, that because different welding processes have different heat inputs and cooling rates, the effect of welding on the grain structure will vary depending on the nature of the welding process used.

Examples of welding processes that produce coarse grain structures are:

- electroslag welding
- submerged arc welding
- oxy-acetylene welding.

Each of the above processes has a high heat input and slow cooling rate.

Manual metal arc and gas metal arc processes tend to give a much more localised heat and have faster cooling rates, therefore grain growth does not occur to the same extent. In fact, grain refinement is common during multi-pass welds.

Steel that has suffered grain growth can be restored to its original structure by reheating to just above its recrystallisation temperature and by controlling the cooling rate.

**Heat treatment**

Heat treatment is the process of applying a controlled heating/cooling cycle to a metal to bring about desirable changes in the properties of the material.

The commonly applied heat treatment processes are:

- annealing
- normalising
- hardening
- tempering.

In addition, heat treatment processes peculiar to welding are:

- pre-heat
- post-heat
- concurrent heating
- stress relieving.
Annealing

Annealing involves heating to above the UCT (50–70 °C above for steel), holding at temperature to ensure complete and even heating throughout, followed by slow controlled cooling. Cooling is usually in the furnace, but can be in a lime bin or under thermal blankets. The slow cooling allows full transformation of the grain to take place (new grain structure is formed).

Annealing gives maximum softness to a metal and improves ductility, but may produce coarse grains. Some tensile strength is also lost, but residual stress is relieved. Annealing is commonly carried out prior to cold working or prior to repair welding of hardened steels.

Holding time is variable, but never less than one hour per 25 mm of thickness. A heating/cooling temperature curve for annealing is given in Fig 6.13.

![Fig 6.13 – Time/temperature curve for annealing](image)

Normalising

Normalising involves heating to above the UCT (50–70 °C above – as for annealing). Normally, steel is ‘soaked’ for one hour per 25 mm of thickness – to ensure a uniform temperature. Cooling is then in still air (usually just outside the furnace). The purpose of normalising is to restore a fine and regular grain structure to the metal as a means of improving mechanical properties.

A time/temperature curve for normalising can be seen in Fig 6.14.
Normalising yields a finer-grained, slightly harder (because of distribution of pearlite) and stronger steel.

This process of re-crystallisation is commonly applied to weldments and plates during manufacture, where mechanical properties are of prime importance.

**Grain size after welding**

**Grain size after normalising**

![Diagram showing the effect of normalising](image-url)
Hardening

Hardening involves heating the steel to above the UCT (but slightly below that for normalising or annealing). This temperature is maintained for a time to dissolve the carbides fully in the austenite. The metal is then quenched rapidly in a suitable quenching medium. The rapid cooling rate due to quenching results in martensite formation in steels with carbon contents above 0.3%. Steel below 0.3% carbon is not hardenable by heat treatment.

Quenching rate

The quicker the cooling rate, the greater the hardness which will result when a given steel is quenched from a given temperature. Common quenching media in order (most rapid first) are:

- brine (salt water)
- water
- oil
- air.

Tempering

Tempering is a common term for a low temperature process that relieves internal stresses and improves ductility and toughness in steels. Tempering is normally associated with hardening, as tempering usually follows hardening as a means of reducing brittleness.

Temperatures of between 200 °C and 300 °C are used, followed by quenching in a suitable medium such as oil or water. The higher the temperature from which quenching is carried out, the softer and more ductile the component will become.

Tempering is carried out below the LCT. A typical time/temperature curve for tempering is given in Fig 6.16.
Temper colours

As a polished steel is heated, the oxide layer that forms on the surface will change colour from a soft yellow at 220 °C through to a dark blue at 300 °C. Temper colours are thus useful guides as to some form of tempering control in the workshop.

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Colour</th>
<th>Temper and typical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>pale yellow</td>
<td>(hard) scrapers, turning tools</td>
</tr>
<tr>
<td>230</td>
<td>straw</td>
<td>dies, hammers</td>
</tr>
<tr>
<td>240</td>
<td>dark straw</td>
<td>shears, drills for steel</td>
</tr>
<tr>
<td>250</td>
<td>light brown</td>
<td>(med) knives, shears, punches</td>
</tr>
<tr>
<td>260</td>
<td>purple brown</td>
<td>reamers, drills for wood</td>
</tr>
<tr>
<td>270</td>
<td>purple</td>
<td>axes, hand tools</td>
</tr>
<tr>
<td>280</td>
<td>deep purple</td>
<td>chisels, screw drivers</td>
</tr>
<tr>
<td>290</td>
<td>bright blue</td>
<td>(soft) wood chisel</td>
</tr>
<tr>
<td>300</td>
<td>dark blue</td>
<td>springs</td>
</tr>
</tbody>
</table>

Table 6.1 – Temper colours
Heat treatment processes peculiar to welding

Pre-heat
Pre-heat is the application of heat to a weldment prior to welding. The prime purpose of pre-heating is to slow the cooling rate as a means of reducing the likelihood of cracking. Pre-heating will also assist in the dispersion of hydrogen from the weld and weld zone. Pre-heat is also employed as a means of distortion control and for drying wet plates prior to welding – however these are relatively minor applications for pre-heat.

Post-heat
Post-heat is the application of heat to a weldment after welding has been completed. Post-heat is done to:

- ensure an even temperature prior to cooling
- slow the cooling rate.

Post-heat should not be seen as a replacement for pre-heat, as post-heat in itself will not prevent rapid cooling through the transformation range.

Concurrent heating
Concurrent heating is the application of heat to the weldment during welding. This is done essentially as a means of maintaining the interpass temperature between weld runs.

Stress relief
Residual stresses in a metal from forming processes or welding can lead to failure of the weldment – particularly if it is subjected to live (fatigue) type loading in service. Stress relief involves heating the component to 75–125 °C below the LCT (usually around 600 °C), holding for a minimum time of one hour per 25 mm of thickness, followed by slow and uniform cooling in the furnace. Because heating is below the LCT no re-crystallisation occurs, but residual stresses will be removed (Fig 6.17).

![Time/temperature curve for stress relief](image-url)

**Fig 6.17 – Time/temperature curve for stress relief**
Methods of heating

- Furnace – A furnace is the preferred method of heating where large components are to be heat treated, or where close control of the heating/cooling cycle is required. The evenness of temperature in furnaces is a decided advantage. Furnaces can be fired with oil, gas or pulverised coal.
- Heating coils/blankets, which can be wrapped around the job, are popular, particularly for heating sections of a fabrication. These are heated by electrical resistance and are ideal for heating butt welds in piping and for on-site applications. Electric induction heating can also be used.
- Gas heating blowpipes are best suited to heating small components, for site work and for pre-heating and post-heating of welds.

Temperature measurement

The most commonly used temperature measuring devices are:

- temperature sensitive crayons and paints
- thermocouples
- pyrometers.
Temperature sensitive crayons and paints

These crayons and paints are designed to measure a broad range of temperatures. The job is marked with the crayon or paints and when the required temperature is reached, the mark either melts or changes colour. Crayons come in sets, each crayon sensitive to a particular temperature.

Fig 6.18 – Temperature sensitive crayons
Thermocouples

A thermocouple consists of two wires of dissimilar composition joined at the ends and attached to a voltmeter. The wires are made from dissimilar metals which change their potential voltage as the temperature changes. The scale of the voltmeter is graduated in degrees of temperature, giving a direct temperature readout. For furnace heat treatment, the thermocouple is commonly attached to a chart that will record the temperature cycle and give a printed readout.

Photograph reproduced with permission, Furnace Technologies Pty Ltd

**Fig 6.19** – Thermocouple units (a) older style, (b) digital readout
Optical pyrometers

An optical pyrometer is a temperature measuring device that employs the use of colour comparison, either by chart or a wire through which electrical current is passed. The chart or wire sits in line with an eyepiece, through which the item to be measured is viewed. In the wire type, as the amount of current is increased, electrical resistance causes the wire to glow more brightly. The chart or wire is then compared to the surface colour of the object being measured. When they are the same colour, they are at the same temperature. This method can only be used on steels which are below approximately 800 °C, at which point the steel begins to glow red.

Optical pyrometers were once commonly used, but have now been superseded by more modern devices.

Fig 6.20 – Optical pyrometer

Surface pyrometer

Electronic surface pyrometers are now relatively cheap and reliable. These pyrometers can be used to conveniently measure the surface temperature of any material. The electronic pyrometer makes use of liquid crystal technology, which is sensitive to heat and light variations. When exposed to heat, by pointing the device at the surface of the material, they display the temperature directly on a small screen.

Digital thermometer and non-contact thermometer

The use of non-contact thermometers with a larger sighting (refer Fig 6.22) or a digital thermometer with probes (Fig 6.21) has introduced new technology into the industry.

Non-contact is by the use of a laser beam (8:1) distance, for a temperature range of -50 °C to 550 °C. See Fig 6.22. Digital probe-types temperature range is -50 °C to 1300 °C.
Fig 6.21 – Digital thermometer with probes

Fig 6.22 – Laser beam digital thermometer
Chapter 7 – Weld testing

Introduction

Testing of welded joints is a routine part of the quality assurance process for welded fabrications. Weld testing is carried out as part of the following.

- Weld procedure qualification – to ensure that the welding procedure is capable of delivering welds that are defect-free and have the required mechanical properties.
- Welder qualification/certification – to ensure that the welding operator is capable of producing defect-free welds.
- Prototype testing or product inspection – to ensure that the completed weldment meets specifications and is fit for purpose.

There are few, if any welds which may be described as perfect. Virtually all welds have some minor imperfection or discontinuity.

In this chapter we will look at the following.

- Weld defects
  - cracks
  - cavities
  - inclusions
  - incomplete fusion (lack of fusion)
  - contour defects
  - others (secondary discontinuities)

- Product inspection
  - visual inspection
  - penetrant inspection
  - ultra sonic testing
  - radiographic testing
  - pressure testing
  - destructive testing.
Weld defects

A weld discontinuity becomes a defect when it exceeds accepted standards.

It must be kept in mind that every imperfection in a weld is not necessarily a defect. Minor imperfections are known as ‘weld discontinuities’. These discontinuities only become defects when they exceed limits imposed upon them by the code or specification to which they are made. Australian Standard® codes, such as AS/NZS1554.1 and AS 1796, specify the minimum acceptable standards for welds.

AS/NZS 1554 – Part 1 Welding of steel structures for example specifies two categories of weld – GP CATEGORY (general purpose) and SP CATEGORY (structural purpose).

GP category welds are suitable for low stress applications and static loaded structures. SP category welds are designed for dynamic loads and higher stress loadings, therefore a better quality of weld is demanded. Section 6 of AS/NZS 1554 – Part 1 sets out the allowable surface imperfections for each of these categories of welds. From the extract of this table below, it can be seen that an ‘allowable imperfection’ in one instance may be classified as a ‘weld defect’ on another.

Table 7.1 – Extract from AS/NZS 1554

This table has been removed. It was reproduced from page 61, Section 6, Part 1 of AS/NZS 1554.
Permissible levels of imperfections in butt and fillet welds, as determined by visual magnetic particle and liquid penetrant examination of the weld zone, are as per section 6 of AS/NZS 1554 Pt 1.

Weld quality is hard to define, but generally a quality weld is a weld that does what it is designed to do (fit for purpose). Weld quality is relative to the application for which the weldment is intended. Generally speaking, the requirement for ‘higher quality’ will increase the cost of fabrication and this should be kept in mind when specifying or working to quality requirements.

The most common discontinuity types and their likely location are described in six basic categories, according to International Welding Institute (IWI) standards.

- Class 100 Cracks
- Class 200 Cavities
- Class 300 Solid inclusions
- Class 400 Incomplete fusion/lack of penetration
- Class 500 Contour faults
- Class 600 Others (secondary discontinuities):
  - undercut
  - excessive penetration
  - stray arcing
  - misalignment
  - excessive spatter
  - edge of plate melt off
  - excessive penetration
  - over roll/overlap
  - underfill
  - laminations/delaminations.

**Cracks**

Defined as a weld discontinuity produced either by stress, tearing of the metal in the plastic condition (hot cracks), or by fracturing when cold (cold cracks).

**Hot cracking**

Hot cracks are common in materials with high coefficient of expansion and/or which suffer from hot shortness. Hot cracking occurs at elevated temperatures soon after solidification. This mode of cracking is common in aluminium and stainless steel, longitudinal cracks and crater cracks being the most common examples.

**Cold cracking**

Most commonly occurs in the base metal adjacent to the fusion zone, particularly when cooling rates are rapid. The most common example of this is underbead cracking in hardenable steels.

Cracks may occur in the weld metal, or in the parent metal, fusion zone or HAZ.
Cracking is considered to be a serious weld fault and rarely is any amount of cracking tolerated.

Most types of cracks are named according to their direction or location, such as:

- longitudinal cracks generally occur along the axis of a weld
- transverse cracks generally across a weld
- crater cracks tend to occur in the weld crater at the start or finish of a weld
- toe cracking occurs at the toe of the weld
- underbead cracks occur under the weld shape.

**Crater cracks**

These come from hot shrinkage. The crater solidifies from all sides toward the centre, leading to a high concentration of stress at the centre of the crater. If the metal lacks ductility, or the hollow crater cannot accommodate the shrinkage, cracking may result. Crater cracks may, under stress, propagate from the crater and lead to failure of the weldment.

**Underbead cracks**

This defect occurs in the HAZ of welds in heavy rolled sections and appears as a crack or tear running in the direction of rolling. One factor which most limits the weldability of carbon and low alloy steels is the tendency toward underbead cracking when the welding conditions are not right. As the name suggests, these cracks occur in the HAZ of the weld bead. These cracks may appear at the plate surface as toe cracks, but are commonly subsurface.
Underbead cracking mechanism

During welding, some hydrogen (a decomposition product of moisture from the air, electrode coating, wire, flux, shielding gas, or the surface of the plates) can dissolve into the molten weld metal and from there into the extremely hot (but not molten) base metal. If cooling occurs slowly, the process reverses and the hydrogen has sufficient time to escape through the weld into the air. But if the cooling is rapid, some hydrogen may be trapped in the HAZ adjacent to the weld metal. The hydrogen is absorbed and produces a condition of low ductility known as hydrogen embrittlement.

Rapid cooling of the base metal produces a hard, brittle HAZ which is unable to yield to accommodate the shrinkage stresses and the stresses caused by the liberation of the now insoluble hydrogen at the grain boundaries. This may result in cracking within the narrow HAZ adjacent to the weld. If this mechanism is combined with either stress or impurities in the parent metal, lamellar tearing may occur.
Three major factors contribute to underbead cracking:
- a hardenable parent metal
- rapid cooling from elevated temperatures
- the presence of hydrogen.

**Hardenable parent metal**
Underbead cracking seldom occurs in steels of low carbon content or low carbon equivalent. Steels above 0.35% carbon content or carbon equivalent are hardenable. The problem is most severe with materials such as the heat-treated construction steels having tensile strengths of 680 MPa and higher. The chapters on special steels include recommendations for welding these materials. Low grade structural steels do not present a problem in this regard, as they have insufficient carbon for hardening to occur.

**Rapid cooling cracking**
Rapid cooling of the weld zone caused by the quenching effect of the surrounding plate can lead to a hard, brittle heat-affected zone which cannot accommodate the shrinkage stresses placed upon it. The faster the cooling rate, the harder and more brittle the HAZ will become.

**Hydrogen induced cracking**
Hydrogen which may be liberated in the weld zone due to moisture or other contaminants is soluble in the microstructure of steels at elevated temperatures. Because the gas is in solution, it occupies no space in the microstructure. As the metal cools below the transformation range where the hydrogen is no longer soluble, bubbles of the gas now form at the grain boundaries and exert pressure in the HAZ to cause cracking.

Causes of cracking include:
- the base metal is susceptible to cracking or of poor weldability
- contaminated or dirty weldments
- improper preparation of the weld joints
- incorrect welding procedure
- the weld joint is too rigid
- undersized welds
- unfilled craters
- stray arcing
- incompatible filler metal.

**Effect** – A crack may not cause any problems at all in a static loaded structure. In a heavily loaded or dynamically loaded structure, any crack will probably become a start point that will allow a crack to propagate along a weld and this will cause ultimate weld failure.

**Correction** – Cracks should preferably be removed in their entirety; care must be taken to ensure that no portion of the crack remains. Failure to do this may result in further cracking occurring. Any re-welding of the joint should be undertaken using correct weld procedures and consumables.
Cavities
Defined as a pore or group of gas pores in the weld metal. Porosity may be conveniently differentiated according to size and distribution. A number of different size-related terms are used:

- **gas pore** – a cavity (usually spherical) formed by entrapped gas during the solidification of molten metal
- **wormhole** – an elongated or tubular cavity in the weld metal caused by entrapped gas being forced away from the solidifying weld metal
- **cluster** – a group of pores in close proximity to each other.

![Gas pores, Wormholes, Cluster](Fig 7.4 – Porosity types)

Causes are as follows.

- **parent metal composition** – if the plate has excessive amounts of sulphur and/or phosphorous, these will burn and produce gases in the weld region
- **parent metal contamination** – any surface contaminants such as oil, grease, paint or rust may cause porosity if present in excessive amounts
- **moisture** – a major cause of porosity is moisture on the metal surface or in welding consumables
- **excessive amperage** – causing the electrode to overheat and a breakdown of the flux coating
- **excessive arc length** – reducing the effectiveness of the atmospheric shielding
- **condition of electrode coating** – damp electrodes will cause porosity, particularly at the beginning of a run, due to the vaporisation of moisture. Most electrodes, (except the low hydrogen types) require some moisture for best running characteristics, but this must be kept within certain limits
- **ineffective shielding gas** – caused by blocked nozzle, wind, or wrong settings.

**Effect** – A cluster of pores may cause a loss of weld strength due to the loss of cross-sectional area of weld metal. Isolated pores scattered throughout the weld have little effect on weld strength. Surface porosity has a detrimental effect on weld appearance. Clusters of porosity are considered to be more serious as they may concentrate stress in dynamically loaded joints.

**Correction** – If porosity in a weld exceeds the limits set by the code, then affected sections of weld must be removed and welded again, using correct preventative measures.
Inclusions

Defined as metal oxides and other solid compounds which occur as irregular or globular inclusions in the weld metal.

Fig 7.5 – Inclusions

Causes include:
- low amperages – lack of arc force makes slag control difficult
- incorrect electrode angles
- undercut – slag may become trapped in undercut from previous runs
- restricted joints – restricts electrode manipulation
- surface contamination – rust or scale may become trapped in the weld
- incorrect electrode – heavy or fluid slag may be unsuitable in some positions or joint configurations
- poor starting technique
- lack of interim/interrun cleaning.

Effect – May cause a serious loss of cross-sectional area. Additionally, the irregular shape and sharp corners/edges may propagate cracks.

Correction – Slag inclusions are removed when they exceed the allowable limits set by the code. The best method is to gouge out affected areas (flame or arc), or they may be chipped or ground. Thoroughly clean the preparation and re-weld. Inclusions are usually in the form of slag inclusions, but may also be in the form of other metallic inclusions such as tungsten from the GTAW process or silicon from GMAW wire. Inclusions may occur at various points within the weld metal or at the weld metal/parent metal boundary.
Incomplete fusion (lack of fusion)

This weld fault commonly occurs at the weld metal/parent metal boundary and between the runs of a multi-run weld. Common occurrence is when narrow preparation angles are used, the plate is of heavy section, the plate is dirty or scaled, or when the GMAW process is used.

Causes include:
- amperage too low
- electrodes – too small an electrode used on heavy, cold plate
- electrode angles – heat of the arc not being directed into the parent metal
- speed of travel – too fast, not allowing time for proper fusion
- joint preparation – inadequate angles of bevel tend to stop correct electrode manipulation, hence lack of fusion
- cleanliness – any slag, scale, rust or other foreign material may prevent the underlying metal from reaching fusion temperature.

Effect – Lack of fusion is difficult to detect and may cause a serious loss of weld zone soundness. The fault may propagate cracks or cause failure of the joint.

Correction – Lack of fusion should be removed. The best method is to gouge out affected areas (flame or arc). Thoroughly clean the preparation and re-weld using correct weld procedures.
Contour defects

Fillet welds should have the correct leg size and weld profile that provides the correct DTT (design throat thickness). Concave fillet weld profiles reduce the throat thickness and this may lead to weld failure. Convex fillet weld shapes represent over-welding and tend to set up a notch effect at the toes.

Butt welds should have a fully filled groove with a weld reinforcement within specified limits. The transition at the toes should be smooth and of approximately 135° or greater.

Causes include:
- welding speed too fast or too slow
- too large or too small an electrode
- incorrect electrode manipulation
- incorrect electrode angles.

Effect – If the weld is too large or too convex, the extra weld metal causes increased distortion. If the weld is too small or concave, the chilling effect of the parent metal will cause embrittlement and cracking and/or the weld may not be of the specified size.

Correction
- Too large a weld must be ground down to size and to the correct profile.
- Too small a weld must be built up with extra metal.
Inadequate penetration (lack of penetration)

Occurs at the root of butt and fillet welds. On a butt weld radiograph, the defect shows up at the centre of the weld as a straight line/lines.

Causes include:
- root face too large
- gap too narrow
- arc length too long
- amperage too low
- incorrect angle of electrode
- joint included angle too narrow
- incorrect electrode choice
- travel speed incorrect.

Effect – This is two-fold: first, there is a reduction in the effective throat thickness of the weld and second, a notch effect is produced due to the void in the root. It has the same effect as putting a hacksaw cut along the root of the joint.

Correction – In butt welds that can be reached from the other side, the root is completely ground out and a backing run is made – this is normal procedure for all such welds, to ensure full penetration. When a butt weld is only accessible from one side, defective parts must be completely removed and re-welded. One method used to stop this occurring is to use backing plates or rings. In fillet welds, it is very difficult to tell if full penetration has been obtained – these welds are difficult to x-ray. The welder must depend on maintaining approved procedures.
Chapter 7 – Weld testing

Others (secondary discontinuities)

Undercut

Defined as a groove or channel in the parent metal occurring continuously or intermittently along the toes or edge of a weld. Undercut is caused by the arc melting the parent plate at the toes of the weld and not being filled with weld metal.

**Causes** – Undercut is usually caused by operator faults such as a long arc length, travel speed too fast, or incorrect electrode angles. Excessive amperages or poor electrode choice can exacerbate the problem. Other causes include:

- arc length too long
- high amperage
- incorrect type of electrode – cellulose electrodes are very prone to undercut
- joint preparation incorrect – not allowing the electrode to be manipulated correctly
- incorrect angle of travel or approach
- travel speed incorrect
- insufficient pause at the edge of a weave.

**Effect** – Undercutting is not a very serious defect in statically loaded joints unless it causes a substantial reduction in plate thickness, thereby reducing the strength of the joint. In joints which are dynamically loaded, undercut is regarded as much more serious and may ultimately cause failure due to the stress concentration produced. Undercut of around 1 mm or 10% of the metal thickness may be allowed on some welded joints, however it can cause stress concentration and notching. Additionally, the sharp corners and/or edges may propagate cracks.

**Correction** – To rectify undercut, an extra run of weld is deposited in the undercut groove. The operator must be very careful, however, in the manner that this repair is carried out. Usually, the undercut groove is opened out in order to accommodate the extra weld metal and reduce the risk of slag inclusions. Electrodes must be of sufficient size to ensure good fusion, but small enough to deposit a bead that will conform with requirements for weld contour.

![Fig 7.9 – Undercut](image-url)
Excessive penetration (burn through)
Defined as excess weld metal protruding through the root of a butt weld.

This occurs in butt welds only.

Causes – Excessive penetration is essentially the opposite of insufficient penetration, as are causes such as:
- root face too small
- root gap too big
- amperage too high
- travel speed incorrect.

Effect – This is two-fold: firstly, there is excessive reinforcement (or over-welding) on one side of the joint; secondly, the excess metal has a notch effect on the joint. As with insufficient penetration, this defect must be avoided in pipe work as it causes eddy currents in the fluid. These can erode the pipe wall downstream, particularly if the fluid is abrasive.

Correction – In butt welds which are accessible from both sides, the excess metal may be ground off to the desired contour.

In butt welds accessible from one side only, the whole affected area may have to be removed and re-welded. This may prove difficult, especially in pipes and the whole joint may have to be removed.

Stray arcing
Defined as the damage on the parent metal resulting from the accidental striking of an arc away from the weld.
**Causes** – Most often, stray arcing is the result of operator error, but sometimes faulty connections can have the same effect. This defect may possibly occur:
- between the electrode and the work (most commonly)
- between the electrode holder and the work
- between the work and the work lead connection.

**Effect** – Small globules of metal are deposited on the plate surface and chill very quickly, resulting in hard spots and pitting. On work that is subject to high working loads and extremes in temperature, particularly in hardenable steels, these spots become points of stress concentration and can result in cracking of the material leading to ultimate failure.

**Correction** – Stray arcing has little effect on most mild steel joints; however, on highly stressed joints and most alloy steels, this defect is undesirable. Prevention is the best and sometimes the only acceptable method, but sometimes the area may be ground smooth and in some cases stress relieved, or a weld placed over the affected area and ground flush. When correcting by grinding, care should be taken to ensure that any reduction of thickness is within allowable limits.

**Misalignment**

Misalignment occurs in the parent plate as a result of bad fit-up or weld metal shrinkage.

**Excessive spatter**

Defined as the metal particles expelled onto the surface of the parent metal or weld during welding and not forming part of the weld.
Causes include:
- excessive amperage
- incorrect type of electrode; cellulose electrodes are prone to cause spatter
- too long an arc length
- electrode angle too flat.

**Effect** – Besides detracting from the appearance of a weld, this defect is similar in effect to stray arcing, in that chill spots and minor pitting in the surface of stainless steel are caused.

**Edge of plate melt-off**
Defined as an imperfection in a welded joint due to a free edge of plate being melted off. This defect only occurs on lap and outside corner joints.

![Fig 7.14 – Edge of plate melt-off](image)

Causes include:
- arc length too long
- high amperage
- incorrect electrode size
- incorrect type of electrode
- incorrect angles of electrode
- insufficient deposition time at the edge of a weave.

**Effect** – Reduces the effective plate thickness. In lap welds it reduces the effective leg length and in corner welds it reduces the effective throat thickness.

**Correction** – Extra runs are placed in the joint to increase the throat or extend the leg length of corner and lap joints respectively.

It is usually a requirement that a witness of the plate edge is left to ensure that edge of plate melt-off has not occurred.
Over-roll or overlap

Defined as an imperfection at the toe of a weld caused by an overflow or spilling of weld metal on to the surface of the parent metal without fusing to the latter.

Fig 7.15 – Over-roll or overlap

Causes include:
- insufficient heat – causing weld metal to lie on top of the parent metal
- contaminated parent metal surfaces
- incorrect electrode angles
- travel speed incorrect.

Effect – Over-roll has an effect similar to undercut, in that it produces a concentration of stress in the joint. The effective weld may be of inadequate size.

Correction – Where over-roll is to be rectified, the excess metal should be removed by chipping or grinding. Care should be taken to ensure that the desired contour is retained. Further runs should be deposited as necessary.

Underfill (incompletely filled groove)

Defined as a longitudinal continuous or intermittent channel in the surface of a butt weld due to insufficient deposition of weld metal. Underfill occurs in the weld metal of butt joints and is the failure of the metal to completely fill the groove. This should not be confused with undercut.

Fig 7.16 – Underfill

Effect – Loss of strength due to loss of cross-sectional area. Creates a concentration of stress due to irregular surface contour.

Correction – Deposit additional weld metal, ensuring that requirements for weld contour are met.
Laminations and de-laminations

Laminations occur in the parent metal during manufacture, producing a possible discontinuity in the through-thickness of the section. This discontinuity may ‘de-laminate’ (pull apart or open-up), due to shrinkage stresses or external load.

![Fig 7.17 – De-lamination](image-url)
Product inspection

Weld quality is hard to define, but generally a quality weld is one that does what it is designed to do (fit for purpose). Weld quality is relative to the application for which the weldment is intended. Generally speaking, the requirement for ‘higher quality’ will increase the cost of fabrication and this should be kept in mind when specifying, or working to quality requirements. It can also be reasonably assumed that if the welding procedure is capable of delivering the required mechanical strength, then all welds made using that procedure will possess the required mechanical strength, provided that the welds are fault free.

Product inspection is usually carried out by simple visual methods. Where strength of the weld is critical, or when a structure is to be subjected to high or dynamic loads, then further inspection and testing methods may be required. For example, in the case of pressure vessels proof tests are required on top of NDT testing.

Selection of a testing method

The testing procedure and associated costs form part of the overall cost of the product. The procedure must be cost-effective if overall fabrication costs are to be contained.

In most cases, the type and extent of testing will be specified by the code to which the weldment is constructed. It is important that the test method employed is capable of disclosing the defects that are likely to occur. The method and extent of testing need only ensure that welds comply with specifications. Overdoing the amount of testing required will increase costs. As the method of testing becomes more sophisticated, costs increase. Simple methods of testing should be applied first. It costs much less to determine a weld non-compliance by visual examination than it does to determine that non-compliance by radiographic examination.

If testing of welds is to be successful, it is essential that the testing technician knows:

- what defects are likely to occur
- the likely location of these defects within or adjacent to the weld
- the test method/s which will best disclose these defects.

Non-destructive testing (NDT)

Non-destructive testing is carried out by various processes which do not destroy the weldment. NDT is about examination to ensure freedom from defects, rather than to determine mechanical properties.

Destructive testing (DT)

DT (or mechanical testing) involves the application of force as a means of determining the mechanical properties of the welded joint. These tests, by their nature, usually involve testing of the part to failure; thereby destroying the part being tested.

It can be seen therefore that destructive testing methods are usually not suitable as a means of product inspection, as all the products produced would be destroyed during testing. Destructive testing is usually applied to the proving of welding procedures, or to the testing of production welded test plates. In some cases, however, finished weldments may be selected at random from the production line and tested to failure as a means of ensuring the integrity of the production process.
Non-destructive test methods
There are six NDT methods that we will examine. These are:

- visual inspection
- penetrant inspection
- magnetic particle inspection
- ultrasonic inspection
- radiography
- pressure testing.

Visual inspection
Visual inspection is the cheapest, the simplest and the most widely applied method of inspection. Visual inspection can be used not only to examine the finished weld, but unlike other inspection methods, it can be applied at all stages of the welding process.

Prior to welding – check the following
- Parent metal defects – such as laminations, cracks, or surface irregularities.
- Joint fit-up, including the edge preparation – angle of bevel, root face, root gap, backing material (where required), alignment of parts and general fit-up of the joint.
- Joint cleanliness – is the joint as clean as required? Heavy scale, oxide film, grease, paint and oil are all sources of weld defects.
- Assembly – whether any special set up is required, such as jiggling, bracing, or cambering.

During welding – check the following
- Electrodes – compatibility of the electrode type to the weld metal and joint preparation. This includes a check on the welding current, size of electrode and speed of deposition.
- Root run – the appearance, penetration (if required) and any external defects will give a good indication of weld quality.
- Slag removal – ensure that all slag is completely removed after each run – particularly watch the toes of the root run.
- Inter-run – each run of weld metal is going to be part of the completed weld, so check each run individually – one bad run may ruin the whole weld. It is much easier to correct defects as they occur, than to wait until the weldment is completed. Watch corners, weld junctions, craters and weld toes.

After welding – check the following
- The final appearance of the weld and the presence of external defects such as undercut, reinforcement, weld profile, craters, misalignment, porosity, cracks and slag inclusions. The external appearance of a weld gives a good indication of its quality.
- Conformity – all welds should be checked against the drawings and/or specifications to ensure that they meet the requirements laid down.
Aids to visual inspection are devices such as fillet gauges, calipers, other measuring devices and a low powered (up to 10 x) magnifying glass.

The major limitation of visual inspection is that it will disclose only surface defects and defects which are able to be seen by the naked eye, eg fine surface cracks may not be readily apparent by visual inspection but may easily be detected by some other method.

**Penetrant inspection**

Penetrant inspection is a test method for locating any defect open to the surface. It is particularly advantageous for inspection of non-magnetic and non-ferrous materials and is widely used on stainless steel, magnesium, aluminium, brass and other metals of cast or welded construction.

Basically, two different methods are used: dye (usually red) penetrant and fluorescent (visible under ‘black light’) penetrant.

![Fig 7.18 – Dye penetrant testing (20 x actual size)](image)

**Testing with dye penetrants**

In this method, the penetrant (a suitable dye solution, usually red in colour) is drawn by capillary action into any surface discontinuity. A developer with a chalky base is then applied to the surface. This chemical dries on contact and is stained by the dye, which rises to the surface again by capillary action. Pores or cracks are then revealed as red dots or continuous red lines respectively. The spread of the dye indicates fairly accurately the size of the flaw. An essential requirement in this method is the pre-cleaning of the weldment so that the penetrant is not prevented from entering the discontinuity. The penetrant can be applied either by spraying, painting or by immersion, the ‘contact’ time varying from a few minutes to about an hour. The excess penetrant is then removed, either by water in the case of water soluble penetrants, or by wiping the surface with a rag soaked with solvent. Developer is then applied to disclose any surface defect which may be present.

The steps involved in this method of inspection are to:

- thoroughly clean scale, grease etc from the surface
- apply the penetrant
- allow sufficient penetration time
- remove all excess penetrant from the surface
- apply the developer
- inspect.
Testing with fluorescent penetrants

Inspection with fluorescent penetrant is a variant of penetrant testing, in which penetrant that fluoresces under black light is used. Penetrant is applied to the surface to be inspected by dipping, spraying or brushing and a period of time from five minutes upward is allowed for the penetrant to enter any small surface opening through capillary action. Excess penetrant is removed from the surface. The surface is dried and a developer is applied, ultimately to form a film of dry powder over the surface to act as a ‘blotter’ and to draw the fluorescent penetrant back from the defects.

After processing, the surfaces are viewed while illuminated with high-intensity ultraviolet lights (black lights) in a semi-darkened area. Any defect such as a fine crack is easily recognised by the glowing, fluorescent line of penetrant.

Leak testing of welded containers is an additional important application of fluorescent penetrant testing. Wherever such containers are of moderate wall thickness (up to around 10 mm), it is only necessary to paint one surface, and after allowing sufficient time, examine the other surface with a portable black light. Leaks such as pores or cracks passing through the wall are indicated on the uncoated surface by the brilliant fluorescence of the penetrant.

General advantages of the penetrant method

- Relatively simple to operate
- Can be used on non-magnetic materials
- Provides convincing indications to the Inspector
- No limitations as to size or shape
- Adaptable to a production line method, either batch or continuous treatment
- Particularly suited to the detection of surface cracks.
General limitations of the penetrant method

- Will only disclose discontinuities open to the surface.
- The surface of the material must be impervious to the penetrant (unsuitable for sintered products).
- Must not react with surface of the material.
- Must not be temperature sensitive.
- Unsuitable where penetrants may cause contamination.

Magnetic particle inspection (MPI)

If a bar magnet is placed beneath a sheet of paper and iron filings sprinkled onto it, the filings will arrange themselves to show the lines of magnetic force flowing between the north and south poles of the magnet (Fig 7.20).

![Fig 7.20 – The magnetic field surrounding a bar magnet](image)

If the magnet is now broken in half, effectively making two magnets, it will be seen that a concentration of filings now occurs as the lines of force come together (Fig 7.21).

![Fig 7.21 – Concentration of iron filings where lines of force meet](image)
Magnetic particle inspection makes use of this, to disclose surface imperfections in magnetic metals. The method is particularly suited to finding surface cracks and other surface defects in iron and steel components.

The work piece is ground clean and white background paint may be applied in some cases. The part is magnetised by one of a number of methods. The most common and simplest method used to generate a magnetic field is to apply an AC yoke to the surface of the material. The AC yoke has a coil that produces a magnetic field and has adjustable legs that connect the magnetic field to the surface. The AC yoke produces longitudinal magnetic flux lines on the material surface. The other popular method is to apply a high current flow directly to the material surface. The resultant current flow produces circular magnetic flux lines on the surface of the material.

Fig 7.22 – Magnetic particle testing equipment
(a) magnetic coil, (b) permanent magnetic yolk and (c) magnetic yolk
The area to be inspected is then covered with fine magnetic particles, either as a dry powder or in suspension in a liquid. This is commonly a light, kerosene-based liquid known as magnetic ink.

Where the crack runs across the lines of magnetic force, the powder will congregate and disclose the defect. If, however, the crack runs along the lines of magnetic force, it is highly unlikely that any indication of the defect will be seen.

Once the crack runs at an angle greater than 50° to the magnetic flux, it will be visible. It is common practice to test twice, the second test being carried out at right angles to the first so as not to miss any defects that may be present.

For most applications, weldments do not require demagnetisation after magnetic-particle inspection. A strong magnetic field may, however, interfere with subsequent machining or arc welding operations. Also, if the magnetised part is to be used in structures such as an aircraft, it may affect sensitive instruments. Demagnetisation, when required, is accomplished by drawing the part through a high intensity AC field coil.
Ultrasonic testing

Audible sound has been used in the testing of material since ancient times. It is possible, especially in the case of ceramics, to detect whether a flaw is present by listening to the sound emitted when the specimen is tapped.

Very high frequency sounds known as ‘ultrasonic energy’ provide a method for the non-destructive testing of materials. In many cases this may be used to advantage instead of, or in association with, other methods of examination. In other cases it provides a test method when none existed before.

Ultrasonic testing employs waves above the frequency limit of human audibility and usually in the range 0.6 to 5 MHz. A pulse consisting of a number of these waves is projected into the specimen under test. If a flaw exists in the specimen an echo is reflected from it and from the type of echo the kind of flaw can be deduced.

The equipment comprises an electrical unit which generates the electrical oscillations, a visual display unit on which pulse and echo can be seen and probes which introduce the waves into the specimen and receive the echo. The electrical oscillations are converted into ultrasonic waves in a transducer.

To transmit the ultrasonic waves through the metal, a good contact is required between the probe and test plate, as the waves will not transmit if there is an air gap. For this reason a thin oil or water film is spread over the test plate and the probe is slid over this surface.

![Ultrasonic equipment diagram](image)

**Fig 7.24 – Ultrasonic equipment**
Three types of probe are available.

- A single probe which acts as both transmitter and receiver, the same ‘piezoelectric’ elements transmitting the pulse and receiving the echo. The design of the probe is complicated in order to prevent reflections within the perspex block confusing the echo.

- The twin transmitter-receiver probe in which transmitter and receiver are mounted together (either side by side or one in front of the other) are quite separate electrically and ultrasonically, so that there is no trouble with interference from the echo. This type is the most popular and most common.

- The separate transmitter and receiver each used independently (two-handed operation).

To make a ‘length scan’ of the weld, the transmitter-receiver unit is moved continuously along a line parallel to the welded seam so that all points of the whole area of the welded joint are covered by the scanning beam. Care must be exercised so that too high a spread of the beam does not cause double echoes from a single flaw.

Some of the materials that can be inspected by this method are carbon and low alloy steels, aluminium, brass, magnesium, monel, steel, stainless steel and other non-porous metals. The dimensions of the work are usually not critical, suitable techniques being available for the testing of plate stock as thin as 1.5 mm and larger structures as long as 6 m. Defects can be indicated to the extent that they are actual mechanical discontinuities such as cracks, laminations, voids, open welds and segregations. Extremely small weld defects can be detected, regardless of thickness.
Radiographic testing

This inspection method relies on the ability of short-wave radiation, such as x-rays or gamma rays, to penetrate thick, dense objects which will not transmit ordinary light. This method is a most useful and widely applied non-destructive testing method and many codes specify radiographic examination for all or some of the joints in a weldment.

Radiography is expensive. It is necessary to visually inspect the weld prior to radiography. If the weld fails the visual inspection, it is unnecessary to take a radiograph.

General principle

When x-rays or gamma rays fall onto a metal, their passage is obstructed by the metal and part of the radiation is absorbed. The extent of this absorption depends upon the density and thickness of the weld. If a cavity such as a blowhole or crack exists in the interior of a weld, the radiation beam will have less metal to pass through than in a sound weld. Consequently, this region will absorb fewer rays.

If we record this variation in absorption on a sensitive film, it will produce an image that will indicate the presence of the defect. This image is called a ‘radiograph’ (Fig 7.27).
The radiation which passes through the specimen strikes the film behind. The radiation exposes the film so that regions of lower weld density (which allow radiation to pass through more readily) appear dark on the radiograph in comparison with regions of higher weld density which absorb more of the radiation. Thus the defects or discontinuities, being less dense than the base metal, will appear as darkened regions on the radiograph.

X-rays

X-rays are produced in an electrical apparatus (see Fig 7.28) by placing a high voltage (60 000 to 180 000 volts) across the ends of two terminals. These are called the ‘cathode’ (negative) and ‘anode’ (positive). They are contained in a vacuum tube and the high voltage causes a stream of electrons to flow from the cathode to the anode. When these electrons strike the anode, their high energy causes the anode to give off heat plus short wave rays which are termed x-rays. These rays will penetrate metal.
X-ray tests

Cracks, slag, blowholes, lack of fusion and all internal defects can readily be detected by x-ray testing. In general, the testing procedure consists of placing the x-ray tube on one side of the piece being tested and the film on the other. The time of exposure may range from a fraction of a minute to several minutes, depending on the power of the tube and the thickness of the metal. The exposed film is then developed and examined for defects in the weld.

Gamma rays

Gamma rays are given off by all radioactive materials. In the testing of welds, artificial radioactive elements called ‘isotopes’ are generally used.

Gamma rays are electromagnetic radiation of very short wavelength and high frequency and they can penetrate solid matter more readily than x-rays. Like x-rays, they can create an image on a sensitised film.

In the gamma ray testing of welds, the isotopes generally in use are cobalt 60, iridium 192, caesium 137 and thulium 170. Using a radioactive isotope, radiographic pictures or ‘gammagraphs’ similar to x-ray pictures can be taken without an electricity supply, with great penetration and at lower cost. The small size of the isotope enables work that is inaccessible to an x-ray unit to be examined.

The radiation source is housed in a small but heavy container, lined with lead to contain the radiation. Requiring no external power and being easy to transport, it is well suited for on-site and workshop use. When located on the central axis of a pipe or shell, a full circumferential weld can frequently be radiographed in one exposure.
Another application might consist of arranging several large weldments radially around a capsule containing radium. The films, of course, would be placed on the side of the weldment opposite to the radium. Gamma ray exposure times are usually longer than x-ray exposures, but require no attention during exposures.

Radiographs made by gamma rays usually lack the sharpness and contrast that characterises x-ray radiographs.

**Safety precautions**

The x-ray or gamma ray operator must be highly trained in the safe use of radiographic equipment. Besides penetrating the human body, these rays have adverse effects on certain parts of the body. Leukaemia, anaemia and sterility are the main dangers.

Factory regulations specify that personnel operating x-ray or gamma ray equipment must either wear film badges or carry dosemeters. Film badges are supplied by a special service which processes them after they have been worn for a specified time and reports on the amount of radiation that the wearer has received. A Geiger counter indicating the intensity of radiation is used to indicate the effectiveness of shielding and the limits of the area in which it is safe for personnel to work.

**Interpretation of radiographs**

Experience is necessary to interpret radiographs correctly and to identify defects. The defect will normally show up as a darker area within the general confines of the weld.

Porosity is usually smooth and usually regular in shape compared with trapped slag, which is generally irregular in shape. The position of the defect within the weld area is significant, as it indicates whether the fault is in the root, interpass, or on the surface of the weld.

Straight lines occurring down the centre of a butt weld indicate that edges along the root have not been fused. Wider and less clearly defined lines in a similar position may indicate internal undercut or defects along the toes of the root run. Wider spaced defects running parallel with the weld can usually be identified as interpass problems, such as undercut, lack of fusion or slag entrapment at the toes of internal beads.
Contraction cracks will show clearly as sharp lines, but not necessarily straight or parallel with the weld. Cracks usually appear slightly wavy. Radiography of butt welds is a relatively simple process, however fillet welds are more difficult to radiograph and special methods have to be adopted, often using more than one exposure taken from different angles.

**Pressure testing**

Where absolute leak tightness of all joints is essential (such as in tanks, pressure vessels and pipe lines), the soundness of the weld may be tested by the application of internal pressure. Leaks are discovered by observation or by loss of pressure. The pressure medium may be water, oil, air, or gas; each one of these having a definite field of application. Oil, particularly when thin or hot, will frequently penetrate leaks that do not show up with water under an equal pressure. Air will also leak out more readily than water and hydrogen will escape where air will not.

Wherever possible when testing to high pressures, hydrostatic (rather than pneumatic) testing should be used, as liquids are incompressible and will not result in a violent explosion should the vessel fail. Pneumatic testing is usually restricted to low volume, low pressure tests.

Non-destructive test methods are summarised in Table 7.2.
<table>
<thead>
<tr>
<th>Inspection method</th>
<th>Equipment required</th>
<th>Enables detection of</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISUAL</td>
<td>Magnifying glass.</td>
<td>EXTERNAL DEFECTS:</td>
<td>Low cost.</td>
<td>Applicable to surface defects only.</td>
<td>Should always be the primary method of inspection, no matter what other techniques are required.</td>
</tr>
<tr>
<td></td>
<td>Weld size gauge.</td>
<td>Cracks, porosity, unfilled craters, slag inclusions, warpage, under welding, over-welding, poorly formed beads, misalignment, improper fit-up.</td>
<td>Can be applied while work is in progress, permitting correction of faults. Gives indication of incorrect procedure.</td>
<td>Provides no permanent record.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pocket rule.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Straight edge.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Workmanship</td>
<td></td>
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<tr>
<td></td>
<td>standards.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIQUID PENETRANT</td>
<td>Commercial kits, containing fluorescent or dye penetrants and developers.</td>
<td>EXTERNAL DEFECTS: Surface cracks not readily visible to the unaided eye. Excellent for locating leaks in weldments.</td>
<td>Applicable to magnetic and non-magnetic materials. Easy to use. Low cost.</td>
<td>Only surface defects are detectable. Cannot be used effectively on hot assemblies.</td>
<td>In thin-walled vessels will reveal leaks. Irrelevant surface condition (smoke, slag) may give misleading indications.</td>
</tr>
<tr>
<td>MAGNETIC PARTICLE</td>
<td>Special commercial equipment. Magnetic powders – dry or wet form. Black light may be required for viewing fluorescent penetrants.</td>
<td>EXTERNAL DEFECTS: Surface discontinuities – especially surface cracks.</td>
<td>Simpler to use than radio-graphic inspection. Relatively low cost method.</td>
<td>Applicable to ferro-magnetic materials only. Requires skill in interpretation of indications and recognition of irrelevant patterns. Difficult to use on rough surfaces.</td>
<td>Elongated defects parallel to the magnetic field may not give pattern. For this reason the field should be applied from two directions at or near right angles to each other.</td>
</tr>
<tr>
<td>Inspection method</td>
<td>Equipment required</td>
<td>Enables detection of</td>
<td>Advantages</td>
<td>Limitations</td>
<td>Remarks</td>
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</tr>
<tr>
<td><strong>RADIOGRAPHIC</strong></td>
<td>X-ray equipment or gamma radiation source. Facilities for processing and viewing of radiographs.</td>
<td>Cracks, porosity, blowholes, slag inclusions, incomplete root penetration, undercutting, excessive penetration. Virtually all internal and external defects in which there is a reduction in the through-thickness of the test specimen.</td>
<td>When the indications are recorded on film, gives a permanent record.</td>
<td>Requires skill in choosing angles of exposure, operating equipment and interpreting indication. Requires safety precautions. Not generally suitable for fillet weld inspection.</td>
<td>X-ray inspection is required by many codes and specifications. Useful in qualification of operators and welding procedures. Because of cost, its use should be limited to those areas where other methods will not provide the assurance required.</td>
</tr>
<tr>
<td><strong>ULTRASONIC</strong></td>
<td>Special commercial equipment either of the pulse-echo or transmission type. Standard reference pattern for interpretation of RF or video pattern.</td>
<td>INTERNAL AND EXTERNAL DEFECTS: Surface and sub-surface flaws, including those too small to be detected by other methods. Especially for detecting sub-surface lamination-like defects.</td>
<td>Very sensitive Permits probing of joints inaccessible to radiography.</td>
<td>Requires high degree of skill in interpreting pulse-echo patterns. Permanent record is not easily obtained.</td>
<td>Pulse-echo equipment is highly developed for weld inspection purposes. The transmission-type equipment simplifies pattern interpretation where it is applicable.</td>
</tr>
<tr>
<td><strong>PRESSURE</strong></td>
<td>Water pumps or air compressors. Pressure gauges and piping.</td>
<td>Water/air tightness leaks through weldments in tanks, boilers, etc.</td>
<td>Low cost. Sensitive.</td>
<td>Can only be applied in last stages of fabrication.</td>
<td>Care should be applied when carrying out pneumatic testing. All air must be excluded when hydrostatic testing.</td>
</tr>
</tbody>
</table>

Table 7.2 – Summary of NDT methods
Destructive testing

Destructive testing can be divided into two areas.

- laboratory-type mechanical tests to measure the properties of weld metal and the heat-affected parent metal
- workshop-type mechanical tests to prove weld metal acceptability and freedom from significant defects.

Weld specimens for testing can be obtained as extensions of actual welded joints, as separate but representative welds carried out either before or concurrently with actual work, or from welded test plates.

Mechanical tests provide information about the ‘mechanical properties’ of a metal. Mechanical testing machines are normally situated in a laboratory and operated by specialist personnel. Consequently the welding operator is more concerned with results than the actual tests. The welder should be aware of the tests available and the properties being tested.

The properties which these tests will disclose are as follows.

- **Ductility** – The ability of a material to be permanently deformed without failure, i.e. to be bent or drawn. Brittleness is a term used to describe a lack of ductility.
- **Toughness** – The ability of a metal to withstand shock loading. A tough metal has a good resistance to impact.
- **Hardness** – The resistance a metal has to forcible penetration by another substance. A hard metal resists scratching or wear.
- **Malleability** – The property of a metal that enables it to be rolled or hammered into thinner sheets or shaped by forging. Most metals are more malleable when hot.
- **Elasticity** – The ability of a metal to stretch and then return to its original shape and size when the forces causing it to stretch are released. Elasticity and ductility must not be confused.
- **Tenacity** (tensile strength) – The ability of a metal to resist a force that is acting directly to pull it apart.

The mechanical properties of metals determine their suitability for different purposes. High tensile properties are necessary for some uses, whereas hardness and wear resistance are required for other applications. Tests are also used to measure the effects of heat treatment or mechanical working to which the metal has been subjected, thereby assisting in the control of manufacturing processes.

**Laboratory type destructive tests**

Four types of mechanical tests are commonly used to provide information on material properties. These are:

- tensile tests
- hardness tests
- impact tests
- fatigue tests.
Tensile tests

In this type of test, a specially prepared sample of the metal is subjected to a steadily increasing load acting to pull it apart and is stressed until failure occurs. During the test, both the load and the increase in length are constantly noted and the results are plotted on a graph (Fig 7.31).

![Stress/strain diagram for tensile testing of low carbon steel](image)

**Fig 7.31 – Stress/strain diagram for tensile testing of low carbon steel**

A tensile test will disclose information about the test specimen regarding its:
- ultimate tensile strength (UTS)
- yield strength
- elasticity
- ductility.

**Ultimate tensile strength (UTS)**

UTS is the greatest tensile force that a test piece can withstand prior to failure.

**Yield strength**

Some metals (particularly low carbon steels) exhibit a noticeable yield point during tensile testing. When this point is reached, the metal will be seen to continue to stretch with no increase in load. In some cases the load will even decrease. Not all metals exhibit a noticeable yield point; for example, it is not evident in high strength steels.
Elasticity

When the load is first applied to a tensile test specimen, the increase in length is directly proportional to the load. If this load is released, the test specimen will return to its original length, provided that the elastic limit of the material has not been exceeded. Once the elastic limit of the material is exceeded, permanent deformation will begin to occur.

Ductility

Ductility will enable the metal to stretch prior to failure, due to the tensile force being applied. Ductility is an important property as it enables metals to be bent or rolled during fabrication and to withstand shrinkage forces due to welding.

The ductility of the metal is expressed as a percentage as this allows for direct comparison between metals. This percentage can be calculated as either:

- % elongation, or
- % reduction of area.

Prior to tensile testing, the specimen is marked at two points and the distance between them is noted as the ‘gauge length’.

![Tensile test specimens diagram](image)
Once the test piece has been stressed to failure, the two pieces are placed back together and the increase in the gauge length is noted (see Fig 7.32). These two distances are used to calculate ductility using one of the following formulas.

\[
\text{% elongation} = \frac{\text{increase in length} \times 100}{\text{original length}}
\]

\[
\text{% reduction of area} = \frac{\text{decrease in cross-sectional area} \times 100}{\text{original cross-sectional area}}
\]

**Example 1**

Consider a test piece of a gauge length of 50 mm which stretched 12 mm prior to failure.

\[
\text{% elongation} = \frac{\text{increase in length} \times 100}{\text{original length}}
\]

\[
= \frac{12 \times 100}{50} = 24\% \text{ elongation}
\]

**Example 2**

Consider a specimen whose original diameter was 10 mm, where this diameter was reduced to 8 mm at the point of fracture.

Original area

\[
= \frac{\pi D^2}{4}
\]

\[
= \frac{\pi \times 10 \times 10}{4} = 79 \text{ mm}^2
\]

Decreased area

\[
= \frac{\pi D^2}{4}
\]

\[
= \frac{\pi \times 8 \times 8}{4} = 50 \text{ mm}^2
\]

Reduction of area

\[
= 79 - 50 = 29 \text{ mm}^2
\]

% reduction of area

\[
= \frac{\text{decrease in cross-sectional area} \times 100}{\text{original cross-sectional area}}
\]

\[
= \frac{29 \times 100}{79} = 37\% \text{ reduction of area}
\]
Hardness tests

The hardness of a material is an important property in itself, but measurement of hardness will also provide a useful indicator with respect to tensile strength, ductility and impact resistance. In general, the harder of two metals of similar composition has the higher tensile strength, lower ductility and more resistance to abrasive wear. High hardness also indicates low impact strength, although some steels when properly heat treated have both high hardness and good impact strength.

To the welder, the hardness of the metal will give an indication of its weldability. Generally the harder the metal, the lower its weldability. The hardness of a weld’s HAZ is important as it can give a reliable indication of susceptibility to underbead cracking and suitability of a welding procedure.

There are four main methods of hardness testing, three of which involve measuring the resistance that a metal has to indentation.

Brinell hardness test

The Brinell test employs the use of a hardened steel ball of 10 mm diameter which is pressed into the surface of the metal with a load of 3 000 kg. The diameter of the impression is measured with a special microscope and the reading is converted by consulting a table.

Soft iron is about 100 BHN and file-hard steel about 600 BHN.

Brinell readings are listed as BHN (Brinell Hardness Number).

Rockwell hardness tests

In the Rockwell method of hardness testing, the penetrator is smaller and the loads are lighter than in the Brinell method.

When testing comparatively hard materials, a diamond cone is pressed into the metal with a load of 150 kg. The depth of impression is indicated on a dial and the reading is referred to the ‘Rockwell C’ scale of hardness.

To determine the hardness of softer metals the diamond is replaced by a steel ball of 1.5 mm diameter and a load of 100 kg. The reading is then given on the ‘Rockwell B’ scale.
Fig 7.33 (a) – Hardness testing by the ‘Rockwell B’ method

Fig 7.33 (b) – Rockwell hardness tester
Chapter 7 – Weld testing

The Vickers hardness test consists of pressing the point of a square-based diamond pyramid into the surface of a specimen with a predetermined load. The load is maintained for a set period and then automatically released.

The surface impression appears as a dark square on a light background. Measurements are taken across the diagonals of the impression by means of a special measuring microscope and the actual hardness figure is then obtained by referring to a chart, or calculated by the following formula.

\[
\text{DPN (Diamond Pyramid Number)} = \frac{\text{load}}{\text{contact area of impression}}
\]

Shore scleroscope hardness test

Another method of testing hardness is to use a Shore direct reading scleroscope. This instrument consists of a small diamond-pointed hammer, weighing 2 grams, which is allowed to fall freely from a height of 254 mm down a glass tube onto the test specimen. The distance that the hammer rebounds after it contacts the specimen can be read on the scale on the machine. The hardness of the metal as indicated by the scale number will range from 0–140. The higher the number, the harder the metal. A high carbon steel will indicate about 95 points on the scale.

Impact testing

Impact testing measures the toughness of a metal, ie its ability to withstand shock loading.

It has been found that the ability of a material to withstand impact depends not only on the velocity of the impact, but also on the temperature of the material and the presence or otherwise of notches in the material. Certain steels become quite brittle at low temperatures, as do the welds which join them. It may be necessary to carry out impact tests at various temperatures to fully establish a metal’s suitability for use. Tests may be carried out on parent metal, weld metal, or the weld HAZ.

In the impact test, a weighted pendulum swinging from a predetermined height strikes a notched test specimen. The distance that the pendulum swings through after fracturing the specimen is dependent on the amount of energy required to break the specimen. This distance is recorded by a pointer, the energy absorbed being measured in Joules.

Common impact tests differ in the dimensions for the test piece and the way in which each is supported. In the Izod test, the specimen is held vertically in a vice by one end only. The hammer strikes the end protruding from the vice.

The Charpy test employs a specimen which is supported at both ends, lying in the horizontal position. The sharp end of the hammer strikes the test piece in the centre. Impact testing is illustrated in Fig 7.34.
Fatigue testing

A knowledge of the metal’s tensile properties makes possible the design and fabrication of a structure that will support a steady load pulling in one direction. These properties, however, do not indicate the strength a metal will have if used in a structure where the load is applied first in one direction and then in another. When alternating load is applied, the loading on the component alternates between compression and tension. Alternating stresses are present in such components as axles, connecting rods, transmission shafts, boiler drums and pressurised storage tanks.

Metals will fail at a lower stress under a changing load than if the load were steady. Failure under a cyclic load is called ‘fatigue failure’.

Fatigue failure is invariably triggered off by some surface imperfection such as inclusions near or on the surface, undercut, overlap, excessive build-up, or even grinding marks. Failures start at the surface as tiny cracks which spread into the metal until failure occurs.
Fatigue tests are made by subjecting a test specimen to varying loads. Tests may be made by:

- bending the specimen alternately in one direction and then the other
- applying and removing tensile loads.

For practical purposes, 10,000,000 cycles is taken as the number of reversals which a specimen must withstand to establish the endurance limit. It is considered that a metal able to withstand a given stress for this number of cycles will continue to do so indefinitely.

**Practical type destructive tests**

These can be easily carried out in most workshops as no sophisticated equipment is required. Practical tests most commonly used to examine weld quality are:

- bend tests
- nick-break tests
- fillet weld break tests
- macro testing.

**Bend testing**

Bend tests will give an indication of the ductility of the metal, but bend tests are primarily used to disclose defects such as lack of fusion or inclusions in the weld.

Tests may be free bend tests, where bending is free to occur at any point, or guided bend tests where the location of the bend is closely controlled.

When bend testing weld specimens, three types of tests are used:

- root bend test
- face bend test
- side bend test.

The tests are identified by stating the surface of the weld test specimen that is placed in tension. For thinner plates, root and face bends are common. When welds in thick plates are being tested, side bend tests are usually employed.
Preparation of specimens and acceptance standards for bend testing

The preparation of specimens for bend testing and the position from which they are cut must comply with the relevant code. Specimens are normally prepared as the full thickness of the material with weld reinforcement removed. Cut edges are dressed smooth and corners rounded slightly to a radius not exceeding 10% of material thickness. The acceptance standards are also clearly defined in relevant codes; AS 1796 may be referred to as an example.

Nick-break tests

The nick-break test is used to reveal the presence of internal defects such as porosity, slag inclusions and lack of fusion. This test may also give an indication of the toughness of the metal, as some distortion may take place prior to fracture.

In the nick-break test, the weld reinforcement is not removed and the specimen is not dressed in any way. Saw cuts are made at both sides of the weld and the test specimen is supported on edge and broken by pressing or by sharp blows. Fig 7.36 illustrates a typical nick-break specimen.
Fillet weld break tests

The fillet weld break test is used to reveal the presence of internal defects such as slag inclusions, lack of root or sidewall fusion and porosity or wormholes.

The completed fillet weld test is located on a suitable flat surface, as shown in Fig 7.37 and fractured by steady loading or by blows.

![Fig 7.37 – Fillet break testing](image)

Acceptance standards may be obtained by reference to the relevant code.

Macro examination

Both fillet and butt welded structures are macro tested to show the weld, the fusion zone and surrounding area. A small cross section is removed from a completed weld and polished using various grades of grit paper until its surface has a mirror finish. The surface is then etched using an acid solution. This highlights:

- the weld
- the number of runs used to complete the joint
- the level of penetration and fusion zone
- the HAZ
- any defects.

Different etching solutions are used for different metals. It is important that thermal cutting processes are not used to cut the test specimen from the plate, as these will recrystallise the metal adjacent to the cut, which when polished and etched will give misleading information about the grain structure.
Fig 7.38 – Macro testing
Chapter 8 – Weld preparation and set up

Introduction

In this chapter we will look at the following.

- Weld preparation and workmanship
  - selection of joint type
  - effective area
  - preparation of plate edges for butt welds.
Weld preparation and workmanship

By definition (according to AS/NZS 1554.1) welds may be one of four basic types:

- fillet weld
- butt weld
- pad weld (surfacing)
- plug and slot weld.

Welds may be singular, or combined to produce compound welds.

Plug and slot welds and pad welds are not commonly used in general fabrication and welding and will not be considered in this text.

Selection of joint type

The type of joint depends on three factors.

- **Intensity of loading** – Butt welds are better able to transfer stress because of the fact that stress lines act closer to the neutral axis when forces are essentially static, as in buildings for example. Fillet welds tend to have indirect stress lines and therefore may concentrate stress at the root or toes of the weld.

- **Ease of welding** – Fillet welds are generally simpler to construct and fit-up and require less operator skill.

- **Cost** – Fillet welds are generally cheaper to produce as the cost of weld preparation and fit-up for butt welds is often considerable.
Compression of stress lines raises stress here

Stress lines follow a smooth line through the weld – less stress

**Fig 8.1 (a) – Stress flow in fillet welds**

Compression of stress lines raises stress here (stress point)

Stress lines

**Fig 8.1 (b) – Stress flow in butt welds**

Stress lines follow a smooth line through the weld – less stress
Fillet welds
A fillet weld is a weld approximately triangular in cross-section lying external to the planes of the parts being joined.

![Diagram of a fillet weld](image)

**Fig 8.2 – Parts of a fillet weld**

- Parent metal – the parts to be jointed.
- Root – where the parts to be joined are in the closest proximity.
- Face – the exposed surface of the weld.
- Toe – where the weld face meets the parent metal.
- Depth of fusion – the degree to which the weld penetrates the parent metal.
- Leg length – the distance from the root to the toe.
- Actual throat thickness – the distance from the root to the weld face, measured through the centre of the weld.
- Design throat thickness – the distance from the root to the hypotenuse of a triangle lying wholly within the weld (used for design calculations).
- Reinforcement – the distance between the design throat thickness and the actual throat thickness.
Fillet weld configuration

The weld configuration relates to the relationship of the plates to be joined. The joint types may be made in various positions, eg flat or vertical.

![Fig 8.3 – Fillet weld configurations (a) T joint, (b) outside corner (c) lap or edge weld](image)

Lap joints

The minimum overlap for parts carrying stress is five times the thickness of the thinner part joined. Both ends of the lap require welding.

- eg min lap on 2 x 6 mm plates = 5 x 6 mm = 30 mm
- min lap on 5 plate lapped onto 8 mm plate 5 x 5 mm = 25 mm

![Fig 8.4 – Lap joint](image)

Fillet weld profile

Three fillet profiles are possible.

![Fig 8.5 – Fillet weld profile (a) convex, (b) mitre (c) concave](image)
Ideally, fillet welds will be slightly convex. It should be noted that concave fillet welds require longer leg lengths to meet the requirements of nominal size.

**Fillet weld size**

The amount of fillet weld required to obtain the necessary strength may be specified in one of two ways:

- nominal size
- effective area.

**Nominal size**

The nominal size of a fillet weld is the length of the leg of a triangle that can be inscribed wholly within the cross section of the weld. Where a gap exists in the root of the joint, a reduction in the nominal size may be made.

Where the amount of weld required is specified on an engineering drawing by nominal size, it will be specified by stating the length of weld of the required size; for example, 200 mm of 6 mm fillet or continuous 8 mm fillet.

The preferred sizes for fillet welds are: 2, 3, 4, 5, 6, 8, 10 and 12 mm.

**Design throat thickness**

For stress calculations, the design throat thickness (DTT) is used.

The DTT of a fillet weld is the shortest distance from the root of the weld to the weld face without reinforcement. The DTT is approximately 0.707% of the leg size.

For example, the DTT of a 10 mm fillet x 0.707 = 7 mm.
Reinforcement

Fig 8.7 – Design throat thickness (DTT)

Effective length
The length of weld which is of the specified size (including end returns).

Effective area
The amount of weld required may also be expressed in terms of effective area.

The effective area of a weld is the effective length multiplied by the design throat thickness (DTT).
Example 1

What is the effective area of 400 mm of 8 mm fillet weld?

Design throat thickness = 0.7 x nominal size
= 0.7 x 8
= 5.6 mm

Effective area = Effective length x design throat thickness
400 x 5.6
2240 mm$^2$
Example 2

A lifting lug requires 1600 mm² of fillet weld to provide the necessary strength.

What length of 10 mm fillet is required?

Design throat thickness 0.7 x nominal size

\[ 0.7 \times 10 \text{ mm} = 7 \text{ mm} \]

Effective area = design throat thickness x effective length

Effective length = \( \frac{\text{effective area}}{\text{design throat thickness}} \)

\[ = \frac{1600}{7} \]

\[ = 228 \]

Required length of 10 mm fillet is 230 mm.

Use of the effective area method allows the fabricator flexibility in the welding process.

eg If an effective area of 2000 mm² were specified:

200 mm of 10 mm DTT Fillet = 2000 mm²

400 mm of 5 mm DTT Fillet = 2000 mm²

End returns

Welds terminating at the ends or sides of parts of members should, whenever possible, be returned around the corners for a distance of not less than twice the nominal size of the weld. The weld carried around the corner is not taken into account for purposes of strength calculations, as this is counted as the allowance for start and finish of the weld (Fig 8.9).

Fig 8.9 – End returns
Intermittent fillet welds

There are many applications where the required strength can be achieved without the need for a continuously welded joint. Where this is the case, it is common to use intermittent fillet welds. There are two types of intermittent fillet welds.

![Intermittent fillet welds](image.png)

(a) Chain welds and (b) Staggered welds

Any section of intermittent fillet welding shall have an effective length of not less than four times the weld size, with a minimum length of 40 mm.

The clear spacing between the effective lengths of each weld carrying stress shall not exceed the following number of times the thickness of the thinner part joined:

- 16 times for compression
- 24 times for tension and in no case be more than 300 mm.

Chain intermittent welding is preferred to staggered intermittent welding.

Where staggered intermittent welding is used, the welds on each side of the parts joined shall be continued to the end of the part.
Fillet welds failure

Fillet welds should not be left unwelded on the opposite side of the joint, except where any stress is shared by other members or where the joint is adequately supported.

(a) Welded on side

(b) Force opposed by low resistance

(c) Corner fillets

(d) Corner fillets

Fig 8.11 – Fillet welds welded one side
Butt welds

Butt welds are used to join metal products such as sheet, plate and rolled and pressed sections. This type of joint has the advantage of giving high strength without changing the profile of the structure. Butt welds are better able to transfer stress than fillet welds and are preferred for live or cyclic loading.

Industrial uses for butt welds include:
- boiler and pressure vessel construction
- ship building
- earth moving equipment
- aircraft and submarines.

Butt weld terminology

The terminology that applies to the parts of a fillet weld applies equally to butt welds, the major difference being design throat thickness which in a full penetration butt weld is equal to the plate thickness. The terms concerned with the preparation for butt welds require explanation at this stage.

![Butt weld definitions](image-url)
Weld root
The portion of the weld where the parts to be joined are in the closest proximity to each other.

Root face
That portion of the prepared edge of a part to be joined by a butt weld that has not been bevelled. This unbevelled section will support the first run of weld metal deposited in the groove.

![Root face](image1.png)

Root gap
The separation between parts to be joined by a butt weld. The gap is for the purpose of ensuring, as far as possible, complete fusion or penetration through the full thickness of metal.

![Root gap](image2.png)

Angle of bevel
The angle of the prepared edge of a component bevelled for welding.

![Angle of bevel](image3.png)
Chapter 8 – Weld preparation and set up

Included angle
The angle between the fusion faces of components prepared for welding.

Throat thickness
The distance from the root to the weld face measured through the centre of the weld.

Design throat thickness (DTT)
In a full penetration butt weld, the DTT is equal to the thickness of the thinner part joined.
Reinforcement

Reinforcement in a butt weld is the term given to the metal lying outside of the planes of the parts being joined.

![Reinforcement](image)

**Fig 8.19 – Reinforcement**

Preparation of plate edges for butt welds

Workmanship

In most cases, especially when joining metal of considerable thickness, it is difficult to execute satisfactory butt welds unless the edges to be joined are adequately prepared. Sheet metal and thin plate may be welded without preparation, but for metal over 6 mm in thickness the edges must be prepared in such a way as to provide a ‘V’ or ‘U’ shaped groove in which the weld metal is deposited, so allowing for complete fusion or penetration through the full thickness of the metal.

Failure to properly prepare the edges may lead to the production of faulty welds, as the correct manipulation of the electrode may be impeded and/or the desired degree of penetration may not be achieved.

Plates prepared for welding by flame cutting should have an even surface free from cracks, notches or grooves. Machine flame cut surfaces are preferred to hand flame cut surfaces. Scale, slag, rust and any grease or paint in the weld vicinity should be removed. Imperfections on bevelled edges may be removed by filing or grinding.

**Note**

Pre-heat may be required when flame cutting weld preparation on hardenable steels, particularly in heavy thicknesses.
Plates that have been cut by shearing or bevelling machines should have all burrs and irregularities removed before welding and may also require a dressing by grinding.

Parts should be aligned correctly. Weld preparation is commonly applied by:

- shearing
- grinding
- machining
- flame or plasma cutting
- arc or flame gouging.

Butt welds can be either a ‘complete penetration butt weld’ where fusion exists through the full thickness of the joint, or an ‘incomplete penetration butt weld’ where the depth of the weld is less than the thickness of the plates joined.

At this stage it is only intended to discuss complete penetration butt welds and even here the types of butt welds referred to will be the more common types. Additional information can be gained by referring to AS/NZS 1554, Part 1.

**Types of butt welds**

Butt welds are made between the edges of abutting plates and are generally described according to the way these edges are prepared. The edge preparation chosen for a particular type of joint must generally ensure that complete penetration can be achieved with minimum weld metal and effort, while bearing in mind other relevant factors such as:

- the accessibility of the joint to be welded – whether it can be welded from both sides of the joint or only one
- the position of the joint to be welded, i.e. vertical, horizontal or flat.

The type of butt weld selected for a particular job is usually the one which is easiest and cheapest to make when all other factors have been considered.

**Edge preparation and specification**

The various types of edge preparation in common use for the welding of steels are as follows.

**Closed square butt joint**

The edges are not prepared and are fitted together without a gap. This preparation is suitable for steel up to 3 mm thick and is welded from both sides.

![Fig 8.20 – Closed square butt](image-url)
Open square butt
The edges are not prepared but are separated slightly to allow fusion through the full thickness of the plate. The gap is equal to half the plate thickness + or - 1.5 mm. Suitable for steel up to 6 mm in thickness, but must be welded from both sides.

![Open square butt diagram]

\[ G = \frac{t}{2} \]

Fig 8.21 – Open square butt

Open square butt joint with permanent backing material
This type of joint is used when welding plates up to 6 mm thick, where welding is possible from one side only. The gap is equal to the plate thickness. Complete fusion of the weld into the backing material must be obtained.

![Open square butt with backing material diagram]

\[ G = t \]

Fig 8.22 – Open square butt with backing material
Single V butt joint

Used on steel up to 12 mm thick and on metal of greater thickness where access from both sides is difficult. Where possible, the back of the first run must be cleaned out and the job completed by deposition of a backing run.

Fig 8.23 – Single V butt

Single-bevel butt joint

Applications for single-bevel butt joints are as for single V joints described above.

Fig 8.24 – Single-bevel butt
Double V butt joint

Used on plate 12 mm and over when welding can be applied from both sides. It allows a reduction in weld metal compared to a single V preparation on the same thickness of steel. This type of preparation also tends to minimise distortion, as the weld contraction is equal on each side of the joint. Not usually economical on steel over 50 mm thick.

![Double V butt joint diagram](image)

Fig 8.25 – Double V butt

Double-bevel butt joint

Applications for double-bevel butt joints are as for double V joints described previously.

![Double-bevel butt joint diagram](image)

Fig 8.26 – Double-bevel butt
J and U joint

Where the weld metal volume required is large (in thick joints), the basic shape of the preparation may be modified.

![Fig 8.27 – Single J butt](image)

![Fig 8.28 – Single U butt](image)

![Fig 8.29 – (a) Double J, (b) double U butt welds](image)
Transition joints

When butt welds are completed between materials of different thicknesses, the edges must be chamfered to allow the smooth transition of stress or tension. The maximum slope or transition at the edges is 1:1.

(a) Chamfer before welding

(b) Chamfering thicker part

(c) Transition through sloping weld face & chamfering

(d) Chamfering wider part of unequal width plates

Fig 8.30 Transition joints
Chapter 8 – Weld preparation and set up

Backing runs
Where possible, complete penetration butt welds should be welded from both sides. The back of the root run should be gouged and/or ground to clean metal to ensure complete penetration of the backing run.

Backing material
Backing material is used to support the root run of a butt weld, or to provide a sound weld through the full plate thickness when access is possible from one side only. Permanent backing material is known as a backing strip. Temporary backing material is known as a backing bar.

Backing strips are fused into the weld and:

- should be no less than 3 mm thick and be of sufficient size to ensure they are not burnt through
- have weldability not less than that of the parent metal
- fit as close as possible, with a maximum gap between the parent metal and the backing strip of 1.5 mm.

Here are some points to remember.
- Test welds should be carried out to ensure the suitability of amperage/root face/gap combinations. Frequent tacks and a consistent gap should be used.
- For economy, an electrode of the largest possible size should be employed and where possible welding carried out in the downhand position.
- Small variations in gap or root face dimensions can significantly affect penetration and fusion in the root of a joint. Accuracy and consistency of weld preparation and fit-up is essential.
Chapter 9 – Weld procedures

Introduction

The objective in establishing welding procedures is to develop the best and most economic means of producing welds to a set standard.

Once a suitable procedure has been established and proved suitable for use and providing that suitably trained and qualified welders are employed, the welds that result should consistently prove fit for purpose.

In this chapter we will look at the following.

- Definitions
- The necessity for welding procedures
  - obtaining the welding procedure specification
  - application of code books
  - carbon equivalent
  - calculation of pre-heat
  - Australian Standard® specifications
  - selection of consumables
  - qualification by testing
  - writing a welding procedure qualification/specification (WPQ).
Definitions

**Welder certification** – Shows the ability of a welder to pass an examination in welding competency, to a minimum acceptance standard (eg AS 1796). It does not indicate current competency nor the welder’s ability to complete specific weldments to code requirements. Welder certification is portable.

**Welder qualification** – The ability of a welder to execute welding to a given procedure specification, at a particular place and/or time, on a particular type of weldment. Generally, welder qualification is not portable and becomes redundant at the end of a contract or after a specific period of time.

**Welding procedure** – A specific, pre-planned course of action followed to complete a particular weldment. Procedures may be informal (passed to welders verbally) or formal such as written instructions to be followed.

**Welding procedure qualification (WPQ)** – A welding procedure setting out proposed variables for a proposed production weldment. The procedure is then used by a welder to make a test weld(s), which must then undergo a series of tests (destructive and/or non-destructive) to ‘prove’ the procedure. Once qualified, a welding procedure usually has no time limitation – it remains in force indefinitely.

**Welding procedure test** – Completion and testing of a weldment, representative of that to be used in production, in order to prove the feasibility of a proposed welding procedure.

**Qualified welding procedure** – Also known as the following.

- **Welding procedure specification (WPS)** – A documented welding procedure that has been approved by the inspecting authority (and client), either by means of testing, or by documentary proof of previous satisfactory welding of joints to which that procedure applies.

- **Procedure qualification record (PQR)** – A record of the welding procedure and test results with all amendments, kept for future reference and possible use in other weldments. In fully traceable weldments, a record of qualified welders (and the joints they welded) is also required.

- **Production weld test (PT)** – A production test is normally a part of production welding. A test coupon may be cut from the product, or an extension piece may be welded to the end of a production joint. If neither is practical, sometimes a test plate welded to represent production as closely as possible may be acceptable. The production test weld is then tested to ensure weld quality is being maintained.
The necessity for welding procedures

A welding procedure provides:

- information stating the precise methods of completing weldments
- clients with relevant information to satisfy themselves that the weldments are correctly welded and quality is assured
- the basis of in-house inspection, client inspection and use by the inspecting authority and a means of quality assurance
- a start point for investigation and repair in the event of defective welding that may occur during fabrication or failure in subsequent service
- basic information required for subsequent repair procedures.

Each manufacturer (or sub-contractor) is responsible for all welding they complete and are therefore responsible for writing, qualifying and recording their own welding procedures. Alternatively, procedures qualified by the client may be used. The welding procedure specification should contain all the necessary information that the operator needs to make the weld. The document should be clear, concise and easily understood by the operator. A clear, complete WPS will reduce the amount of supervision required and maximise weld quality.

Obtaining the welding procedure specification

There are three ways of obtaining a welding procedure specification:

- use of an existing procedure
- use of a ‘pre-qualified’ procedure
- welding procedure approval.

Use of an existing welding procedure

Procedures previously qualified may be used for subsequent jobs, providing that the work is not outside the scope of the procedure and all documentation is recorded. This is common practice where a company carries out a certain type of work on a repetitive basis.

Use of a ‘pre-qualified’ procedure

It is not necessary to carry out WPQ testing in all cases, as it is possible to ‘pre-qualify’ procedures. For example, AS/NZS 1554.1 covers the welding of steel structures using steels with minimum yield strength not exceeding 450 MPa. These steels exhibit good weldability and present little likelihood of weld cracking and mechanical properties are not significantly affected by welding.

On this basis AS/NZS 1554.1 allows for pre-qualified welding procedures provided that the parent metal, weld preparation, welding consumables and workmanship standards all comply with the requirements of the relative clauses of the code. Qualification testing is not required in such circumstances.

Other codes also provide for the use of pre-qualified procedures. Pre-qualified procedures are usually restricted to the welding of steels that present little likelihood of cracking.
Welding procedure approval

Where existing or pre-qualified procedures are unavailable, it will be necessary to develop and qualify a procedure.

Where procedures and welding operator approvals are required, fabricators must take the following actions prior to production:

- write up a proposed welding procedure (WPQ)
- qualify the procedure by testing
- record all details of welding procedure qualification as a WPS.

All of the factors that need to be considered when writing a WPQ cannot be dealt with here, as many of these factors depend upon the application code, welding process and other variables. There are however some considerations which need to be addressed. These are:

- application of code books
- carbon equivalent
- calculation of pre-heat
- qualification range
- selection of consumables.

Application of code books

The most important clause in any code book is the ‘scope’ clause. The scope clause details the applicability of the code; eg the scope clause of AS/NZS 1554.1 states that the code applies to the welding of steel structures using steels with a maximum specified minimum yield strength of 500 MPa. Anything else is outside the scope of this code.

Once you have determined from the scope clause that you have the correct code for the application, it must then be established that you have the correct edition. The edition of the code should be the one stated in the specification. As frequent amendments to code books are published, these should be taken into account.

Carbon equivalent

Carbon has a greater effect on the properties of steel than any other element. We know by now that increased levels of carbon in steel bring about improvements in the properties of hardness and tensile strength, but that they also increase hardenability and reduce ductility.

Increases in carbon content will produce a harder and more brittle heat-affected zone due to welding and this must be taken into account when formulating welding procedures.
General guidelines

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon steel (&lt; 0.3%)</td>
<td>Generally weldable with any grade of consumable without pre-heat, except for heavy thickness.</td>
</tr>
<tr>
<td>Medium carbon steel (0.3% – 0.5% C)</td>
<td>Usually require hydrogen-controlled consumable and increases in pre-heat as carbon content hardness and thickness increases.</td>
</tr>
<tr>
<td>High carbon steel (0.5% – 1.7% C)</td>
<td>Usually always requires hydrogen-controlled consumable and pre-heat. As hardness and thickness increases, post-heat may be required, and possibly annealing of the weldment prior to welding.</td>
</tr>
</tbody>
</table>

Most welders would understand these general guidelines for welding carbon steels, however welding of alloy steels is far more complex due to the range of alloying elements used and their effect on weldability. Such ‘rules of thumb’ would be difficult to apply.

An alternative approach is to calculate a ‘carbon equivalent’. We can, by use of formulae, equate alloy content to percentage of carbon and apply the general rules mentioned, for the purpose of determining pre-heat and welding procedures. The major difference here of course is electrode composition.

There are two main formulas in common use.

**Method 1**

\[
CE \text{ (Carbon equivalent)} = C\% + \frac{Mn\%}{6} \text{ for carbon manganese steels}
\]

**Method 2**

\[
CE = \frac{C\% + Mn + (Cr + Mo + V)}{6} + \frac{Ni + Cu}{15} \text{ (for other low alloy steels)}
\]

Example

Calculate the equivalent for a low alloy steel having the following composition.

0.12\% C 0.12\% Mn 2.5\% Cr 1.0\% Mo 0.015\% Cu

\[
CE = \frac{C\% + (Mn) + (Cr + Mo + V) + Ni + Cu}{6} + \frac{Ni + Cu}{15}
\]

\[
= \frac{0.12 + 0.12 + (2.5 + 1.0) + 0.015 + 0}{6} + \frac{0.015 + 0}{15}
\]

\[
= 0.12 + 0.02 + 0.7 + 0.01
\]

\[
CE = 0.85
\]
This particular steel would have similar hardenability to a plain carbon steel containing 0.85% C and welding procedures would be similar.

The carbon equivalent is usually only calculated to two (2) decimal places.

Calculation of pre-heat

Pre-heat is an essential factor in maximising the weldability of hardenable steels. The amount of pre-heat required is determined by calculation using tables contained in the following.

- AS/NZS 1554.1 Structural steel welding – Part 1: Welding of steel structures
- WTIA Technical Note 1: ‘The weldability of steels’.

The prime function of pre-heat is to slow the cooling rate of the weld zone. When calculating pre-heat, the following factors are taken into account.

1. The weldability of the steel.
2. The cooling rate on the basis of the quenching effect of the parent metal.
3. The heat input from welding.
4. The hydrogen levels that can be expected via the welding consumables.

The first step in calculating pre-heat is to determine the weldability of the steel. This is done by consulting tables from which the weldability group number can be obtained, or by calculating the carbon equivalent which can then be converted to a weldability group number using tables. (See Table 9.1)
Australian Standard® specifications

This table has been deleted. It was reproduced from Table 1 on page 12 of AS/NZS 3679.1:1996, Table 1 on page 9 of AS/NZS 3678 and Table 1 on page 8 of AS/NZS 1548-1995.

Table 9.1 – Relationship between carbon equivalent and group number
Table 9.2 – CE – Relationship between carbon equivalent and group number
as per AS/NZS 1554.1:2004

Once the weldability of the steel has been established, the combined thickness of the metal conducting the heat away from the weld zone is determined. This is done by adding together the thickness of all the plates adjacent to the weld. By this means the cooling rate can be determined. The method of doing this is explained in Fig 9.1.

The group number and combined thickness are combined to give a ‘joint weldability index’. This is done by cross-referencing the group number and combined thickness (see diagram Fig 9.1) and the closest curve selected.

The heat input is then calculated using the formula.

\[ \text{Heat input} = \frac{\text{Amperage} \times \text{volts} \times 60}{\text{Travel speed in mm/min} \times 1000} \]

The heat input and joint weldability index are then combined to give the minimum pre-heat temperature. For this purpose, either Fig 9.2 or Fig 9.3 is used, depending whether or not hydrogen-controlled welding consumables are used.
Fig 9.1 – Relation of joint weldability index with joint combined thickness and group number

These graphics have been removed. They were redrawn from Figure 5.3.4 (A) on page 53 of AS/NZS 1554.1:2004.
This graph has been removed. It was redrawn from Figure 5.3.4 (B) on page 54 of AS/NZS 1554.1:2004.

Fig 9.2 – Pre-heat – Energy input requirements for hydrogen-controlled electrodes (EXX15, EXX16, EXX18, EXX28 and EXX48) semi-automatic and automatic welding processes

This graph has been removed. It was redrawn from Figure 5.3.4 (C) on page 54 of AS/NZS 1554.1:2004.

Fig 9.3 – Pre-heating determination for manual metal-arc electrodes other than hydrogen-controlled Reproduced from AS/NZS 1554.1:2004
Example

A buff weld is to be made between two pieces of 20 mm AS 1548-5-490 plate. Calculate the minimum pre-heat temperature when the root run is to be made using an E4816 electrode with the following variables.

- Amperage – 120A
- Arc voltage – 25V
- Travel speed – 180 mm/min

1. Weldability group No = 5.
2. Combined thickness = 20 + 20 = 40 mm.
3. Joint weldability index = C.
4. Heat input \[ \frac{\text{Amps} \times \text{Volts} \times 60}{\text{Travel speed} \times 1000} \]
   \[ \frac{120 \times 25 \times 60}{180 \times 1000} \]
   \[ = 1.0 \text{ kJ/mm} \]
5. Minimum pre-heat = 50 °C.

The minimum pre-heat temperature should be obtained prior to welding and maintained during welding. The weldment must be brought to the pre-heat temperature for a minimum of 75 mm on each side of the joint or a distance equal to the plate thickness, whichever is the greater.

It is generally accepted that the maximum interpass temperature is a maximum of 250 °C above the minimum pre-heat temperature.

As pre-heating is an expensive exercise, the competent welding supervisor will commonly manipulate the welding variables to increase the heat input. By this means, pre-heat can be avoided where the pre-heat temperature initially calculated is low.
Selection of consumables

Welding consumables are chosen that will match the parent metal composition and properties and give the deposited weld metal similar tensile strength, weld metal toughness and alloy content. The welding situation must be taken into account and the consumable chosen must provide cost effective welding.

Qualification range

Most codes allow qualification to cover a stated range of parent metal thickness either side of the test piece.

For example, a 10 mm butt weld is to be made using AS 1210 as the application code and the procedure qualification test weld made in 10 mm plate (ie t = 10 mm). Table 5.14.3 of the code allows qualification in the range of 5 mm – 2t for joints of this type.

This means that welds in plates ranging from 5–20 mm can be qualified using this procedure.

The person writing the procedure should consider the range of joints to be welded and use the qualification range to best advantage so as to minimise the number of procedures to be qualified.

Qualification by testing

To establish whether or not welds made with the proposed welding procedure will comply with the specification, test plates are welded and tested. Testing is used to disclose the presence of weld defects, but more importantly at this stage to verify that the procedure will deliver finished welds that exhibit the required mechanical properties.

The level of testing required is governed by the application code (eg AS 1210).

Recording details of the welding procedure

When testing is completed and it has been ascertained that the WPQ will deliver welds of the desired standard, this now becomes a qualified welding procedure and can be issued as a welding procedure specification (WPS). All details of the procedure are recorded and along with all the other procedures and testing that the company has qualified become part of the procedure qualification record (PQR).

A welding procedure will contain the following information:

- procedure number
- date
- contract details
- code details
- material specifications
- joint details
- welding process
- welding sequence
- pre-heat requirements
- NDT requirements
• welding variables consumables
• test plate and welder identification
• signature
• notes.

Refer to Table 9.3 for further information.

**Qualification of welders by testing**

To be qualified, welders deposit test welds in accordance with the WPS. The test plates are inspected to determine the welder’s ability to deposit sound welds in accordance with the WPS.

**Note**

A welder who completes the test plates used for procedure qualification shall be deemed to be qualified if the test plates conform to the code requirements. The process of procedure qualification and welder qualification is time consuming and costly.

Every attempt should be made to minimise the number of qualification tests required, firstly by making best use of qualification range and secondly by ensuring that the welder is kept current and his/her qualification is not allowed to lapse, necessitating re-qualification.

**Writing a welding procedure qualification/specification (WPQ)**

A WPQ is usually written up by a qualified welding supervisor or welding engineer. It is normally written on a proforma that addresses all the relevant information required. The format of such a proforma should ensure that all information is clearly stated and is easily understood by the welder. Information which is not relevant to the welding operator should not be included.

The welder may be a skilled tradesperson, but may not understand the importance of the procedure in a metallurgical sense. If the procedure is to be effective, the supervisor must ensure that the operator both understands the need for and follows the procedure.

An example of a WPQ proforma is given in Table 9.3.
Chapter 9 – Weld procedures

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Table 9.3 – Welding procedure qualification
Chapter 10 – Metal cutting and gouging

Introduction

Weld preparation is commonly applied by:

- grinding
- shearing
- machining
- flame or plasma cutting
- arc or flame gouging.

In this chapter we will look at the following.

- Weld preparation
  - grinders
  - machining
  - oxy-flame cutting
    - flame-cutting techniques
  - flame gouging
    - flame gouging techniques
    - flame gouging applications
  - air-arc gouging
    - air-arc gouging technique
    - air-arc gouging applications.
Grinders

Angle grinder

The angle grinder is in common use in the fabrication industry, particularly for the fabrication of steel. It provides a convenient and efficient means of edge preparation, slag and scale removal and final finishing/shaping to accurate dimensions.

The angle grinder is so called because the disc rotates at right angles to the electric motor.

The angle grinder employs the use of a hard (and usually recessed) disc, which is protected by a guard that must be kept in place at all times. A range of discs is available for grinding materials such as carbon steel, stainless steel and aluminium.

Choice of the correct disc for the material being ground is important, as material contamination, or clogging of the disc may result if the incorrect disc is chosen. Manufacturer’s recommendations should be followed in this regard.

Grinders come in a range of sizes from 100 mm (wheel diameter) up to 230 mm. It is important to select the correct size grinder for the job. 100 mm and 125 mm grinders are suitable for light work only and are easily overloaded. Larger grinders provide for faster and more efficient removal of metal. 180 mm and 230 mm grinders are powerful tools and the operator will be unable to stop the wheel should it jam due to inappropriate use. A firm grip of both handles of the grinder is essential and use should be in line with recommended procedures.

Cut-off wheels are available for use with angle grinders. These discs are thinner than a grinding disc and do not have a recessed centre. They can be used to clean out or repair root runs or faces. Care should be taken to avoid jamming or kick back. Once again it is essential that both handles are gripped firmly, guards are in place and the machine is used in line with manufacturer’s recommendations.

Cutting-off wheels should not be used for grinding applications, as they are thin and unable to withstand sideways pressure.
Straight grinder

The straight grinder (or barrel grinder as it is commonly called) is used for numerous grinding applications. It is ideal for grinding narrow areas, such as when weld reinforcement needs to be ground flat, or for the removal of scale alongside welds – particularly inside pipes. As with all grinders, it is important to hold the machine firmly. Movement of the straight grinder should be backwards, against the direction of rolling where possible, as this will reduce the tendency of the straight grinder to run with the rotation of the wheel.

As with all portable grinders, they should be allowed to stop before putting them down. This is particularly important with straight grinders, even if care is taken to put them down with the wheel clear of the bench. Centrifugal force of the motor can cause the body of the grinder to rotate and to fall or wrap up the lead.

Disc sander

Disc Sanders are available either as a straight, or in-line type, or as an angled sander – the type most commonly used in the fabrication industry. Sanders are ideal for cleaning of the material surface. They are particularly useful in the aluminium industry where they are used for removal of surface oxide prior to welding, or for cleaning up and final polishing.

Sanders employ the use of a flexible abrasive disc supported by a rubber or fibre back-up pad. The discs are held in position by a broad, flat locknut, which fits into a depression in the centre of the pad. Alternatively, the disc may self-adhere to the pad. Sanders operate at lower RPM than grinders, to minimise clogging of the disc and burning of the surface being sanded.
Safe use of sanders and grinders

- Inspect and ensure electrical safety.
- Ensure guards are correctly and securely fitted.
- Inspect the disc/wheel for any signs of damage and ensure that it is tightly fitted.
- Ensure you are well balanced.
- Grip the grinder securely with both hands.
- Eye protection must be worn.
- Hearing protection must be worn.
- Ensure no fire hazard exists from flying sparks.
- Direct sparks away from others and towards a safe place.
- Stop the wheel before putting the grinder down.
- Ensure the grinder cannot fall.
Machining

The edge preparation of the circular material such as pipes may be easily carried out on a lathe, provided the lathe capacity is appropriate. The edge of flat material can be milled or machined. A hand-machining tool is now commercially available for the preparation of long plate edges.

Fig 10.4 – Manually held curve

Fig 10.5 – Pipe beveling
Plate beveller (nibbler)

Plates above 6 mm in thickness that are to be joined by butt welding will generally require weld preparation to be applied to the plate edges. Applying preparation with the plate beveller (or ‘nibbler’, as it is more commonly called) is a simple and versatile method of doing so. This electrically operated machine can be used to apply single or double V preparation to a range of ferrous and non-ferrous materials.

The machine is available in two sizes; the smaller is suitable for bevelling plates up to 25 mm thick and the larger for plates up to 32 mm thick.

In both cases the machines are fully portable and may be used to prepare edges that are straight, or have either convex or concave curves. For concave curves, the smallest radius that can be bevelled is approximately 40 mm.

Fig 10.6 – Balancer attached
Fig 10.7 – Fixed mounting

Fig 10.8 – Bevelling concave curve
The nibbler is capable of preparing bevelled edges to angles of 30°, 37.5°, or 45°. By changing the guide bracket, it is also possible to produce angles of between approximately 15° and 55°. A feature of the beveling machine is that beveling may be started and stopped at any point of the edge being bevelled.

Fig 10.9 – Double V edge preparation (a) first cut and (b) second cut


Safety

When operating a bevelling machine, ensure the following:

- safety glasses are worn
- loose clothing is tied back
- a container is used to collect metal chips
- a firm grip is taken before starting the machine
- a balanced stance is adopted
- the blade is correctly adjusted
- metal is not forced into the machine.
Oxy-flame cutting

Outline of the process

The process of oxy-flame cutting makes use of the reaction between heated iron and oxygen combining to form iron oxide.

When iron is heated to 815 °C (called the ignition temperature), it readily combines with oxygen. The resulting reaction produces iron oxide. This reaction (combustion) also gives off extra heat, which keeps the process of oxidation going.

The important point to note is that the reaction occurs at a lower temperature than the melting point of steel (approx. 1500 °C).

The molten iron oxide, together with some free iron which runs off as molten slag, is removed by an introduced jet of oxygen, thus exposing more pre-heated iron and iron oxide.

With the movement of the cutting blowpipe and with it the cutting stream, a narrow cut or kerf is produced (Fig 10.11).

---

Oxy-flame cutting can only be successfully employed on materials that have a lower ignition temperature than their melting point, eg carbon steels and low alloy steels. Materials, such as aluminium and stainless steel cannot be successfully cut because their oxide melts at a higher temperature than their melting point.
Flame adjustment

With all flame cutting, a pre-heating flame is necessary. This usually surrounds the orifice through which the oxygen jet passes and its purpose is to bring the surface of the metal to ignition temperature and to maintain it at that temperature. The flame is adjusted to neutral with the oxygen cutting stream ON.

![Correct adjustment (neutral flame). This should be checked with the cutting oxygen flowing at recommended pressure. The cutting oxygen stream should be clearly defined as shown.]

**Fig 10.12 – Correct flame adjustment**

Principles of flame cutting

The principles of flame cutting may be summarised as follows.

1. The heating of the metal to its ignition temperature 815 °C.
2. The burning or oxidation of the iron in the path of the oxygen jet. The oxide remains molten as its melting point is lower than that of the steel – this is important, for if the oxide has a higher melting point than the metal then normal oxy-cutting would not be possible.
3. The removal of the molten slag (a mixture of oxides and molten steel by the force of the oxygen stream – kinetic energy).
4. The continued and even movement of the blowpipe along the line of the cut.

**Note**

The burning or oxidation process produces heat. This is what pre-heats the next layer of iron prior to oxidation.
Oxidation

Elements have the property of combining or uniting with one another to form new substances that have chemical and physical properties entirely different from those of the two substances that entered into the combination. This new substance is called a compound and the process is known as a chemical combination or chemical reaction, eg iron will combine with sulphur to form iron-sulphide.

Oxidation is a chemical reaction in which oxygen combines with another element to form an oxide, eg iron + oxygen = iron oxide. When steel (an alloy of iron) is heated to about 815 °C (or above) and is not protected from the atmosphere, oxidation of the surface of the metal occurs, ie oxygen combines with the iron, an element in the steel, to form iron oxides. This oxidation results in the weld being porous, hard and brittle. Therefore during welding, care has to be taken to prevent oxygen coming into contact with the metal. In the case of gas welding, this is done by careful use of outer envelope of the flame and/or use of fluxes. Flame cutting relies on this process of oxidation.

Quality of the cut

A satisfactory cut may be defined as one fulfilling the following requirements:

- accurate shape and size of finished object
- reasonably smooth surface of cut face (drag lines not too pronounced)
- sharp upper and lower edges of cut
- slag adhesion light or non-existent.

To produce high quality cuts, the following factors should be observed.

- Make sure that the cutting equipment is in good condition.
- Select a nozzle size appropriate to the thickness of metal to be cut.
- Ensure that the nozzle face and the cutting and heating orifices are clean.
- Adjust gas pressures to suit nozzle size and plate thickness.
- Correct heating flame adjustment (ie neutral flame of suitable size).
- Clean surface of work along the line of the cut (ie free of rust, scale, etc).
- Nozzle is the correct distance from plate (ie tip of pre-heating cones about 2 mm above the work).
- Cutting blowpipe is held at correct angle.
- Suitable and uniform speed of cutting.
- A suitably trained operator.

A nozzle that has been correctly cleaned and in good condition will exhibit a clean, long jet of cutting oxygen. This appears as a long parallel-sided pipe or zone through the centre of the heating flame.

A short, indefinite or bushy jet indicates a dirty or damaged nozzle. When inspecting the cutting jet, it should be viewed from two positions at right angles to each other.
Other factors which may affect the quality of the cut are the:

- quality of the material, e.g., presence of laminations, slag pockets, and heavy surface scaling
- purity of the oxygen
- angle of nozzle to place surface, e.g., bevel cutting is more difficult than a 90° cut
- training and experience of operator.

By observing all the above factors, oxy-cutting will be of a very high standard.

The positive results of good quality oxy-cutting are:

- less time and effort spent in cleaning up the job by grinding and filing
- greater accuracy means final finishing or machining is kept to a minimum.
- less material wastage
- overall quality and finish is attained, which promotes a general feeling of pride in those associated with the work or product.

When all the conditions are correct, a good quality cut should have the following features (Fig 10.13):

- a sharp top edge
- a smooth surface, with drag lines barely visible
- a very light scale or oxide film on the cut face, which is easily removed
- a square face
- a sharp bottom edge.

Fig 10.13 – Features of a good quality oxy-cut
A good tradesperson will endeavour to maintain a high standard of workmanship when it comes to oxy-cutting.

Before starting, it’s important to check the equipment and settings and prove the procedure by a trial cut, preferably on scrap steel. Periodic checks should be made to see that the quality is maintained and if not, determine reasons for the low quality.

Possible causes include:
- too much pre-heat
- cutting oxygen pressure too low
- cutting speed too slow
- pre-heat flame too high above work
- pre-heat flame too close to work
- dirty nozzle
- dirty or rusty plate.

Flame-cutting techniques

The following segments outline the recommended techniques and methods to be used when oxy-cutting.

**Straight line cutting – by hand**

1. It is usual to start the cut from the edge of the plate (other starting positions will be covered later).
2. Heat the metal until it reaches red heat ignition temperature. The tips of the pre-heating cones should be held 2–3 mm from the surface of the plate for this operation.
3. Depress the cutting oxygen lever slowly and allow the oxygen to come into contact with the heated iron; and allowing the resultant reaction oxide stream to track down the face of the plate edge.
4. The cutting action is continued by a smooth movement of the cutting blowpipe. The cutting oxygen stream produces a fine spray of sparks under the cut, together with droplets of molten metal. The correct cutting speed is accompanied by a spluttering sound.

Straight line oxy-cutting by hand demands a high degree of skill to maintain a smooth travel and to keep the cut to a given line.

To assist the operator when cutting straight lines, a set of roller guides can be attached to the cutting blowpipe.

Roller guides can also be adopted for cutting bevels and for assisting with the cutting of circular shapes.
Straight line cutting – using aides

Roller guides

1. Fit the roller guides to the cutting blowpipe, making sure the cutting nozzle fits snugly into the recess provided in the roller guide body.

2. Partially tighten clamp nut so that the roller guides are at 90° to the cutting blowpipe (Fig 10.14). Fully tighten the clamp nut.

3. Check nozzle distance off-plate. Adjust by raising or lowering wheels (Fig 10.15).

4. Finally, make sure the cutting nozzle is at 90° to the horizontal by having both wheels placed on the metal surface. This ensures that a square cut will be made.
Angle irons or heavy steel section

Fig 10.16 shows how an angle iron (ASA) can be used in conjunction with the cutting blowpipe. Any steel section which will not distort easily due to the local heat can be used. The section is set away and parallel to the line of cut.

Fig 10.15 – Roller guides – elevation

Fig 10.16 – Use of angle as a cutting guide
Bevel cutting

Machine beveling produces a consistently high quality finish, but bevels produced by hand cutting can also be of a similar standard where machines cannot be used conveniently or economically.

Aides such as roller guides (Fig 10.15) or a piece of angle iron (Fig 10.16) can be used to help maintain a straight and even bevel.

The length of the bevel face (T), not the plate thickness, determines the nozzle size, gas pressures and cutting speed (Fig 10.17).

Where small or singular beveling operations occur, an increase in the pre-heating flame and a decrease in cutting speed using the same nozzle as fitted for square cutting can be employed. Pre-heating the plate edges is recommended before cutting is started.

The cutting angle can be proved by inspecting a short trial cut, so that minor adjustments can be made if necessary.

Fig 10.17 – Bevel cutting
Circle cutting

Manual oxy-cutting of a round hole or disc can be made easier using a radius bar or radius rod.

- For circles larger than 100 mm use radius bar
- For circles larger than 100 mm use radius bar

A radius rod (Fig 10.19) is fitted into the roller guide stock. It can be made in a variety of sizes to suit mainly small radii.

The wheel shown fitted (Fig 10.19) is optional, as it may hinder the operator in small work but can be a steadying influence with slightly larger radii.
Radius plate (Fig 10.20) has a larger range than the radius rod and can be used for both small and medium sized radii. The design of the fixing device must be made to suit the particular model of cutting blowpipe used.

Radius bar (Fig 10.21) is used in conjunction with roller guides and is suitable for medium to large circle cutting.
Pipe cutting

1. The tubular section should be supported on rollers, or in such a way that it can be easily turned (Fig 10.22).

2. Half-way round one side, pierce a hole and carry the cut along the required line to the top of the pipe. The operator should maintain the nozzle at 90° to the pipe face by using a rolling action of the wrists.

3. Give the pipe a quarter turn and repeat the operation, continue this procedure until the pipe is severed in two.

Fig 10.22 – Tubular section supported on rollers
Flame gouging

Flame gouging has similarities to the oxy-fuel gas-cutting process such as:

- it relies on the chemical process of oxidation for its operation
- it is suitable only for use on carbon and low alloy steels
- both acetylene and LPG are fuel gases used for the process.

The principal difference between the two processes is that flame gouging uses a low velocity oxygen stream, as opposed to the high velocity oxygen stream used for flame-cutting. This is achieved by increasing the diameter of the oxygen orifice at the outlet end of the gouging nozzle, as opposed to the cutting nozzle which reduces in size.

![Fig 10.23 – Nozzle design](image)

To obtain the volume of oxygen required for gouging, relatively high oxygen pressures must be set at the regulator.

<table>
<thead>
<tr>
<th>Nozzle size</th>
<th>Regulator pressure</th>
<th>Speed</th>
<th>Groove dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oxygen kPa</td>
<td>Acetylene</td>
<td>mm/min</td>
</tr>
<tr>
<td>32</td>
<td>350–450</td>
<td>100</td>
<td>300/500</td>
</tr>
<tr>
<td>40</td>
<td>400–450</td>
<td>100</td>
<td>500/650</td>
</tr>
<tr>
<td>48</td>
<td>450–500</td>
<td>100</td>
<td>500/560</td>
</tr>
</tbody>
</table>

Table 10.1 – Approximate data for flame gouging
Flame gouging techniques

There are three basic techniques in gouging, which are:

- progressive gouging
- spot gouging
- back-step gouging.

**Progressive gouging**

The flame for gouging is adjusted in the same way as the oxy-cutting flame. The pre-heat flame should be neutral, with the oxygen lever fully depressed. When starting to gouge, the nozzle is held at an angle of 20° to 40° from the metal surface and above the line of gouge. As the metal reaches a bright red heat, the oxygen lever is slowly depressed and gouging begins. The nozzle angle is gradually lowered to about 7° and a smooth and constant travel speed is maintained. Cone points of the pre-heat flame should be 6–13 mm behind the reaction zone and the nozzle just clear of the groove bottom.
Spot gouging

Spot gouging uses a step back sequence, which means it is easier to control the depth of the cut. This method uses the same technique for starting as progressive gouging. Once the gouge has been started and the depth of groove obtained, the operation is stopped, moved back along the line of cut and the starting procedure repeated. This action reduces the possibility of damage to the cutting nozzle.

Back-step gouging

For certain types of work, it is necessary to make a long deep gouge. This procedure combines both progressive and spot gouging techniques. The surface of the metal is pre-heated as for normal gouging, the cutting oxygen is turned on and the nozzle angle reduced. The angle is then gradually increased until the desired depth is obtained and the nozzle moved backward approx 25–30 mm while reducing the angle to the normal 7°.

At the end of this sequence, the nozzle angle is again increased and the sequence repeated until the gouge has progressed along the required line. In effect, a spooning action is employed as in Fig 10.26.

Flame gouging applications

Preparation of plate edges for welding

Flame gouging is one method of preparing U and J type weld joints. Individual plate edges can be gouged before assembly, or plates can be abutted when U joints are required and both edges gouged together (see Fig 10.27). Welds may be placed on the underside of a joint before gouging takes place to form a sound backing bead, provided the gouge is deep enough to remove any trace of slag or defect.

When gouging is carried out from both sides, a double U or double J can be produced, as is often required for thicker materials. Plate edges may be prepared by gouging in the vertical position, with the gouging blowpipe travelling downwards and nozzle angles corresponding to those used in the flat position.
Removal of weld defects

Flame gouging is very effective for removing isolated defects in welds. Spot gouging can be applied to minimise repair welding, providing the position of defects is known. It is particularly effective for removing weld metal which has cracked, as the heat tends to open the crack and complete removal can be assured by visual inspection. Removal of the defect is easily witnessed while gouging is in progress.

When faulty welds are removed by flame gouging, no further preparation is usually necessary, apart from clearing away the oxides and slag.

Back gouging welds

It is common practice to back gouge the root of butt welds using the flame gouging process, prior to deposition of the backing run. Back gouging of welds should be carried out in a convenient position, preferably flat. The procedure is the same as for preparing plate edges or removing weld beads and is illustrated in Fig 10.29.
Flame gouging of cracks and defects in steel castings

General rules for this operation are that gouging may be carried out when the material is capable of being oxy-cut and when hardening or other problems will not arise as a consequence. Hardening problems in certain alloy steel and cast steels may be overcome by pre-heating, post-heating and cooling precautions. Tests should be carried out in doubtful situations.

Flame gouging is not generally recommended for quench and tempered steels, due to the risk of a reduction of mechanical properties from the relatively high heat input associated with flame gouging.

Fig 10.29 – Back gouging used in conventional butt weld designs (a) single V preparation, (b) U-groove preparation and (c) double V preparation

Fig 10.30 – Crack in cast steel frame prepared for gouging
Air-arc gouging

The process
Air-arc gouging removes metal by melting it with the heat of an electric arc and directing a jet of compressed air to clear away the molten metal. As the process does not depend on oxidation, it may be used for materials such as non-ferrous metals which do not oxy-gouge. Further advantages over flame gouging include faster operation and a reduced HAZ with less distortion. The advantages are offset to some extent by reduced portability and the need to guard against increased fume and long streams of hot sparks.

The equipment

Power source
Various DC power sources (such as constant current welding generators or transformer rectifiers) are commonly used to supply the current needed.

Constant voltage equipment is often preferred for heavy duty applications. It is essential to connect the electrode holder to the positive pole of the DC power source used. An AC power source may be used, provided suitable electrodes are available. In each case, the power source should have a continuous rating for the current values to be used. An output of up to 450 amperes is required for general purpose arc-air cutting and gouging. Higher current outputs may be required for certain applications.

Electrode holder
The gripping jaw of the holder is fitted with a self-aligning rotating head. When the air valve in the holder is opened, twin jets of compressed air are emitted parallel to the axis of the carbon electrode. The self-aligning rotating head permits the blowpipe to be used in any position and ensures that the air stream is always directed to converge at the arc.

Photograph reproduced with the permission of Lincoln Electric Co. (Aust) Pty Ltd

Fig 10.31 – Electrode holder
Air supply
Compressed air may be supplied by a compressor or from cylinders, usually at a pressure of 560 kPa. The air supply hose must have a bore of not less than 6 mm and be free from restrictions. Although the actual pressure is not critical, it is important that sufficient air is supplied to ensure a clean, slag free cut or gouged surface.

Electrode materials
Electrodes are made of a blended mixture of carbon and graphite, bonded together and enveloped in a thin layer of copper. The copper coating aids electrical conductivity through the electrode and acts as a stiffener to the carbon, increasing its working life and reducing radiated heat.

Electrodes are available in a range of sizes from 4 mm to 12 mm and to suit both DC and AC. The choice will depend on the job application (ie the amount of metal to be removed) and the equipment available.

Air-arc gouging technique
The current setting should conform to the manufacturer’s guide on the electrode packets and be sufficient to obtain a smooth and continuous forward movement but without overheating and rapid burning of the electrode. Compressed air pressure of at least 500 kPa is necessary to clear molten metal from the groove. In addition, the flow of air will tend to cool the electrode and increase its life.

The electrode is gripped in the holder jaws with a forward projection of 75 mm to 150 mm from the air jets. Note that the air jets are underneath the electrode.

Gouging is commenced by turning on the air flow and ‘arching up’ with the electrode. Once the groove is started and reaches correct size, a smooth forward movement is made along the line of gouge. Groove size is determined by electrode size, speed of travel, current and electrode angle. The angle between electrode and work is usually 20°, increasing to deepen the groove. Widening of the groove may be achieved by sideways weaving of the electrode.

Air-arc gouging applications
The applications of air-arc gouging are the same as discussed under flame gouging. Air-arc provides more precise control of the groove and allows for taper. As already noted, materials which do not flame gouge can be grouped by this process.

Additionally, air-arc gouging is ideally suited to quenched and tempered steels and other metals where the high heat input of flame gouging may prove detrimental.
Chapter 11 – Elementary electrical terms

Introduction

The arc welding processes have been a popular and widely applied method of welding for many years. The arc welding process offers sound and reliable welds, simple operation and low capital cost.

In this chapter we will look at the following.

- Arc welding process overview
  - welding voltage
    - welding current
  - welding machines
    - machine characteristics.
Arc welding process overview

There are a lot of arc welding processes that are used in the metal fabrication and welding industries. Some of these arc welding processes are in common use and others are used only in specialist applications. This section introduces some of the welding processes that are most often used, which are:

- manual metal arc welding (MMAW)
- gas metal arc welding (GMAW)
- flux-cored arc welding (FCAW)
- submerged arc welding (SAW)
- gas tungsten arc welding (GTAW).

All these welding processes depend on three main requirements for their operation:

1. a heat or energy source needed for fusion
2. atmospheric shielding to prevent oxygen and nitrogen in the atmosphere from contaminating the weld
3. filler metal to provide the required weld build-up.

The above factors will be looked at in our closer examination of specific arc welding processes and discussed further in later chapters.

All of the arc welding processes have a few basic electrical requirements for their operation. They must have sufficient voltage available for the operator to get the arc started and be maintained. They also must provide sufficient amperage to heat and melt the parent metal and filler material.

Welding voltage

The voltage available at the MMAW power source output must be safe for the operator. To protect the operator from the greater risks associated with high open circuit voltages, the maximum voltage allowed is restricted by law (80 V for AC and 110 V for DC). A high open circuit voltage will however assist the operator to easily strike the arc. At open circuit voltages lower than 45 V, the arc becomes difficult to strike without some form of starting assistance. The load voltage of an MMAW machine should be in the range of 21–28 V and most electrodes will run satisfactorily at load voltages around 24–25 V. Low hydrogen and alloy steel electrodes sometimes require slightly higher load voltages (26–28 V) to run properly.

Welding current

To be suitable for welding, the current used must meet the following requirements.

- There must be sufficient amperage to provide the heat for fusion.
- There must be a suitable means of current control.

Mains supply is unsuitable for direct use for welding as the supply current is too low. Mains supply must be 'transformed' to make it suitable for use in welding, or alternatively, welding current can be produced from a dedicated welding generator or alternator.
Current types

Electric current may be either:
- alternating current (AC)
- direct current (DC).

Alternating current (AC)

Alternating current is produced by an alternator – AC is usually taken from the mains supply which operates at 50 cycles/sec.
- There is a period of current flow from positive to negative, followed by a period of current flow from negative to positive.
- The flow changes direction 50 times/sec.
- The voltage falls to zero 100 times/sec (therefore the arc is broken and re-established 100 times/sec).

Due to the even periods of current flow with AC, the heat is distributed evenly at the electrode and the work piece and there is no choice of polarity.

Direct current (DC)

DC may be produced by:
- a chemical reaction as produced in a storage battery
- a generator driven by a rotational shaft
- converting AC to DC by means of a rectifier or inverter.

Direct current exhibits the following characteristics.
- Direct current flows continuously in one direction at the preset voltage.
- In DC the current always flows from negative to positive.
- With DC, the flow of electrons striking the positive pole (+ve) generates two-thirds of the heat from the arc at the positive pole.

![Fig 11.1 – Typical AC and DC output curves as seen in an oscilloscope](image-url)

(a) sine wave, (b) DC
**Polarity**

Polarity refers to the way in which the electrode lead is connected to the DC welding power source. When welding with positive polarity, the electrode lead is connected to the positive terminal of the welding machine. When welding with negative polarity, the electrode lead is connected to the negative terminal.

Changing polarity with DC **does not** change the direction of current flow, current still flows \(-ve\) to \(+ve\). Changing polarity however alters the point at which the greater portion of heat is generated in the welding circuit, ie:

- most of the heat is generated at the electrode with \(+ve\) polarity (electrode connected to positive)
- most of the heat is generated at the work piece with \(-ve\) polarity (electrode connected to negative).

---

There is no polarity with AC welding circuits. As current flow is equal between both the positive and negative poles, the heat is distributed evenly between the electrode and the work piece.

**Arc blow**

Arc blow is a problem peculiar to DC circuits. Arc blow is the effect of electromagnetic forces within the circuit that deflect the metal droplets as they flow across the arc gap. As the current within the circuit increases, the magnetising effect increases accordingly. Consequently, arc blow is more severe at higher amperages, particularly above about 300 A.

Among the methods used to control or minimise the effects of arc blow are:

- change to AC
- change polarity
- change the position of the work return lead
- use two work return connections
- change the direction of welding
- wrap the work return lead around the job
- reduce the amperage.

**AC versus DC**

AC and DC welding circuits each have their own advantages and disadvantages. Essentially, AC welding machines are cheap and lack portability but are simple and trouble-free in their design and operation. Not all of the electrodes will run on AC.

DC generator machines are generally portable and offer better control of welding conditions, but are more expensive to buy and maintain. Some welders prefer the smooth arc characteristics of pure DC and like the advantages of polarity choice and heat control.
### Alternating current (AC) vs. Direct current (DC)

<table>
<thead>
<tr>
<th>Feature</th>
<th>AC Description</th>
<th>DC Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Portability</strong></td>
<td>These machines generally consist of static step-down transformers and they are considered as stationary types.</td>
<td>Most modern types have features that allow portability (especially the self-contained types).</td>
</tr>
<tr>
<td><strong>Power supply</strong></td>
<td>The use of these machines is restricted to the location of the nearest alternating current power point.</td>
<td>Petrol or diesel engine driven machines can be used in any location.</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>70–90% electrically efficient.</td>
<td>40–60% efficient but some modern types compare with alternating current efficiency.</td>
</tr>
<tr>
<td><strong>Polarity</strong></td>
<td>No polarity.</td>
<td>Choice of polarity.</td>
</tr>
<tr>
<td><strong>Arc blow</strong></td>
<td>Unaffected.</td>
<td>Arc blow occurs even in normal currents and it is difficult to control above 300 amperes.</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>As there are no moving parts to be considered, maintenance costs are low.</td>
<td>Revolving and wearing parts adds to maintenance.</td>
</tr>
<tr>
<td><strong>Initial costs</strong></td>
<td>Cheaper plant as less construction is required.</td>
<td>Most costly due to generator and motor construction involved.</td>
</tr>
<tr>
<td><strong>Electrodes</strong></td>
<td>Restricted to use of electrodes that are suitable for alternating current only.</td>
<td>Suitable for all types of electrodes.</td>
</tr>
<tr>
<td><strong>Running cost</strong></td>
<td>Cheaper running costs due to the use of an installed power supply.</td>
<td>Added costs due to the use of electric motors or internal combustion engines.</td>
</tr>
<tr>
<td><strong>Voltage control</strong></td>
<td>Constant open circuit voltage.</td>
<td>The open circuit voltage can be varied by the operator.</td>
</tr>
<tr>
<td><strong>Arc length</strong></td>
<td>Limited arc length.</td>
<td>Greater tolerance in arc length due to the characteristics of the machine.</td>
</tr>
</tbody>
</table>

*Table 11.1 – Comparison of AC and DC machines*
Welding machines

There are various types of welding machines available to accommodate the wide range of welding processes and applications that comprise ‘welding’.

Welding machines range from small ‘hobby type’ machines putting out as little as 100 amps, to large industrial types with outputs in the thousands of amps.

To ensure the safety of the welding operator, the open circuit voltage (OCV) of welding machines is restricted by regulations to:

- AC – maximum OCV 80 V
- DC – maximum OCV 110 V.

AC machines

When an AC mains supply is available, it is possible to use a step-down transformer to reduce the supply voltage of 415 V to a safe OCV of around 70–80 V. At the same time, current is increased so as to provide sufficient heat for welding.

The step-down welding transformer consists of a laminated soft iron core carrying two coils which are not electrically connected. The first is connected to the supply (primary). Voltage applied across the first coil will produce, by induction, a voltage in the second coil. The value of this secondary (induced) voltage will be proportional to the ratio between the turns in the two coils. If each coil has an equal number of turns, equal voltage will appear at the secondary connections. If however a transformer has 400 turns in the primary coil and 50 turns in the secondary coil, then a primary voltage of 400 V will induce 50 V to appear at the secondary connections.

The power into the welding machine is calculated by multiplying the volts by the amps and is expressed as volt-amperes (VA). This figure is generally quite large and divided by 1000 and expressed as kilovolt amperes (kVA).

Power IN = volts x amps.

Therefore – 400 V x 50 A = 20 000 VA.
Since transformers have very low losses, we can consider here that the total power put into the machine must equal the power output. Therefore, in this machine which is theoretically 100% efficient:

\[
\text{Power OUT} = 20\ 000\ \text{VA}.
\]

The output voltage is determined by the ratio of the windings of the transformer. Therefore in this case, the output voltage will be equal to 50 V.

If power = amps x volts, it can be seen that:

\[
\text{AMPS} = \frac{\text{POWER}}{\text{VOLTS}}
\]

Therefore, in our welding machine, the output current is equal to:

\[
20\ 000 = 400\ \text{A}
\]

\[
50\ \text{V}.
\]

The output current of 400 A at 50 V would now be suitable for welding, particularly if some form of current control were added.

We have considered a transformer that was theoretically 100% efficient, however in practice this would not be the case. Let’s say that our transformer was only 80% efficient; this means that we would have a power loss of 20%.

Since the open circuit voltage is determined by the ratio of the input and output windings of the machine and is therefore fixed, the power loss would be in the form of reduced output amperage and heat. A loss also occurs in the output voltage of the machine because as the output current increases, the energy required to build up the magnetic field and then collapse it also increases (drooping characteristic). Therefore, our load voltage and output amperage would be 25 V @ 320 A.

**DC machines**

Direct current for welding may be obtained from a generator set, a transformer rectifier unit or an inverter.

**Generators**

A welding generator basically consists of an armature carrying a number of windings that rotate in a magnetic field produced by electro-magnets (field coils). The passage of the armature through this field induces a voltage through the windings. The current is collected by carbon brushes running on a copper commutator at one end of the rotating armature and current will flow when the circuit is made. The armature is rotated by an electric motor connected to an AC supply or by a diesel or petrol engine.
Welding generators are constructed to produce high current flow at the comparatively low voltages suitable for welding. The current produced by the generator should be steady and the voltage must not fluctuate during welding. A steady current is maintained by compensation coils or reactors to absorb current fluctuations and produce a more stable arc.

Generators can be engine driven using either petrol or diesel engines. These machines offer the advantage of being portable and are popular for site work where line power is unavailable. Some generators also provide auxiliary power, which is useful for power tools and lighting.

Most modern portable power supplies utilise a highly efficient high frequency alternator and electronics to provide both AC and/or DC current at constant voltage, or constant current type outputs suitable for use in a wide range of welding operations.

**Rectifiers**

A rectifier is a device that permits current flow in one direction only and can therefore be used to convert AC to DC. They can be supplied as an individual unit, but most often are incorporated into the welding power source. The rectifier consists of metal plates coated with a selenium compound of silicon diodes, each unit having the special property of allowing the current to flow in one direction only. This means that when an alternating voltage is applied, only the positive half cycles are effective. This ‘half wave rectification’ is undesirable and uneconomic, so the rectifier units are arranged in the form of a bridge to achieve ‘full wave rectification’.

**Transformer/rectifiers**

Where both AC and/or DC welding current is desirable, for example with gas tungsten arc welding (GTAW), or when DC is required from mains supply (eg for gas metal arc welding (GMAW)), a transformer/rectifier is commonly selected. GMAW machines usually provide DC output. Manual metal arc welding (MMAW) and GTAW machines usually provide both AC and DC output. By means of a switch or by changing leads, the welder can select either positive or negative polarity on the DC output.

Most GTAW machines are equipped with a high frequency oscillator that provides a high frequency spark to enable the arc to be started without the electrode making contact with the work. The high frequency spark may be used simply to start the arc when using DC, or may be continuous to re-establish and maintain a steady arc with AC.
Fig 11.4 – Single phase transformer with bridge (full wave) rectifier

Inverters

Inverters are fast taking over from other types of welding machines as they are able to provide AC and smooth stable DC output at high efficiency levels and they feature lightweight construction.

The machines operate on either 240 V or 415 V AC input current and immediately rectify this to DC, using a series of high temperature diodes. This DC current is stored in filter capacitors and then converted to an oscillated AC output in an oscillator stage at a much higher frequency than the input supply. This high voltage/high frequency signal is then fed into a high efficiency transformer primary coil and high frequency AC current is produced in the secondary coil. The frequency can be anything from 5 kHz upward, depending on the design and type of output required.

Because of the high frequency AC generated by the oscillator, the weight of transformers can be reduced dramatically because there is no magnetic loss or heat loss through the windings, therefore much greater transformer efficiencies can be achieved.

Now that a high frequency, low voltage but high current power supply has been created, it can be used as high frequency AC welding power for MMAW or GTAW of aluminium. Alternatively, the AC can then be rectified into DC current again and passed through a second filtering system to produce a very smooth DC current flow. Welding machines with an output frequency of around 5 kHz demonstrate a characteristic whistling sound during welding.

Inverter welding machines have very good electronic controls that offer excellent control over the characteristics, voltage and current. They are also very efficient and highly portable, due to their reduced weight.
The inverter cycle

- mains current rectified to DC and stored
- DC is oscillated to high frequency
- HF/high voltage AC is transformed to low voltage AC
- AC rectified to produce DC
- DC filtered to smooth current.

Amperage control

If a welding operator draws current direct from a transformer with no form of current control, the welding current is fixed and will only be limited by the resistance of the arc, the welding leads and transformer characteristics. Current may be excessive and there will be no means of enabling the operator to select the correct setting for the job. Some method of current control is required if a machine is to be practical to use. Four common types of current control devices are described here.

Movable coil

This consists of a special arrangement in the transformer so that the distance between the primary and secondary windings may be varied, enabling the amount of current induced in the secondary coil to be varied.

Amperage is usually selected by winding a hand wheel or shifting a lever. This action moves the primary coil in the machine either closer to or away from the secondary coil, which is usually mounted on the machine base. The closer the two coils are together, the greater the magnetic force between them and consequently the higher the amperage. As the coils are moved further apart, efficiency is lowered — resulting in reduced current output.
Resistance

Electrical resistance in a circuit opposes the flow of current. By varying the resistance in the welding circuit, the amperage can be controlled. This is usually done by passing the current through one variable resistance coil, or a series of coils with fixed resistance. Resistance is inefficient where high currents are used, as large amounts of heat are generated.

Fig 11.6 – Moveable coil AC transformer
With machines as in Fig 11.7, amperage is selected by pushing in buttons to make contact with the appropriate resistance coil. Each coil allows only a certain amperage to flow through it. The more coils selected, the greater the amperage.

**Moving core choke**

This consists of a coil of wire or copper strip heavy enough to carry the welding current, which is wound around an iron core. This induces a counter-voltage that chokes back on the current flow. By adjusting the amount of iron within the coil, the amount of current can be controlled. The further the core is pushed into the coil, the greater the choking effect, consequently less amperage flow.

A strong magnetic field is also generated and this will tend to draw the core into the coil, so a locking device is necessary.
Reactors

Various forms of reactors are used to control welding current. By saturating the laminated iron core of the reactor with the magnetic flux of direct current, the available output alternating current is reduced. In DC circuits, the current passes through the reactor prior to being converted to DC in the rectifier section of the power source.

Silicon controlled rectifier (SCR)

Modern welding machines use silicon controlled rectifier (SCR) devices to provide a ‘one knob’ output control system. The SCR circuit is fitted into the transformer output circuit and is an electronic device that can be switched on and off at various points in the AC cycle. When this is coupled with a feedback circuit, the output voltage and current can be easily controlled. These machines can provide AC and/or DC current choice and may also offer constant current or constant voltage type output from the same machine.
Machine characteristic

Further to classifying welding machines as AC or DC, welding machines are also classified according to their characteristic output curve. Machines are classified as either:

- constant current (CC) – also known as drooping characteristic
- constant voltage (CV) – also known as constant potential of flat characteristic.

The machine characteristic is often referred to as the slope of the machine, as it can be seen that the output curve slopes downward.

![Volt/amp curves](image)

**Fig 11.11 – Volt/amp curves (a) constant current machines (CC), (b) constant voltage machines (CV)**

The curves on the above graphs represent the power output of each type of machine; they show voltage output at a given load amperage. It can be seen from the output curves that a change in arc voltage produces a change in the output amperage of the power source.

Some welding processes (such as GMAW) are intolerant of changes in arc voltage. Others (such as MMAW or GTAW) are intolerant of fluctuations in amperage. Because the arc length (electrical stick-out with GMAW) varies by natural movement of the operator’s hand during welding, resistance across the arc varies. An increase of arc length would cause an increase in arc voltage and a decrease in amperage. Shortening the arc length would have the opposite effect. These fluctuations in amperage and voltage are controlled by manufacturing machines which have the desired characteristic curve.

**Constant current machines**

Constant current machines translate fluctuations in arc length to changes in arc voltage and permit little change in the output amperage. This is desirable in hand held welding processes such as MMAW or GTAW where changes in arc voltage have little effect on welding, but fluctuations in amperage would make it difficult for the welding operator to control the welding process.
Constant voltage machines

Constant voltage machines are designed to hold the arc voltage steady and allow the amperage to fluctuate with minor variations in arc or stick-out length. In power feed processes such as GMAW, arc conditions are greatly affected by even small changes in arc voltage. Therefore, changes which would naturally occur in stick-out length with the movement of the operator’s hand are translated to fluctuations in amperage whilst holding the arc voltage constant. It should be noted that small variations in stick-out length will produce relatively large changes in amperage.

Variable slope machines

Some machines allow adjustment of the open circuit voltage, however not only does the OCV change but the slope (current response) of the machine changes also.

It can be seen from Fig 11.12 that when the maximum OCV is selected, the machine has the output curve associated with a constant current machine. When the minimum OCV is selected, a different output curve results. This slope is infinitely variable between the maximum and the minimum OCV. This type of machine is ideal for applications such as pipe welding, as it gives the operator the ability to control amperage by means of adjusting the arc length.

![Fig 11.12 – Typical volt-ampere curves possible with a variable voltage power source. The steep curve (a) allows minimum current change. The flatter curve (b) permits the welder to control current by changing the length of the arc](image-url)
Duty cycle

An essential factor in the performance of any welding machine is the machine duty cycle.

The duty cycle is the percentage of a five minute period that the machine can operate at the rated output amperage. It is important to realise that:

- the duty cycle rating may not be at the maximum current output of the machine
- semi-automatic and fully automatic processes may require that the machine be rated at or near 100%
- if the current required is higher than the amperage at which the machine is rated, the operating time will have to be reduced
- welding at an amperage lower than the amperage at which the machine is rated will enable the operating time to be increased
- simply reading the maximum output current on the dial of a welding machine is not a reliable indicator of the machine’s performance capability.

Example

A welding machine is rated at 60% duty cycle at 300 A on the front label.

The maximum amperage output of this machine is 350 A.

At 100% duty cycle the allowable amperage would be 232 A.

Selecting a welding power source

The choice of machine depends on three major factors:

- the type of work the machine is required to do
- the operating conditions – field or site work, shop work, power available
- the type of machine that satisfies type of work and operating conditions for the least cost.

There are six basic machine types commonly available. These are:

- AC transformers
- transformer rectifiers
- inverters
- motor generators
- independently driven generator
- engine driven generator.
AC transformers
These stationary machines require mains current to operate. They are cheap to buy and maintain and electrically efficient, but offer limited control of the welding current and restricted electrode choice.

Transformer rectifiers
These stationary machines provide AC/DC welding current from an AC main by means of a rectifier. They offer quiet efficient operation with virtually no moving parts. These machines are commonly used for GTAW and GMAW.
Inverters

Inverters also require mains primary current. Compared to other machines of similar current capacity they are compact, lightweight and provide a smooth DC output. They are commonly used as MMAW, GMAW and GTAW machines.

Operating Controls

1. Negative (−) dinse connection
2. Positive (+) dinse connection
3. Overload protection indicator
4. Welding current regulator
5. Main power switch and signal light
6. Carry strap
7. Selector switch for welding process
8. Machine body
9. Work clamp and cable
10. Electrode holder and cable

AC motor generators

An AC electric motor and a DC generator are built on a common shaft. The AC motor turns the shaft and direct current is produced in the generator section and output to the welding terminals. These machines offer smooth current with a choice of polarity. OCV small machines (typically to 300 A) are commonly used for MMAW and larger machines are commonly used to provide current for SAW.
Independently driven generator

These machines are normally purchased where a power take off (PTO) is available, such as those on a truck, tractor or 4WD. Welding current is then available wherever the host vehicle can go. Often this type of machine has a power pack built in to provide power for lights, drills, grinders and other equipment.

![Independently driven generator](image1)

Engine driven generator

These machines are DC generators or AC alternators with electronic control coupled to a diesel or petrol internal combustion engine. They are extremely portable and are commonly used for site construction work. These machines are equipped with governors to maintain constant engine speed and with idling devices to reduce engine speed when welding is not in progress. Most machines are water cooled, but machines with air cooled engines are available for light duty use. Initial cost and maintenance cost for machines of this type is high. Diesel engines cost more than petrol engines, but are more economical to run and maintain.

![Engine driven alternator](image2)
Chapter 12 – MMAW, arc conditions and electrodes

Introduction

Manual metal arc welding (MMAW) is one the earliest of the arc welding processes, but has remained in popular use despite the introduction of newer and more sophisticated processes. Indeed this lack of sophistication is one of the major attractions of the process.

In this chapter we will look at the following.

- The process
  - applications of the process
- Manual metal arc welding (MMAW) electrodes
  - AS/NZS 4854
  - AS/NZS 4855
  - AS/NZS 4856
  - AS/NZS 4857.
The process

- A low voltage, high amperage current flows to create an arc between the tip of the electrode and the workpiece. This generates the heat for welding and causes the workpiece and the tip of the electrode to melt.
- The flux coating on the electrode decomposes (burns) due to the intense heat of the arc and generates a gaseous shield which protects the weld pool and surrounding hot metal from the atmosphere.
- The electrode melts off and is transferred across the arc in the form of droplets. The molten metal provided by the electrode adds to the molten parent metal and they become the weld metal when solidified.
- Molten electrode flux that is transferred across the arc acts as a scavenger, picking up impurities from the surface of the parent metal. The slag that forms covers the weld pool, then solidifies and protects the hot weld metal as it cools.
- The flux constituents provide arc ionisation (the air gap between the tip of the electrode becomes electrically conductive), enabling the use of alternating current.

Applications of the process

Many welders have grown up using the MMAW process. This familiarity and the fact that it is simple to set up and use, make it first choice in many instances. The low cost of equipment makes the process accessible to most people and MMAW has no special requirements such as external gas shielding or high frequency arc initiation. Sound welds are easily produced and the process suffers from no tendency towards particular weld defects such as lack of fusion, which is common when using the gas metal arc welding process.
MMAW is widely used for:
- structural work
- pressure vessels
- piping
- maintenance welding
- site construction
- general fabrication.

**Advantages of the process**

One of the greatest advantages of the MMAW process is its versatility. A wide range of consumables is available. Set-up time for use is low, making the process ideal for small jobs, short production runs and where the welding is carried out on site.

MMAW offers many advantages over other welding processes, including:
- low capital cost for equipment
- versatility across a wide range of applications
- simple reliable equipment
- low maintenance of equipment
- ideal for site work
- wide operator appeal
- sound reliable welds.

**Limitations of the process**

Although faster than some welding processes, MMAW has lower deposition rates than many of the newer welding processes that employ higher current densities. The process has a low operator duty cycle with the welder spending much of his/her time changing electrodes and chipping slag. These two factors combine to limit the application of the process where high production rates are required.

**Equipment**

Equipment for manual metal arc welding consists of the following.
- A power source – Usually a constant current type output transformer or transformer rectifier is used, although various other types of power sources such as generators or inverters can also be used. The function of the power source is to supply welding current with sufficient amperage to provide the necessary heat, at a voltage that is safe to use.
- Electrode hand piece and lead – To carry current to the arc via the electrode.
- Work return lead – Connects the workpiece to the power source, thereby completing the welding circuit. A closed circuit is necessary for current flow.
Fig 12.2 – Manual metal arc welding equipment

**MMAW variables**

The major variables of the MMAW process are:

- amperage
- arc length
- travel speed
- angle of approach
- angle of travel.

Arc voltage is not considered to be a variable in the MMAW process, as this is essentially dependent on the electrode flux type and only varies from around 22–28 V.

**Amperage**

An increase in amperage will:

- increase the heat of the welding arc
- increase fusion and penetration
- give a higher deposition rate
- increase arc force
- enable easier arc starting
- give a more fluid weld pool
- increase spatter
- increase emission of ultraviolet radiation.
Fig 12.3 – Effects of amperage

A decrease in amperage will have the opposite effect.

As the size and thickness of the metal to be welded increases, so the heat required for fusion increases, necessitating higher amperages. Also, the higher the heat input the slower the cooling rate of the weld zone. Slow cooling rates are generally desirable when welding most metals.

A simple equation for welders is:

Voltage x amperage = heat.
Arc length

Arc length is fairly self regulating in MMAW, because of the constant current type output characteristics of the power source. An increase in arc length will, however, increase voltage slightly whilst current will remain relatively stable. The slight voltage increase will cause the arc width to increase and decrease overall heat into the weld area.

Typical arc length for MMAW is about equal to the electrode core wire diameter. Too long an arc will cause loss of metal transfer across the arc and lead to poor shielding. A short arc may cause the electrode to freeze into the weld zone.

Fig 12.4 – Effects of arc length
Travel speed

The ideal travel speed for MMAW is determined by where the arc (and thus heat) is positioned on the material surface, balanced by the weld size and shape required and finally where the molten flux is running in relation to the arc.

Travelling too fast will not allow sufficient arc time to heat and melt the parent metal. The electrode core wire will also not have enough time to be deposited in sufficient quantities to produce an even width and height. The resultant weld will be low in penetration and have a skinny, rope-like appearance.

Travelling too slow may allow the weld to run under the arc and therefore decrease heating and melting of the parent metal. The weld and slag may react with the arc and thus produce a rough looking weld that may also have slag inclusions.

Correct speed

Too fast

Too slow

Fig 12.5 – Effects of travel speed
Angle of approach

Another simple rule for welders is that the metal goes where you point the electrode. Following that rule, it can be seen in the fillet weld example below that to get an even weld build up, the electrode must be pointed evenly at both plates, ie 45° (half the angle). Also the welding arc is ‘directional’, ie metal transfer is essentially along the line of the electrode.

Unless attention is given to the angle of approach, defects such as slag inclusions, lack of fusion and penetration and unacceptable weld contours may result.

Angle of travel

The angle of travel is established essentially as a means of keeping the molten weld pool behind the arc and preventing the slag from catching up to electrode and causing slag inclusions. Although the angle of travel is commonly set at 70–80°, many factors such as amperage, electrode type and travel speed will determine the actual angle used.

It should be noted, however, that the angle of travel used should be the minimum required for slag control, as laying the electrode too flat causes problems such as poor appearance, excessive spatter, reduced penetration and a narrow, convex bead shape.
MMAW electrodes

The MMAW electrode consists of a core of wire surrounded by a flux coating. The wire is generally of similar composition to the metal to be welded. The flux is applied to the wire by the process of extrusion. For welding carbon and low alloy steels (the metals most commonly fabricated using the MMAW process), electrodes will have one of four flux types, which are:

- cellulose type coating
- rutile type coating
- hydrogen-controlled coating (low hydrogen)
- iron powder type coating.

AS/NZS 4855 covers the full range of coatings.

The flux coatings (from which the electrode types take their name) account for the major differences between electrode types.

The constituents of the flux coating are carefully controlled so as to give desirable running characteristics and weld metal properties.
Among these desirable running characteristics are:

- arc stability
- ease of striking
- elimination of porosity
- minimum spatter
- elimination of noxious fumes and odours
- a tough durable coating
- control of penetration
- high deposition rates
- desirable physical and mechanical weld metal properties.

The above list is by no means exhaustive and many characteristics are incompatible, eg deep penetration and minimum spatter. Therefore when choosing an electrode for use, compromises must be made. The choice of an electrode for a particular application depends upon:

- the composition of the parent metal
- the size and thickness of the parent metal
- the mechanical and physical properties required of the weld metal
- the welding position
- the amount of penetration required
- the amount of spatter allowable
- available welding current
- deposition rate required
- appearance
- cost
- slag detachability
- weld contour and size
- fluidity of the slag
- operator appeal.

Functions of the flux coating

In the early days of arc welding, bare wire electrodes were used. The results obtained from these electrodes left much to be desired. Over the years, electrodes have been improved and flux coatings have evolved to the stage where the deposited weld metal now in many cases has better metallurgical properties than the parent metal.

The flux coating of the electrode has many functions, among these:

- to provide a gaseous shield to protect the weld from atmospheric contamination
- to provide arc ionisation, which gives a stable arc and enables the use of AC to control the chemical composition and properties of the deposited weld metal and control the deposition rate
- to control spatter
- to influence the degree of penetration.
Additionally, it provides slag which performs several functions. The slag:

- forms a protective cover over the weld metal to prevent the formation of oxides while the weld metal is cooling
- acts as a scavenger to remove oxides and impurities from the weld
- helps to produce the correct bead shape and improve weld appearance
- slows the cooling rate of the weld metal
- enables 'positional' welding.

Some of the ingredients used in the flux are:

- wood pulp (cellulose), titanium dioxide (rutile), limestone, fluorspar, silica, feldspar – for producing slag and shielding gas
- ferro-manganese and ferro-silicon – used as de-oxidisers
- potassium and sodium silicates – used as binders
- clays and gums – used as binders
- ferro-chromium, ferro-molybdenum and nickel powder – for alloying
- iron powder and iron oxide – to increase deposition.

**Electrode coating types**

<table>
<thead>
<tr>
<th>cellulose (wood pulp base)</th>
<th>rutile (titanium dioxide)</th>
<th>basic (calcium carbonate)</th>
<th>rutile plus iron oxide</th>
<th>rutile plus iron powder</th>
</tr>
</thead>
</table>

As shown above, there are five basic electrode coating types used to make electrodes for the welding of carbon and low alloy steels. Reference should be made to AS/NZS 4855 for the full range of coatings.

These coating types are then arranged into four basic electrode types or groups, which are:

- cellulose
- rutile
- hydrogen-controlled
- iron powder.

The general characteristics for each of these groups are as follows. For the purpose of this text, only part of the ISO 2560-X classification has been shown.

**Cellulose type**

These electrodes contain a high percentage of alpha flock (wood flour) and from 3–7% moisture in the coating. This provides the fiery, deep-penetrating arc characteristic of cellulose electrodes. Cellulose electrodes run on low amperages compared to rutile electrodes (approximately 15% lower) and the thin, fluid slag does not completely cover the finished weld deposit. High spatter levels are produced and the weld appearance is characterised by coarse, uneven ripples.
Applications: Used for the first (root) run on pipes and plates, welding in the vertical position (particularly vertical down) and wherever deep penetration is required.

Storage conditions: Should contain 3–7% moisture for best results (do not store in electrode ovens).

**Rutile type**

These electrodes contain a high proportion of titanium-dioxide and are known as the general purpose group of electrodes. They are used for the general welding of low carbon steels and are suitable for use in all welding positions.

Rutile electrodes have a smooth running and stable arc, low to moderate spatter levels and moderate penetration. Most of them operate on AC or DC operation and have good appearance and easy slag detachability.

Rutile electrodes may also have small amounts of iron oxide added, to give them a fiery more penetrating arc.

Applications: Used for general purpose welding on most joint types and weld positions.

Storage conditions: Rutile electrodes have no special storage requirements. Storage in a warm dry place is sufficient.

<table>
<thead>
<tr>
<th>Electrode diameter</th>
<th>E4312</th>
<th>E4313</th>
<th>E4314</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6 mm</td>
<td>50–90</td>
<td>50–90</td>
<td>60–110</td>
</tr>
<tr>
<td>3.25 mm</td>
<td>90–140</td>
<td>90–140</td>
<td>95–150</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>130–190</td>
<td>130–190</td>
<td>140–200</td>
</tr>
</tbody>
</table>

**Table 12.1 – Approximate amperages for rutile electrodes**

**Hydrogen-controlled (low hydrogen) type**

These electrodes have coatings of calcium carbonate and are designed to produce low hydrogen levels in the deposited weld metal as a means of minimising cracking in the heat-affected zone. They are characterised by a globular transfer of metal across the arc, low penetration as a means of minimising weld metal dilution and fluid slag.

Applications: Hydrogen-controlled electrodes are used for welding high strength steels and produce tough, ductile weld metal with tensile strengths in excess of 480 MPa. Amperages used are similar to rutile electrodes, but they require a minimum of 60 OCV.

Storage conditions: Should contain less than 0.2% moisture. They are supplied in sealed packets or cans to prevent absorption of moisture from the atmosphere. Upon opening, the electrodes should be transferred to an electrode oven and conditioned at 300 °C for at least one hour before use. Once they have been conditioned (all moisture is driven off), they should be kept at a temperature of 100 °C minimum. They should be used ‘hot’ from the oven and not allowed to cool.
Iron powder/iron oxide

These electrodes have coatings that contain a high percentage of iron, in the form of iron powder and/or iron oxide. They are characterised by high deposition rates, smooth arcs, low spatter, good appearance and excellent slag detachability. The heavy flux coating necessitates that higher amperages be used than for other electrode types.

Applications: Electrodes containing iron powder in the flux coating are commonly used for structural welding of low carbon steels and are suitable for welding in the flat position only.

Care and storage of electrodes

The condition of electrodes can seriously affect the quality of the welded joint, particularly when dealing with alloy and high strength steels.

Types of electrode deterioration

The condition of covered electrodes may deteriorate due to the following types of damage to the electrode covering:

- excessive absorption or loss of moisture
- mechanical breakage of coverings
- formation of surface deposits
- contamination.

Excessive absorption or loss of moisture

During the manufacturing process, covered electrodes are dried to a predetermined moisture level, giving the optimum welding characteristics for that particular electrode. Hydrogen-controlled electrodes require the minimum of moisture; on the other hand, cellulose electrodes require up to 7% moisture.

The absorption of excessive moisture by the covering, either from the atmosphere, condensation, or from other sources, can give the following difficulties:

- weld metal porosity
- excessive spatter
- arc instability
- poor weld contour
- undercut
- difficulty with slag removal
- blistering of the flux coating, especially with cellulose types
- increased risk of lamellar tearing
- increased risk of hydrogen-induced cracking.

Mechanical breakage of coverings

Covered electrodes are reasonably robust, but the covering can be damaged by rough, careless handling or by excessive bending. Loss of covering leads to erratic arcing and inadequate protection of the molten weld metal. For this reason, it is good practice to discard electrodes with mechanically damaged coverings.
Formation of surface deposits
Electrodes that have been kept for long periods of time in non-ideal storage conditions usually form a white powdery deposit on the flux coating. This deposit is produced by a chemical reaction between the carbon dioxide in the atmosphere and the sodium silicate of the flux binder. This reaction forms crystals of sodium carbonate and silica powder. If there are heavy deposits on the covering, it is possible that rusting of the core wire has occurred, which may lead to hydrogen-induced cracking. Heavy surface deposits indicate that re-drying of the electrodes is required.

Contamination
The covering of electrodes can become contaminated by oil, grease, paint and other fluids through bad handling or storage practices. Some contaminants such as paint may introduce undesirable material into the weld or interfere with the welding process. Oil, for instance, is also a source of hydrogen and may lead to hydrogen-induced cracking.

Recommended practices
Deterioration of the types described can be prevented or sometimes corrected by adopting good practices in packaging, handling, transport and storage.

Storage of electrodes
Electrodes are supplied in sealed packets or cans to prevent absorption of moisture. They should be stored in a moisture-free environment that has a fairly even temperature. Electrode packets, cans and bulk packs should not be opened or unsealed until required for use.

Once the electrode container is opened, the following procedure should be adopted.
- Mild steel electrodes should be stored in a warm dry place.
- Cellulose electrodes must not be stored in an electrode oven.
- Hydrogen-controlled electrodes should be conditioned and stored in an electrode oven at 100 °C minimum.
- When obtaining electrodes from storage, they should be used in order of receipt. This method will ensure that electrodes do not remain in storage for any length of time.

Re-drying of electrodes
Re-drying of electrodes when their moisture content exceeds the recommended range should be carried out in accordance with the manufacturer’s specifications. Further to this, WTIA Technical Note 3 ‘Care and Storage of Manual Arc Welding Steel Electrodes’ provides guidance in this area.
- Electrodes other than hydrogen-controlled that are affected by excessive moisture content can be re-dried at 120 °C for approximately one hour.
- Hydrogen-controlled electrodes that are affected by excessive moisture content can be re-dried at 400 °C for half to one hour's duration. If facilities to carry out this procedure are not available, then drying for a minimum of one hour at 250 °C will suffice for most applications.
The re-drying or reconditioning of hydrogen-controlled electrodes is not recommended for critical welds.

Electrode classification

MMAW electrodes are classified under Australian Standard® AS/NZS 4855 – Welding consumables – covered electrodes for manual metal arc welding of non-alloy and fine grain steels – Classification.

This standard deals with the manufacture, testing, marking and packaging and classification of covered electrodes for manual metal arc welding.

The classification system of the code provides a mechanism for identification of the various electrodes and a description of the electrode and their characteristics and applications.

AS/NZS 4855 classifies electrodes using letters and numbers. An example of the full classification system using letters and numbers is available in Appendices 3 and 4 at the back of this book. This text deals with the classification system as per ISO 2560B.

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Approximately 0.1 x tensile strength in N/mm²</th>
<th>Flux type</th>
<th>Weld position</th>
<th>Welding current</th>
<th>Suffix</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>XX₁</td>
<td>XX₂</td>
<td></td>
<td></td>
<td>XX₃</td>
</tr>
</tbody>
</table>

The classification system consists of five letters and figures. To assist with the above explanation, the symbols X₁, X₂, X₃ etc are used to represent the variables.

E48

The first group of letters relate to the consumable. E stands for ‘electrode’. After E the two numericals XX1 refer to 1/10th of the minimum strength of the deposited weld, which is measured in Newton millimetres squared. This code only covers electrodes that are 430 or 490 N/mm².

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A second set of two-digit numbers XX2 are used to represent the flux type, the welding position or positions in which the electrode is capable of making satisfactory welds and the welding current to be used.

- Optional indicators relating to notch toughness grading, attainable diffusible hydrogen status and coating moisture absorption resistance.

A brief summary of the electrode types covered in AS/NZS 4855 follows in Table 12.2.
Welding position, current and covering

This table has been removed. It was reproduced from Table 4B on page 6 of AS/NZS 4855:2007.

Table 12.2 – Welding position, current and covering type from AS/NZS 4855

**EXX03 electrodes**

Electrodes of this type contain a mixture of titanium dioxide (rutile) and calcium carbonate (lime), so they share some characteristics of rutile electrodes with some characteristics of basic electrodes.
EXX10/11 electrodes (E4310, E4311, E4910)

Electrodes of EXX10 and EXX11 classification have thin coatings that contain at least 15% cellulose and up to 30% titania as rutile or titanium white.

Cellulose electrodes operate with a forceful, deeply penetrating spray-type arc with fairly high spatter. As a result of the decomposition of the cellulose material, a voluminous gas shield is formed around the arc region, protecting the weld metal from atmospheric contamination. The slag is very fluid, thin, friable and easily removed when cold but may not appear to completely cover the deposit.

These electrodes are readily used in all positions and are suitable for all types of welding on low-carbon steel. Special applications recommended for these electrodes involve changes in welding position during the running of the electrode (e.g., pipe welding in situ). Sizes larger than 5 mm are not generally used in all positions.

For optimum performance, the coating of these electrodes must contain 3–7% moisture. Operating characteristics will be adversely affected if excessive drying occurs.

Owing to the burnout of the coating and high spatter loss, maximum current values are limited. However, with current values near the maximum, these electrodes can be used for deep penetrating welds in the flat and horizontal positions (e.g., square butt joints).

EXX11 electrodes can be used with AC or DC current. EXX10 electrodes can only be used with DC. When operating on DC, positive polarity is preferred.

EXX12 electrodes (E4312)

EXX12 electrodes have thin coatings containing a high proportion of titania as rutile, titanium white or ilmenite.

These electrodes are designed to operate from AC or DC power sources. Electrode negative is the preferred polarity with DC. The arc is usually stable at low open circuit voltages.

They have a fairly viscous, full covering slag that is easily removed when cold, except perhaps from the first run of a deep V. The arc is quiet, medium penetrating and with low spatter.

These electrodes are recommended for general purpose use with structural fabrications and sheet steels. Due to the viscosity of the slag, some of these electrodes are suitable for vertical down welding.

EXX13 electrodes (E4313)

EXX13 electrodes have thin coatings containing a high proportion of titania as rutile, titanium white or ilmenite with the addition of basic materials to increase the fluidity of the slag.

These electrodes demonstrate the same arc characteristics as EXX12 electrodes and can be operated from AC or DC power sources.

Due to the fluid slag that the EXX13 electrode produces (more fluid than the other types of rutile electrodes), the EXX13 electrodes are more suitable for welding in the vertical up or overhead positions and are unsuitable for welding vertical down.
EXX14 electrodes (E4314)

EXX14 electrodes have medium-thick coatings containing a high proportion of titania white or ilmenite and sufficient iron powder to give metal recovery rates of 105–130% of the mass of the core wire melted.

The slag is fairly viscous, full covering and easily removed when cool. It is sometimes self releasing. The arc is medium penetrating and with low spatter.

These electrodes are successfully operated from AC or DC power sources including those with low open circuit voltages.

Due to the medium-thick coating containing iron powder, operating characteristics are improved, allowing touch welding to be carried out. Slag is not excessive and these types of electrodes are recommended for use in general shop and structural fabrication.

EXX15 and EXX16 electrodes (E4915, E4916)

EXX15 and EXX16 electrodes have coatings containing a high proportion of basic material such as limestone and fluorides such as fluorspar. The coating ingredients are specially selected for low hydrogen content and during manufacture the electrodes are baked at high temperatures to remove moisture.

EXX15 electrodes are designed to operate from DC power sources only. EXX16 can be operated satisfactorily on AC or DC, electrode positive being the preferred polarity for these electrode types.

The arc is quiet, medium to low penetrating with globular transfer of metal from the electrode to the weld pool and produces moderate spatter. The slag is very fluid, full covering and easily removed when cool.

These electrodes are particularly recommended for steels affected by underbead cracking. The virtual elimination of hydrogen from the arc atmosphere reduces the possibility of the defect occurring in difficult to weld steels such as medium and high carbon steels and low alloy high tensile steels. Tough, ductile welds are produced with these electrodes and by keeping the hydrogen content low, pre-heat and post-heat temperatures can be reduced. Other uses include the welding of highly restrained joints in heavy sections as the tendency for weld metal cracking is reduced and the welding of free machining (high sulphur content) steels as well as malleable cast iron.

It is recommended that as short an arc as possible be maintained in all positions of welding to prevent porosity and that the electrode be used in a properly dried condition.

EXX18 electrodes (E4918)

EXX18 electrodes have medium-thick coatings containing a high proportion of basic material such as limestone, fluorides such as fluorspar and sufficient iron powder to give metal recovery rates of 105–130% of the mass of the core wire melted. Manufacture of these electrodes is very similar to that of the EXX15 and EXX16 electrodes, ensuring low hydrogen content.

Deposition rates are higher than with EXX15 and EXX16, owing to the iron powder content and the extra thickness of the coating allows a higher current per corresponding core wire diameter to be used.

They are suitable for use with AC or DC, electrode positive being the preferred polarity.
EXX19 electrodes

Electrodes of EXX19 classification have coatings based on the mineral ilmenite and consequently have arc action and slag characteristics intermediate between the EXX12/13 titania types and the EXX20 iron/manganese oxide type.

The electrodes are characterised by a rather fluid slag. They provide deeper penetration than the EXX13 group and excellent radiographic quality weld metal. They are designed for use on AC or DC electrode negative or positive and are suitable for multi-pass welding steel up to 25 mm thick. Stable arc and good operational characteristics provide smooth even beads in all positions including the vertical (using the upward progression only). The weld metal has excellent ductility and crack resistance, with good impact properties.

EXX20 electrodes (E4920)

These electrodes have medium-thick coatings containing a high proportion of oxides and/or silicates of iron and manganese.

Using either AC or DC electrode -ve, a spray type arc is produced with medium to deep penetration according to the current being used. The slag is voluminous, completely covers the deposit and is honeycombed on the underside. The slag is easily removed even from the first run of a deep groove.

These electrodes are principally used for horizontal fillet and flat butt welds in heavy carbon steel plate where good penetration is required.

EXX24 electrodes (E4924)

EXX24 electrodes have thick coatings containing a high proportion of titania as rutile, titanium white or ilmenite and sufficient iron powder to give metal recovery rates in excess of 130% of the mass of the core wire melted.

Using AC or DC electrode -ve or +ve, these electrodes operate with a low to medium penetrating, smooth spray type arc with very low spatter. The slag is fluid, full covering and dense and when cool is self-releasing or easily removed.

Owing to the high iron powder content and increased coating thickness, high currents are required.

These electrodes are recommended for the high speed welding of low carbon steel in the flat and horizontal positions. A touch welding technique is normally used.

EXX27 electrodes (E4927)

EXX27 electrodes have thick coatings containing a high proportion of oxides and/or silicates or iron and manganese and sufficient iron powder to give metal recovery rates in excess of 130% of the mass of core wire melted.

They are similar to the EXX20 electrodes, but contain iron powder to increase deposition rates. They demonstrate similar arc characteristics and can be used with AC or DC current. Electrode negative is the preferred polarity.

Recommended usage of these electrodes is in the flat and horizontal fillet positions and they are particularly applicable to high speed welding of low carbon steel where good penetration and ease of deslagging are required. Touch welding techniques are usually employed.
EXX28 electrodes (E4928)

EXX28 electrodes have thick coatings containing a high proportion of basic material such as limestone and of fluorides such as fluorspar and sufficient iron powder to give metal recovery rates in excess of 130% of the mass of core wire melted. They operate with a medium penetrating spray type arc and low spatter. The slag is fluid, full covering and easily removed. Power sources can be either AC or DC, electrode positive being preferred.

These electrodes are restricted to use in the flat and horizontal positions and are generally used where large amounts of low hydrogen weld metal in heavy sections is required. Touch welding techniques are usually used.

As with all hydrogen-controlled electrodes, it is important to maintain a close arc to reduce the possibility of porosity and that the electrodes are used in a properly dried condition.

EXX48 electrodes

EXX48 electrodes demonstrate the same usability, composition and design characteristics as EXX16 and EXX18 respectively. In addition, these electrodes are specially designed for vertical down welding. Some electrodes of this type are designed to provide a flat to slightly concave fully loaded penetration bead without undercut on single V welding, such as in piping and pipelines.

EXX99 electrodes

The coating and running characteristics of electrodes in this classification are such that one or more features prevent their classification in any of the preceding classes.

Examples

E4818 – A1 C/Mo deposit: 0.12% C / 0.4–0.6% Mo

Note: all electrodes in this group are of similar composition and have an Al suffix.

E5518 – B2 Cr/Mo deposit: 1.0–1.5% Cr / 0.4–0.65% Mo / 0.05–0.12% C
E5515 – B4L Cr/Mo deposit: 1.75–2.25% Cr / 0.4–0.65% Mo / 0.05% C

Australian Standard® 4854

AS/NZS 4854 specifies requirements for corrosion resisting chromium and chromium nickel steel electrodes for MMAW. It covers electrodes in which the chromium content exceeds 10.5% and the nickel content does not exceed 50%. These are essentially stainless steels.

AS/NZS 4854 employs the letter ES for electrode; the AISI steel type of the core wire and a usability designation for the flux type.
An example of the full classification system (B classification) is shown below.

<table>
<thead>
<tr>
<th>Electrode</th>
<th>AISI steel type</th>
<th>Weld position</th>
<th>Flux type</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>X₁</td>
<td>X₂</td>
<td>X₃</td>
</tr>
</tbody>
</table>

The classification system consists of letters and figures. To assist with the above explanation, the symbols X₁, X₂, X₃ etc. are used to represent the variables.

**Australian Standard® AS/NZS 4856 and AS/NZS 4857**

The basic principles of classification AZ/NZS 4856 and 4857 are the same, however there are some important differences.

AS/NZS 4856 and 4857 classify electrodes using letters and numbers. See Appendices 5 and 6 in the back of this book for more details.
Chapter 13 – Welding alloy steels

Introduction

Steel is an alloy of iron and carbon or other additional elements. However, there are many types or groups of steels and many grades within each group.

Steels can be classified into two main groups: plain carbon steels and alloy steels.

In this chapter we will look at the following.

- Plain carbon steels
- Alloy steels
  - general oxy of low alloy steels
  - typical low alloy steels
  - high alloy steels.
Plain carbon steels

Plain carbon steels have different amounts of carbon added to produce changes to the mechanical properties.

The composition of plain carbon steel is:

- iron: nil
- carbon: 0.1–1.7% max
- phosphorous: 0.04% max
- silicon: 0.3% max
- sulphur: 0.04% max
- manganese: 0.8% max.

Plain carbon steels may also be divided into three groups according to carbon content:

- low carbon: 0.1–0.3% carbon
- medium carbon: 0.3–0.5% carbon
- high carbon: 0.5–1.7% carbon.

Carbon has the greatest effect of any of the alloying elements. It only takes relatively small changes in the carbon content of steel to bring about significant changes to the mechanical properties of the steel. The effect of increasing carbon content in low carbon steel is that it:

- lowers the melting point
- increases the tensile strength
- increases hardness
- increases hardenability
- reduces ductility
- reduces malleability
- reduces weldability.

Plain carbon steels are an extremely useful and economical group of steels. The major drawback of the plain carbon group of steels is the progressive reduction in ductility and weldability that accompanies increases in carbon content.
Alloy steels

Alloy steels are those where the mechanical properties of the steel are controlled by the addition of small amounts of carbon and the addition of other elements.

Alloy steels are divided into two basic groups:

- low alloy steels – where the total alloy content is less than 5%
- high alloy steels – where the total alloy content is greater than 5%.

Stainless steels and austenitic manganese steel are examples of high alloy steels in common use.

The major advantage of these steels is that we can bring about improvements in mechanical properties (such as hardness and tensile strength) without the accompanying lack of ductility that occurs when carbon alone is used to improve mechanical properties.

Further to this, we get a combination of desirable properties that the addition of each of the alloying elements brings.

For example, if we alloyed a steel with:

- chromium – to improve hardness, tensile strength and corrosion resistance
- nickel – to improve toughness and promote a fine grain structure
- molybdenum – to impart creep resistance,

we would finish up with a strong, tough, corrosion resistant, creep resistant steel.

Alloying elements in alloy steel

Some common alloying elements used in the manufacture of alloy steels and their effects are as follows.

Manganese (Mn)

Manganese is added to plain carbon steels to counteract the effects of the oxygen left over from the steel refining process (de-oxidiser). Manganese also combines with any residual sulphur to reduce hot shortness. When used in alloy steel, manganese slows down the transformation of austenite. Manganese will increase hardenability. When present in quantities between 11–14%, manganese maintains an austenite grain structure in steels at room temperature and confers the ability to work harden.

Chromium (Cr)

Chromium increases hardness and tensile strength without reducing ductility and increases corrosion resistance at both high and low temperatures.

Chromium alloyed steels retain their strength and resist scaling at high temperatures. Chromium increases hardenability and reduces weldability.

Nickel (Ni)

Nickel is a grain refiner and an austenite former. It improves tensile strength without reducing ductility, ie improves toughness. Nickel improves corrosion resistance.
Molybdenum (Mo)
Molybdenum will increase the hardenability of steels. It reduces temper brittleness of chromium steels and reduces the tendency towards creep (the slow stretching of a metal under stress at high temperatures). Molybdenum also raises the critical temperature in steel.

Vanadium (V)
Vanadium improves the mechanical properties of heat treated steels and can induce secondary hardening in high speed steels. Vanadium produces a fine grain structure and is also used to produce magnet steels.

Tungsten (W)
Tungsten enables steel to remain hard at elevated temperatures and is used in the manufacture of high speed steels.

Copper (Cu)
Copper helps steels to resist atmospheric corrosion and also brings about slight increases in tensile strength.

Cobalt (Co)
Cobalt imparts the quality of red hardness, ie steels may remain hard even though they are red hot.

Sulphur (S)
Sulphur improves the machinability of steels.

General weldability of low alloy steels
Low alloy steels are hardenable (most grades) and are therefore subject to possible cracking as a result of cutting and welding if correct procedures are not followed. The key to successful working and welding of these steels is:
- careful control of heat input
- selection of consumables
- suitable techniques and procedures.

Heat input
Alloy steels are hardenable and rapid cooling may lead to the formation of martensite in the HAZ adjacent to the weld. This can be controlled by:
- pre-heat
- taking advantage of the heat or controlling the heat input of the welding process.
Post-heat

The higher the heat input, the slower the cooling rate. As a general rule, slow cooling rates are desirable when welding low alloy steels.

Correct selection of consumables is desirable as most steels in these categories require the use of hydrogen-controlled welding consumables as a means of eliminating HAZ cracking. Electrodes are chosen which:

- deposit weld metal of similar composition to the base metal
- give the required tensile strength
- give the required impact properties.

For manual welding, electrodes conforming to the relevant standard are normally chosen. These electrodes will provide good ductility of the weld metal and also help minimise dilution.

The use of the following sound welding techniques and procedures can significantly improve the results obtained when welding steels in these groups:

- determine pre-heat requirements prior to flame cutting or welding
- ensure all flame-cut surfaces are clean, smooth and crack free
- ensure alignment and fit-up to close tolerances
- meet all conditions of pre-heat prior to tacking or welding
- make long convex tacks of sufficient throat thickness
- no arc strikes outside the weld preparation area
- use preparation and welding variables aimed at minimising dilution
- ensure removal of all moisture from the weld zone and consumables
- feather tacks.

**Do not** weld over broken tacks.

- deposit convex weld beads to allow for contraction
- use a suitable welding procedure and sequence
- maintain strict control over interpass temperatures
- clean thoroughly between runs
- ensure a smooth notch-free cover pass
- apply post-weld heat treatment as required.
Typical low alloy steels

The low alloy steel group is a particularly useful group of steels. Steels in this group possess excellent mechanical properties and are easy to work and weld. These metals also have additional properties which make them suited to particular applications. Typical low alloy steel types in common use are:

- carbon/manganese steels
- weather resistant steels
- quenched and tempered steels
- chrome/molybdenum steels
- nickel steels.

Carbon/manganese steels

These micro-alloyed steels containing from 0.5–1.8% manganese are manufactured to AS 1548 and are intended for use primarily in the fabrication of pressure vessels and boilers. These plates are silicon-aluminium killed (de-oxidised) and are supplied up to a maximum thickness of 150 mm. Plates may be supplied as rolled, or in the heat treated condition and are supplied with certificates of chemical analysis and mechanical testing.

The manufacturer produces the steel to more stringent quality requirements, ie the chemical composition is strictly controlled to much finer tolerances than is the case with mild steel. The manufacturer also carries out more stringent, non-destructive and destructive testing to ascertain the steel’s physical and mechanical properties. It also clearly identifies the steel with identifying numbers legibly marked on the plate.

The steel is supplied to the purchaser with a set of test certificates showing such things as the:

- purchaser’s order number
- identification code of the material
- process of manufacture
- ladle analysis in respect to all elements
- temperature at which tests are carried out to ascertain mechanical properties
- details of any heat treatment applied to the plate or test samples (if any).

Further to this, each plate shall be clearly identified with the:

- manufacturer’s name or identification mark
- grade designation
- plate or identification number
- direction of rolling.
Classification of steels to AS 1548:1995 – Steel plates for pressure equipment

Steels to AS 1548 are classified as follows.

**Example:** AS 1548 -5- 490 N L20

**Standard**

AS 1548 – Type – UTS-heat treatment – Impact properties

<table>
<thead>
<tr>
<th>Type</th>
<th>Steel</th>
<th>UTS</th>
<th>Heat Treatment</th>
<th>Impact Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>490</td>
<td>N</td>
<td>L20</td>
</tr>
</tbody>
</table>

- Silicon – aluminium fully killed, niobium-treated carbon-manganese
- 490 MPa specified minimum tensile strength
- Normalised
- Notch ductile at -20 °C

**Type** – steel is of two types:

- 5 = silicon-aluminium fully killed, niobium treated carbon-manganese
- 7 = silicon-aluminium fully killed carbon-manganese.

**UTS** – designates the minimum tensile strength in MPa.

- Grades:
  - 430
  - 460
  - 490

**Heat treatment**

- R = as rolled
- N = normalised (870–930 °C)
- A = as rolled (may be normalised)
- T = supplied as material by the TMCR process.

**Impact properties**

- Specifies notch toughness at a particular temperature:
  - H = high temperature (100 to 450 °C)
  - L = 0 °C or below
  - L20 = -20 °C.
Grades available – The grades available under AS 1548 are given in Table 13.1

This table has been removed.
It was reproduced from Table 1 on page 8 of AS 1548:1995.

Table 13.1 – Available grades to AS 1548:1995

Weather resistant steels (weathering steels)

These low alloy steels (alloyed with nickel, chromium and copper) are designed to give increased resistance to atmospheric corrosion. Additionally, they combine high strength with good weldability.

Minimum yield strength is 340 MPa (UTS 480 MPa) and corrosion resistance is four to seven times that of structural carbon steel. Whereas plain carbon steel will oxidise and eventually rust away if left unprotected, weather resistant steels develop a tough purplish oxide on the surface which protects the steel against further oxidation. Weathering steels are used for structural purposes, outdoor locations, offshore plant and for other applications such as transport equipment where the high strength-to-weight ratio can be used to advantage.

Weathering steels are readily weldable with both hydrogen-controlled and non-hydrogen-controlled electrodes. However, if the corrosion resistance of the weld metal is required to match that of the parent metal, an electrode containing 2.5% nickel should be used.

AS/NZS 3678 – Grade designation

Example: AS/NZS 3678 – WR 350/L0 – Mechanical properties grades

The grade designation of weather resistant steels is by:

- the prefix WR indicating weather resisting
- the specification of yield strength
- low temperature impact properties where appropriate.

Indicates weather resistant steel with 350 MPa minimum yield strength and impact tested at 0 °C.
Available grades are as follows:

- WR 350
- WR 350/L0.

**Example:** AS/NZS 3678 – A1006 – Analysed grades

- **Standard**
  - Aluminium-killed
  - Plain carbon steel
  - Specified carbon range

**Example:** AS/NZS 3678 – XK 1516 – Analysed grades

- **Standard**
  - Indicates major deviation in chemical composition
  - Silicon killed
  - Carbon manganese steel

**Chemical composition**

This table has been removed. It was reproduced from Table 1 on page 9 of AS/NZS 3678:1996.

**Table 13.2 – Chemical composition of weather resistant steels**
Mechanical properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>Minimum yield strength MPa</th>
<th>Minimum tensile strength MPa</th>
<th>Min % elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR350 &amp; WR350/L0</td>
<td>340</td>
<td>450</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 13.3 – Mechanical properties of weather resistant steels

Quenched and tempered steels

Quenched and tempered steels are high strength, low alloy steels, which as the name suggests are heat treated during manufacture. Quenched and tempered steels are available in both structural and wear resistant grades. The properties that result in these steels are a product of chemical composition and heat treatment.

Quenched and tempered steels offer several advantages over structural carbon steels.

- **High strength** – The tensile strength of quenched and tempered steels is about three times greater than that of structural carbon steel.
- **Corrosion resistance** – The atmospheric corrosion resistance of quenched and tempered steels is about three times that of structural carbon steel.
- **Toughness** – Quenched and tempered steels are tougher and in particular display good low temperature notch toughness.
- **Abrasion and impact resistance** – Some grades of quenched and tempered steel are heat treated to give high hardness with good abrasion and impact resistance. These grades are used as wear plates.
- **Economy** – For structural fabrication purposes, thinner sections of quenched and tempered steels can offer the same strength as much thicker structural carbon steel sections. Apart from the design advantages of lighter weight, thinner sections make handling easier and welding and cutting faster.

Applications

Quenched and tempered steels, because of their strength, toughness and lighter weight (reduced thickness), are being widely used for such fabrications as bridges, crane jibs, dump truck bodies, gas and liquid tanks and even the structural members for large buildings.

When supplied in the higher hardness grades, quenched and tempered steels are widely used in quarries, mines and ore treatment plants on components such as excavator buckets, ore chutes and wear plates.
Composition
The chemical composition of Bisalloy quenched and tempered steels is as follows.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Typical chemical composition %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Bisalloy 80</td>
<td>0.18</td>
</tr>
<tr>
<td>Bisalloy 320</td>
<td>0.18</td>
</tr>
<tr>
<td>Bisalloy 400</td>
<td>0.18</td>
</tr>
<tr>
<td>Bisalloy 500</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 13.4 – Chemical composition of Bisalloy quenched and tempered steels

Availability
Quenched and tempered steels are produced both in Australia and overseas. A brief list of manufacturers and their product name is given below.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bisalloy Steels</td>
<td>Bisalloy</td>
</tr>
<tr>
<td>Nippon Steel</td>
<td>Welten</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Sumiten &amp; Sumihard</td>
</tr>
<tr>
<td>Kawasaki Steel</td>
<td>Riverace</td>
</tr>
<tr>
<td>Kobe Steel</td>
<td>K-Ten</td>
</tr>
<tr>
<td>Nippon Kokan</td>
<td>Hiten &amp; Everhard</td>
</tr>
<tr>
<td>United States Steel</td>
<td>T1</td>
</tr>
</tbody>
</table>

Bisalloy Steels are produced in Australia and tend to be the most commonly encountered. These are followed closely by the USS T1 steels, due to the fact that machinery such as cranes and earthmoving equipment produced by American-based companies is common in Australia.

Common structural grades are:
- T1 A
- Bisalloy 60, 70, 80, 80PV
- Wel-Ten 60 and Wel-Ten 80c.

Common wear resistant grades are:
- Bisalloy 320, 360, 400 and 500
- Wel-Ten AR430 AR360C and AR500E.
Mechanical properties

The mechanical properties of Bisalloy steels can be seen in Table 13.5 below. Low carbon steel has been included for comparison purposes.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Quench °C</th>
<th>Temper °C</th>
<th>Yield strength MPa</th>
<th>UTS MPa</th>
<th>Elongation %</th>
<th>CE (IIW) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS/NZS 3678 250</td>
<td>-</td>
<td>-</td>
<td>250</td>
<td>410</td>
<td>22</td>
<td>0.44</td>
</tr>
<tr>
<td>AS/NZS 3678 350</td>
<td>-</td>
<td>-</td>
<td>350</td>
<td>450</td>
<td>21</td>
<td>0.48</td>
</tr>
<tr>
<td>Bisalloy 60</td>
<td>900</td>
<td>680</td>
<td>580</td>
<td>640</td>
<td>30</td>
<td>0.50</td>
</tr>
<tr>
<td>Bisalloy 70</td>
<td>900</td>
<td>640</td>
<td>670</td>
<td>760</td>
<td>28</td>
<td>0.50</td>
</tr>
<tr>
<td>Bisalloy 80</td>
<td>900</td>
<td>600</td>
<td>750</td>
<td>830</td>
<td>26</td>
<td>0.50</td>
</tr>
<tr>
<td>Bisalloy 320</td>
<td>900</td>
<td>400</td>
<td>970</td>
<td>1070</td>
<td>18</td>
<td>0.29</td>
</tr>
<tr>
<td>Bisalloy 500</td>
<td>900</td>
<td>175</td>
<td>1400</td>
<td>1640</td>
<td>10</td>
<td>0.40</td>
</tr>
</tbody>
</table>

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Table 13.5 – Mechanical properties of steels

Weldability

Quenched and tempered steels are readily weldable, particularly the structural grades. Quenched and tempered steels can be welded by a range of hydrogen-controlled welding processes. The most widely used are MMAW, FCAW, GMAW and SAW. The cooling rate of welds made with these processes is such that the mechanical properties of the weld are close to those of the parent metal. Welding processes with high heat inputs such as ESW or OAW are not recommended, as excessive heat input will destroy the mechanical properties. Most manufacturers supply data that can be used to help predict the pre-heat required for a given heat input. Maximum allowable heat input and interpass temperatures are also given.

Quenched and tempered steels are hardenable and rapid cooling will cause a loss of ductility and possible cracking in the weld zone. Above 12 mm plate thickness pre-heat should be considered. Hydrogen-controlled consumables should always be used.

Fabrication and welding techniques for quenched and tempered steels

- Flame-cutting – Pre-heat to 100–200 °C max is required where flame cutting is carried out in very cold conditions (below 10 °C) or in heavy plate thickness. Flame-cut edges should be inspected for cracking.
- Gouging – Flame gouging of quenched and tempered steels is not recommended, due to the high heat input. Air-arc gouging is the preferred method.
- Poor fit-up is to be avoided.
- Close control of heat input and interpass temperature must be exercised.
- Minimise joint restraint when welding.
- Allow for shrinkage, or use a more ductile filler material.
- Stringer beads are preferred when welding. When weaving techniques are employed, the maximum width of the weave should be two times the electrode diameter.
Chrome/molybdenum steels (Cr/Mo)

Chrome/molybdenum (or chrome/moly as they are more commonly known) are also known as creep resisting steels. Creep is the slow yielding (or stretching) of a metal at high temperatures, even though the stresses involved are below the yield strength of the material. The addition of molybdenum as an alloying element imparts creep resistance to steel to counteract this tendency.

Chrome/moly steels have excellent mechanical properties. The high strength-to-weight ratio of these steels makes them ideal for applications where a combination of high strength and light weight are needed. Such applications are aircraft frames, race car chassis and motorcycle frames. Pipes and tubing are by far the greatest application for this product. Processing plants, refineries, power stations and other locations which transmit fluids at high temperatures and/or pressures make extensive use of chrome/moly piping.

Commonly encountered chrome/molybdenum steels are given in Table 13.6.

<table>
<thead>
<tr>
<th>Popular name</th>
<th>C</th>
<th>Nb</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>½ Cr - ½ Mo</td>
<td>0.10–0.20</td>
<td>0.30–0.60</td>
<td>0.10–0.30</td>
<td>0.50–0.81</td>
<td>0.44–0.65</td>
</tr>
<tr>
<td>1 Cr 0 - ½ Mo</td>
<td>0.15 max.</td>
<td>0.30–0.60</td>
<td>0.50 max.</td>
<td>0.80–1.25</td>
<td>0.44–0.65</td>
</tr>
<tr>
<td>1¼ Cr - ½ Mo</td>
<td>0.15 max.</td>
<td>0.30–0.60</td>
<td>0.50–1.00</td>
<td>1.0–1.50</td>
<td>0.44–0.65</td>
</tr>
<tr>
<td>2 Cr - ½ Mo</td>
<td>0.15 max.</td>
<td>0.30–0.60</td>
<td>0.50 max.</td>
<td>1.65–2.35</td>
<td>0.44–0.65</td>
</tr>
<tr>
<td>2¼ Cr -1 Mo</td>
<td>0.15 max.</td>
<td>0.30–0.60</td>
<td>0.50 max.</td>
<td>1.90–2.60</td>
<td>0.87–1.13</td>
</tr>
</tbody>
</table>

Table 13.6 – Common Cr/Mo steels

Weldability

As the alloy content of Cr/Mo steels increases, so does the hardenability and the tendency towards cracking. These steels should be welded using hydrogen-controlled processes that deposit weld metal of similar composition to the parent metal. MMAW electrodes are classified in AS/NZS 4855 and have a ‘B’ suffix denoting a chrome/moly weld metal composition. GMAW wire would have a similar suffix.

Pre-heating and interpass temperature control is also employed, in addition to post-heat treatment (stress relieving), when welding creep resisting steels. Also, the completed weld joint is usually subject to stringent non-destructive testing; ie radiography, ultrasonic testing and/or dye penetrant testing. Non-destructive testing is generally carried out after post-weld heat treatment.

Nickel steels

As an alloying element, nickel enables ductility and toughness to be maintained in steels, even at very low temperatures. Consequently, the major use for nickel steels is for cryogenic applications (storage vessels for liquified gases). The cryogenic steels described are intended for use below -60 °C.
The commonly recognised grades are:

- **3½% nickel** – for service temperatures -60 °C to -80 °C
- **5% nickel** – for service temperatures down to -160 °C
- **9% nickel** – for service temperatures down to -196 °C.

The 3½% and 5% nickel grades are not commonly encountered as they have little cost advantage over 9% nickel steels, which have lower service temperatures and superior mechanical properties.

**9% nickel steels**

9% nickel steels are in common use in storage vessels for LNG (-164 °C) and for liquid oxygen and nitrogen (-196 °C).

9% nickel steel is available as quench and tempered – **QT** and double-normalised and tempered – **NNT**. Available grades are as follows.

<table>
<thead>
<tr>
<th>ASTM type</th>
<th>Tensile strength</th>
<th>Yield strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>A353 – QT</td>
<td>689–827 MPa</td>
<td>517 MPa</td>
</tr>
<tr>
<td>A553 – NNT</td>
<td>689–827 MPa</td>
<td>586 MPa</td>
</tr>
</tbody>
</table>

Table 13.7 – Available 9% nickel steels

**Fabrication and welding of 9% nickel steels**

9% nickel steel can be formed hot or cold. It is readily flame-cut and weld preparation can be applied by flame-cutting or machining. Flame-cut surfaces are usually ground, to remove the shallow layer of overheated steel that results.

9% nickel steel does not suffer from hardening of the HAZ and is readily weldable. It can be welded without pre-heat up to at least 50 mm of plate thickness by the common arc welding processes.

The surface oxide melts at a temperature 600 °C higher than that of the base metal and should be removed by grinding, followed by degreasing, prior to welding.

The most commonly used consumables are of the NiCrMo type and interpass temperatures should be kept low.

**High alloy steels**

High alloy steels are steels where the total alloy content exceeds 5%. The groups most commonly encountered by the fabricator are:

- stainless steels
- austenitic manganese steel.
Stainless steels

Stainless steels are essentially iron/chromium alloys where the chromium content exceeds 10.5%. The iron content is greater than that of any other element and the carbon content is purposely kept low to control carbide precipitation. The chromium oxides, which form rapidly on the surface and are self-healing if damaged, render the metal impervious to further corrosive attack.

There are various types and grades of stainless steel, aimed at providing corrosion resistance over a wide range of applications.

Stainless steels are divided into four main groups:

- **austenitic**
- **ferritic**
- **martensitic**
- **ferritic/austenitic duplex alloys.**

Stainless steels are classified under a three digit classification system established by the American Iron and Steel Institute (AISI). This is:

- 200 series – non-hardenable austenitic
- 300 series – non-hardenable austenitic
- 400 series – hardenable martensitic or non-hardenable ferritic.

Austenitic stainless steels are also commonly referred to by their chromium and nickel content, eg 18/8 or 20/12. The approximate chromium content is always stated first, followed by the nickel content.

**Austenitic stainless steels**

These are the most commonly fabricated grades and are consequently of the most importance to the welder. They:

- are essentially non-magnetic and thereby easily distinguished
- are by far the most widely used (18/8 type stainless steel alloys)
- have high strength
- have excellent weldability relative to other high alloy steels (except the free machining types)
- do not harden by heat treatment
- can be cold worked to a high degree of hardness
- may be annealed by heating to 1040–1120 °C and quenching
- have good resistance to scaling at high temperatures
- have a high rate of thermal expansion
- have low thermal and electrical conductivity
- range in analysis from 16–26% chromium and 6–22% nickel.
Weldability of austenitic stainless steel

Factors that limit the weldability of austenitic stainless steel are:

- the tendency of the weld metal, weld fusion line, or HAZ towards hot cracking
- the precipitation of chromium carbide, leading to intergranular corrosion (weld decay)
- the formation of undesirable structures (e.g., sigma phase) within a certain range of temperatures and chromium concentrations.

Cracking occurs when cooling from high temperatures and follows the boundaries of the dendrites as solidification progresses. Cracks can affect a large part of the weld zone. Austenitic stainless steels are sensitive to micro-cracking of the grain, however this sensitivity decreases if there is ferrite present in the microstructure. Ferrite is needed to minimise micro-cracking, however > 3% ferrite is desirable to completely eliminate micro-cracking of the grain structure.

Various diagrams such as the Schaeffler diagram and the DeLong diagram have been used to predict levels of ferrite in deposited weld metal.

Intergranular corrosion (weld decay)

The carbon present in austenitic stainless steels is normally dissolved within the grains. However, in the range from 500–900 °C the carbon forms chromium carbides along the grain boundaries (chromium has a higher affinity for carbon than iron). Chromium carbides are themselves not corrosion resistant. Additionally, the material along the grain boundaries is depleted of chromium, leaving it subject to corrosive attack.

This form of corrosion is generally known as intergranular or intercrystalline corrosion. When associated with the weld HAZ, it is normally called weld decay (see Fig 13.1).

There are two methods of reducing the occurrence of weld decay.

- The production of steels with extra-low carbon content (about 0.03%), which reduces the amount of carbide formed. These steels are designated with an ‘L’ suffix, e.g., 316L.
- The addition of stabilising elements. These elements have a higher affinity for carbon than does chromium. They combine with the carbon present, leaving the chromium free to form the chromium oxides that provide corrosion resistance. The most commonly used stabilising elements are molybdenum (Mo), titanium (Ti) and niobium (Nb).

For information regarding the types and properties of common austenitic steels, visit the website of the American Iron and Steel Institute (AISI) at <www.steel.org>.
Sigma phase precipitation

When steels containing high concentrations of chromium are subjected to prolonged heating at 600–900 °C, some of the chromium forms an intermetallic compound (FeCr) with iron. This compound is extremely brittle and leads to cracking, particularly in heavy, multi-run weldments, or when heat treatment is carried out. The remedy is to ensure quick cooling between runs.

Recommendations for welding austenitic stainless steels

Welding procedures for stainless steels differ dramatically from those used for carbon and low alloy steels. Whereas carbon and low alloy steels suffer from cracking problems largely attributed to rapid cooling, austenitic stainless steels do not generally cold crack, but are subject to hot cracking. Additionally, high levels of weld shrinkage contribute to the problem and it is essential that convex beads are always employed and that craters are always filled.

Austenitic steels should not be held at elevated temperatures for any period of time. Rapid cooling, rather than causing cracking, actually improves toughness.

Welding procedures for stainless steel should be designed to combine cleanliness, low heat input, rapid cooling and distortion control.

- Use matched filler and hydrogen-controlled process.
- Low heat input – high travel speeds, low currents, stringer beads, low interpass temperatures.
- Ensure good fit-up.
- Allow for approximately 50% more distortion than for carbon steel.
- Tack at intervals half of those used for mild steel.
- Use feather tacks.
- The weld area must be clean. All possible sources of carbon pick-up must be removed. Use iron-free grinding disks.
- Use sequence welding, chill bars or jigs to minimise distortion.
- Use a short arc length to reduce the loss of alloying elements.
- Fill craters.
- Avoid heat build-up.
- Ensure rapid cooling.
Consumables

There is a wide range of austenitic welding consumables available. In general, consumables are chosen that give weld deposits which match the base metal chemistry. If in doubt, consumables slightly richer in nickel and chromium should be selected. Higher grade consumables should also be used where dilution may reduce the corrosion resistance, or increase the hardenability of the steel. For selection of stainless steel consumables see Table 13.8.

<table>
<thead>
<tr>
<th>AISI steel type</th>
<th>Filler metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>308</td>
</tr>
<tr>
<td>302</td>
<td>308</td>
</tr>
<tr>
<td>303</td>
<td>312</td>
</tr>
<tr>
<td>304</td>
<td>308L</td>
</tr>
<tr>
<td>304L</td>
<td>308L, 347</td>
</tr>
<tr>
<td>305</td>
<td>308</td>
</tr>
<tr>
<td>309</td>
<td>309L</td>
</tr>
<tr>
<td>310</td>
<td>310L</td>
</tr>
<tr>
<td>316</td>
<td>316</td>
</tr>
<tr>
<td>316L</td>
<td>316L</td>
</tr>
<tr>
<td>316Ti</td>
<td>318, 316ND</td>
</tr>
<tr>
<td>317</td>
<td>347</td>
</tr>
</tbody>
</table>

Table 13.8 – Recommended filler material

Ferritic stainless steels

Ferritic stainless steels contain between 13% and 30% chromium (typically around 16%) and less than 0.15% carbon. When heated, there is no transformation to austenite, the grain structure is essentially ferrite at all temperatures up to the melting point. The relationship between the chromium content and the carbon content is important in maintaining a ferritic grain structure.

Ferritic stainless steels have been developed in what are essentially three generations. The first generation are almost never fully ferritic, due to the comparatively high levels of carbon present. Steels in this group are as follows.

Typical composition – First generation

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>430</td>
<td>0.08% C</td>
<td>17% Cr</td>
</tr>
<tr>
<td>442</td>
<td>0.20% C</td>
<td>21% Cr</td>
</tr>
<tr>
<td>446</td>
<td>0.25% C</td>
<td>25% Cr</td>
</tr>
</tbody>
</table>
The second group are the relatively inexpensive, stabilised ferritic stainless steels. This group comprises the following.

**Typical composition – Second generation**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>405</td>
<td>0.05% C</td>
<td>13% Cr</td>
<td>0.2% Al</td>
<td></td>
</tr>
<tr>
<td>409</td>
<td>0.05% C</td>
<td>11% Cr</td>
<td>0.5% Ti</td>
<td></td>
</tr>
</tbody>
</table>

Commonly used for auto exhaust systems – especially 409. It is usually welded with a low heat input and matching filler using the GMAW process, or when in sheet form, by resistance welding.

The newest group are the modern, low interstitial ferritics or so-called 'super ferritics'. Steels in this group are as follows.

**Typical composition – Third generation**

<table>
<thead>
<tr>
<th>Type</th>
<th>C</th>
<th>N</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>18–2</td>
<td>02</td>
<td>.02</td>
<td>18</td>
<td>2.0</td>
<td>–</td>
<td>.25Ti, .3Nb</td>
</tr>
<tr>
<td>26–1</td>
<td>003</td>
<td>.008</td>
<td>26</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sea cure</td>
<td>.01</td>
<td>.025</td>
<td>26</td>
<td>3.0</td>
<td>2.5</td>
<td>.4Ti</td>
</tr>
<tr>
<td>29–4</td>
<td>.005</td>
<td>.01</td>
<td>29</td>
<td>4.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>29–4–2</td>
<td>.005</td>
<td>.01</td>
<td>29</td>
<td>4.0</td>
<td>2.0</td>
<td>–</td>
</tr>
</tbody>
</table>

These steels have outstanding corrosion resistance, particularly to chlorides, which cause problems for the austenitics.

**Weldability of ferritic stainless steels**

Ferritic stainless steels are non-hardenable, but are embrittled by grain growth and secondary phases that form in the grain, such as sigma phase.

Generally speaking, the weldability of the ferritic stainless steels can be described as fair when compared with austenitic stainless steels. The grain growth problem can be minimised by ensuring low heat input.

For best results when welding ferritic stainless steels, the following general procedures may be adopted:

- pre-heat to 120–200 °C
- low heat input to limit grain growth
- slow cooling from 450 °C to room temperatures.

Where full corrosion resistance is required, full annealing at 800 °C will be necessary.
Consumables

Ferritic stainless steel consumables are available, however they produce welds of low ductility. For this reason, austenitic stainless steel consumables are generally used, as they ensure ductile weld metal in the as-welded condition.

When the use of austenitic consumables is contemplated, consideration should be given to the following.

- They will have no effect on possible corrosion in the HAZ.
- Problems may be encountered with colour match and differences in thermal expansion.
- PWHT can cause weld metal embrittlement and corrosion susceptibility, unless stabilised electrodes are used.

Martensitic stainless steels

Martensitic stainless steels contain 13–17% chromium and 0.1% carbon or above. Chromium in excess of 17% tends to form excessive ferrite in the grain structure.

These steels have good corrosion and oxidation resistance and good high temperature strength up to 600 °C. Their rate of thermal expansion is similar to that of mild steel and some grades may be fabricated by welding.

Common martensitic grades are as follows.

<table>
<thead>
<tr>
<th>Grade</th>
<th>%C</th>
<th>%Cr</th>
<th>%Ni</th>
<th>%Mo</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>403</td>
<td>0.10</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>410</td>
<td>0.10</td>
<td>12</td>
<td>0.5</td>
<td>-</td>
<td>turbines</td>
</tr>
<tr>
<td>410 NiMo</td>
<td>0.04</td>
<td>12</td>
<td>4.0</td>
<td>0.5</td>
<td>turbines</td>
</tr>
<tr>
<td>420</td>
<td>0.20</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>steel mill rolls</td>
</tr>
<tr>
<td>440A</td>
<td>0.70</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td>blades for shears or where abrasion resistance is required</td>
</tr>
<tr>
<td>440B</td>
<td>0.90</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>440C</td>
<td>1.10</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Weldability of martensitic stainless steels

Martensitic stainless steels may be supplied in a variety of heat treated forms, from fully annealed, to fully hardened and tempered. Irrespective of the condition, welding will create a hardened, martensitic HAZ. The hardness of this zone will depend on the carbon content and susceptibility to cracking will increase accordingly. Normally, steels with less than 0.15% carbon such as 403 and 410 will not require PWHT, whereas those above 0.15% carbon, such as 420 or 440, should be post-weld heat treated to ensure freedom from cracking.

Welding procedures for these steels usually involve pre-heat to 250 °C, except where the carbon content is less than 0.1%. The maximum interpass temperature for all grades is 350 °C and where the carbon content exceeds 0.15%, PWHT at 650–700 °C is recommended.
Consumables

Martensitic consumables such as E410 and E420 are available. However, the weld metal lacks toughness, so austenitic consumables such as E308 are generally used. Austenitic consumables produce welds of lower strength and greater ductility. These steels are susceptible to hydrogen induced cracking and austenitic consumables also help in this regard, keeping the hydrogen in solution.

Duplex alloys

Ferritic/austenitic stainless steels contain 18–28% Cr, 4.5–8% Ni and 2.5–4% Mo. In these steels there is insufficient nickel to produce a fully austenite grain structure and a mixture of ferrite and austenite results.

Basic properties

- High resistance to stress corrosion cracking.
- Higher tensile strength than austenitic or ferritic stainless steels.
- Good formability and weldability.

These steels are commonly used where chloride concentrations are high, as a means of minimising stress corrosion cracking.

Duplex alloys are generally specified by proprietary names, eg SAF 2205.

Austenitic manganese steel

As discussed previously, manganese is used in carbon/manganese steels which are used primarily for the construction of pressure vessels. These steels contain manganese in the range of 0.5–1.7%.

If manganese is added to steel in the range of 11–14%, a steel called ‘austenitic manganese steel’ is formed, so called because when manganese is within the range of 11–14%, the grain structure remains in the austenite condition at ambient temperatures.

Composition

The composition of manganese steel is as follows.

- Carbon 1.00–1.40%
- Manganese 11–14%
- Silicon 0.30–1.00%
- Sulphur 0.60% max
- Phosphorus 0.10% max.

Austenitic manganese (11–14%) steel, when quenched in water from temperatures around 1050 °C, is soft but very strong and ductile. It is readily work hardenable and has the ability to form a hard, wear resistant surface when pounded, scraped or cold worked in any manner. This property of maintaining a tough ductile interior with a work hardened surface makes it ideal for applications such as wearing parts of earth moving and crushing equipment.
Austenitic manganese steel can be identified by its non-magnetic properties (it may become slightly magnetic due to cold working) and a bright bushy spark when touched on a grinding wheel.

To join austenitic manganese steel by welding, the electrode recommended is 18/8 chrome/nickel (stainless steel). For building up worn parts, an electrode depositing 11–14% manganese can be used.

**Weldability**

The following precautions should be taken during welding.

- Deposit short welds – well dispersed to affect rapid cooling. Use the smallest gauge electrode and lowest welding current consistent with adequate fusion.
- Allow the parent metal to cool between runs – it can be quenched or cooled with wet rags. The body of the component should not be hotter than can be borne by the bare hand, before depositing another run.
- To reduce cracking due to contractional stresses, peen each weld bead as it is completed.
- Do not let manganese steel cool slowly from high temperatures.

Manganese steel as cast is brittle, it will return to this embrittled state following slow cooling from high temperatures. Toughness and ductility can be restored by quenching from 1050 °C.

**Note**

Austenitic manganese steel must be arc welded and pre-heating must be avoided, otherwise it will become brittle. It can be cut with the oxy-acetylene gas flame without any serious hardening effect on the cut surface. It is suggested however, that oxy-cut surfaces be ground prior to welding.

Hard-facing electrodes with a carbon steel core must never be deposited straight onto manganese steel. The manganese steel must first be buttered with an electrode depositing 18/8 stainless steel. Otherwise, the carbon steel weld metal will be diluted by the parent metal, resulting in extremely brittle welds.

**MMAW of austenitic stainless steel**

Although GMAW and GTAW springs readily to mind in discussion on welding stainless steels, MMAW produces highly satisfactory results, particularly in heavy sections. Electrodes generally require a minimum of 60 OCV, and DC -ve is the preferred current. Provided the following welding recommendations are adhered to, sound welds will generally result.
Welding of stainless steel clad steels

Where corrosion resistance is only required on one side of the plate (for example in a storage vessel), stainless clad steels are commonly selected for use. Stainless clad steels are produced by bonding a thin sheet of stainless steel to a sheet of carbon steel via the rolling process. The cladding is usually of the 18/8 or 18/10 stainless steel types and usually represents 10% to 20% of the total plate thickness.

Advantages of stainless clad steel

- Cost – the cost of clad steels is cheaper than stainless steels of the same thickness.
- Distortion – distortion levels are similar to carbon steels.
- They can be oxy-cut from the carbon steel side.

Welding procedure

The mild or alloy steel backing should be welded first, making sure that the root run does not come in contact with the stainless cladding. This can be achieved either by welding with a fairly close butt weld preparation and a large root face, or by cutting the cladding away from both sides of the root.

After the welding of the steel backing has been completed, the back is grooved out by grinding or carbon-arc gouging. The first run on the clad side is welded with a stainless steel of matching composition and with minimum dilution. A more highly alloyed electrode (such as a 25/20) is often desirable to overcome the effect of dilution. The remainder of the joint is completed with an electrode of matching composition.

For the best corrosion resistance, at least two layers of stainless steel weld metal are recommended. If the cladding is thin and it is only necessary to deposit a single layer, it would be best to use an electrode of higher alloy content.
Fig 13.2 – Weld procedures for clad materials
Chapter 14 – Non-ferrous metals

Introduction

Non-ferrous metals are metals that contain no iron at all, or those in which iron forms only a minor part of the alloy.

Aluminium and copper are typical non-ferrous metals that are widely used in the metal fabrication industry in their alloy form. Aluminium is very abundant on earth in its raw form of aluminium oxide (bauxite). The process used to convert bauxite to aluminium is, however, very expensive. In spite of this, aluminium and its alloys can offer significant advantages over steel when used in specific applications.

The major groups of non-ferrous metals commonly encountered by the fabricator are:

- aluminium and its alloys
- copper and its alloys
- nickel and its alloys
- titanium alloys.

In this chapter we will look at the following.

- Aluminium and its alloys
  - classification of aluminium alloys
  - weldability of aluminium alloys
- Copper and its alloys
- Nickel and its alloys.
Aluminium and its alloys

The material commonly referred to as aluminium encompasses a wide range of aluminium and aluminium alloys, whose properties vary remarkably. While pure aluminium is soft, weak and ductile, some aluminium alloys have mechanical properties that are superior to those of steel.

Properties of aluminium

Density – Aluminium has a density of 2700 kg/m³, i.e., approximately one-third the density of steel. Aluminium is widely used in applications where weight is a factor.

Melting point – The melting temperature of commercially pure aluminium is 660 °C. Alloying (particularly with silicon) lowers the melting temperature of aluminium, with most commercial alloys melting in the range of 520–650 °C.

Corrosion resistance – Aluminium resists atmospheric corrosion and is resistant to corrosion by some other media. This corrosion resistance is gained by the formation of a tough oxide that forms on the surface of the metal. The melting temperature of this surface oxide is 2040 °C.

The oxide must be removed prior to welding; this is usually accomplished by vigorous brushing with a stainless steel wire brush and the action of the welding arc when the polarity is electrode positive.

Tensile strength – The tensile strength of pure aluminium is around 90 MPa UTS (mild steel 300–450 MPa). However, this can be improved substantially by alloying and/or heat treatment. By this means the tensile strength can be raised to in excess of 700 MPa.

Electrical conductivity – Aluminium is second only to copper among the commercial metals in electrical conductivity. Where:

- Cu = 100
- Al = 60
- mild steel = 10
- stainless steel = 2.

Thermal conductivity – The thermal conductivity of aluminium is about five times that of mild steel. While this makes it suitable for applications such as heat exchangers, this property tends to lead to lack of fusion defects when welding.

Co-efficient of thermal expansion – The co-efficient of thermal expansion of aluminium is 0.000026, i.e., for each °C of temperature it rises or falls, it will expand or contract that fraction of its length. This is twice as much as for mild steel (0.000012).

Hot shortness – Aluminium alloys lack ductility at elevated temperatures. This, combined with high thermal expansion, tends to cause hot cracking when welding.

Hydrogen solubility – Aluminium will dissolve substantial amounts of hydrogen in the molten state. Upon cooling, this hydrogen is forced out of solution, resulting in weld porosity. For this reason it is essential that weldments be cleaned thoroughly prior to welding and that there is no possibility of hydrogen being introduced via the welding process or consumables.

Colour change – Unlike many metals, aluminium does not change colour when heated; neither does the surface oxide change colour.
Identification of aluminium

Aluminium can be identified from other metals by testing, as follows.

<table>
<thead>
<tr>
<th>Test</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetism</td>
<td>non-magnetic</td>
</tr>
<tr>
<td>spark test</td>
<td>non-sparking</td>
</tr>
<tr>
<td>colour</td>
<td>silvery-white</td>
</tr>
<tr>
<td>weight</td>
<td>lighter than cast iron, steel lead, tin, zinc alloys</td>
</tr>
<tr>
<td>grain structure</td>
<td>uniform light grey grains</td>
</tr>
<tr>
<td>oxy flame test</td>
<td>does not ‘flare’</td>
</tr>
</tbody>
</table>

Aluminium is often difficult to distinguish from zinc die castings and magnesium alloys. However, zinc die cast when fractured often exhibits shiny pores (fish eyes) in its grain structure, and magnesium filings ‘flare’ and burn when subjected to the oxy flame test.

Uses of aluminium

Aluminium is often selected for use in the fabrication industry where its properties of light weight and corrosion resistance can be used to advantage.

Typical uses of aluminium alloys are:

- aircraft
- boats
- truck bodies
- storage vessels
- lightweight castings and extrusions.

Certain factors may limit the usage of aluminium. Among these are:

- high temperature service
- where hardness is required
- where fatigue stresses are present
- corrosive media such as hydrochloric acid, sodium hydroxide, or nitric acid
- cost.

Classification of aluminium alloys

At least eight elements, in various combinations, are commonly used to produce aluminium alloys. The aluminium alloys available to industry offer a remarkably wide range of properties. To aid the selection of an appropriate aluminium alloy, the Aluminium Development Council of Australia (ADC) has produced a system of classification.

Aluminium alloys are divided into eight basic groups (or series) according to alloy composition, as follows.
Chapter 14 – Non-ferrous metals

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Major alloying element</th>
<th>Alloy series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium (99 005% min. purity)</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Aluminium alloys grouped by major alloying elements</td>
<td>copper</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>manganese</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td>silicon</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>magnesium</td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td>magnesium and silicon</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>zinc</td>
<td>7000</td>
</tr>
<tr>
<td></td>
<td>other elements</td>
<td>8000</td>
</tr>
</tbody>
</table>

Table 14.1 – Aluminium alloys by composition

The effects of alloying elements in aluminium

Copper – Increases strength and hardenability, but decreases corrosion resistance.

Manganese – Improves mechanical properties.

Silicon – Lowers melting point, makes material more fluid when molten (filler wires and castings).

Magnesium – Increases hardness and tensile, greatly improves resistance to corrosion. Magnesium and silicon in combination give a heat treatable alloy.

Zinc – Improves corrosion resistance and strength.

These alloys can be briefly described as follows.

<table>
<thead>
<tr>
<th>Series</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>Pure aluminium for applications requiring excellent corrosion resistance, high conductivity and good workability. They have low strength and are readily weldable.</td>
</tr>
<tr>
<td>2xxx</td>
<td>High strength but lower corrosion resistance. Difficult or impossible to weld by the common welding processes.</td>
</tr>
<tr>
<td>3xxx</td>
<td>Good workability, moderate strength and are readily weldable.</td>
</tr>
<tr>
<td>4xxx</td>
<td>Silicon lowers the melting point without producing brittleness. A major use is in filler rods for welding and brazing.</td>
</tr>
<tr>
<td>5xxx</td>
<td>Moderate to high strength – good corrosion resistance in marine environments. These alloys are readily weldable.</td>
</tr>
<tr>
<td>6xxx</td>
<td>Moderate strength, good formability and corrosion resistance. Readily weldable.</td>
</tr>
<tr>
<td>7xxx</td>
<td>High strength – difficult to weld. Medium strength – limited weldability.</td>
</tr>
<tr>
<td>Clad alloys</td>
<td>Cladding is a means of having a highly corrosion resistant surface with a high strength centre. Weldability depends on the alloys used and the type of joint.</td>
</tr>
</tbody>
</table>

Table 14.2 – Properties and uses of aluminium alloys
Of these groups, the 2000, 6000 and 7000 series are heat treatable and may be heat treated to produce high strength alloys. Of these, the 2000 and 7000 series alloys exhibit poor weldability and are generally not welded.

**Temper designations**

Aluminium alloys can have their mechanical properties enhanced by being worked (wrought) by either mechanical or temperature treatments.

A system is used to indicate the exact condition of the worked material and whether the alloy is heat treatable, consisting of a letter and numbers.

<table>
<thead>
<tr>
<th>Basic letter or designation (first letter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F = as fabricated</td>
</tr>
<tr>
<td>O = annealed</td>
</tr>
<tr>
<td>H = strain hardened</td>
</tr>
<tr>
<td>T = thermal treated</td>
</tr>
<tr>
<td>Non-heat treatable and heat treatable alloy</td>
</tr>
<tr>
<td>Heat treatable alloy</td>
</tr>
</tbody>
</table>

F temper – Applies to products that acquire some temper from shaping but have no special control over the degree of strain.

O temper – Applies to a fully annealed product with the lowest strength and greatest ductility.

H temper – Applies to a product that has had strength improvements by cold working.

<table>
<thead>
<tr>
<th>Basic digit (first number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 = strain hardened only</td>
</tr>
<tr>
<td>H2 = strain hardened/annealed</td>
</tr>
<tr>
<td>H3 = strain hardened/stabilised</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic digit (second number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 = softest (annealed)</td>
</tr>
<tr>
<td>8 = fully hard</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic digit (third number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>= variation degree</td>
</tr>
</tbody>
</table>

For example; H324, H112.
Supplementary information related to temper

<table>
<thead>
<tr>
<th>T digit (first digit) then number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>slow cooled, natural aged</td>
</tr>
<tr>
<td>T2</td>
<td>annealed, cold worked</td>
</tr>
<tr>
<td>T3</td>
<td>heat treated, cold worked then stabilised</td>
</tr>
<tr>
<td>T4</td>
<td>heat treated, natural age to stabilise (after any working)</td>
</tr>
<tr>
<td>T5</td>
<td>cooled from hot shape then aged</td>
</tr>
<tr>
<td>T6</td>
<td>heat treated then aged</td>
</tr>
<tr>
<td>T7</td>
<td>heat treated then stabilised</td>
</tr>
<tr>
<td>T8</td>
<td>heat treated, cold worked then aged</td>
</tr>
</tbody>
</table>

For example; 6063T4.

Common grades

There are many commercial aluminium grades available. However, the range available ‘ex-stock’ is generally limited to the following.

<table>
<thead>
<tr>
<th>Alloy characteristics</th>
<th>Corrosion resistance</th>
<th>Form</th>
<th>Temper</th>
<th>Tensile strength MPa</th>
<th>Yield strength MPa min</th>
<th>Elongation min %</th>
<th>Typical application</th>
</tr>
</thead>
<tbody>
<tr>
<td>5005</td>
<td>moderate strength</td>
<td>very good</td>
<td>sheet</td>
<td>H14, H36</td>
<td>160, 180</td>
<td>150, 165</td>
<td>6, 6</td>
</tr>
<tr>
<td></td>
<td>anodises well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5251</td>
<td>medium strength</td>
<td>very good</td>
<td>sheet</td>
<td>0, H36</td>
<td>185, 270</td>
<td>75, 230</td>
<td>24, 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5083</td>
<td>high strength</td>
<td>very good</td>
<td>plate</td>
<td>0, H321, H323</td>
<td>290, 315, 325</td>
<td>145, 230, 250</td>
<td>22, 16, 10</td>
</tr>
<tr>
<td></td>
<td>good weldability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6063</td>
<td>extrudes well</td>
<td>very good</td>
<td>ext</td>
<td>T1, T5, T6</td>
<td>150, 220, 240</td>
<td>90, 180, 215</td>
<td>20, 12, 12</td>
</tr>
<tr>
<td></td>
<td>good weldability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 14.3 – Availability of aluminium alloys
The 5000 series alloys are supplied as sheet and plate.
6063 is supplied in the form of extrusions.
Sheets supplied up to 4 mm thick may be plastic coated.

Weldability of aluminium alloys

The commonly fabricated 5000 series and 6000 series alloys are readily welded by the inert gas shielded arc welding processes, and to a lesser extent, by other processes.

Factors which tend to reduce the weldability of aluminium alloys are:

- surface oxide
- low melting point
- high thermal conductivity
- high coefficient of thermal expansion
- hot shortness
- solubility of hydrogen.

Surface oxide

Aluminium gains its corrosion resistance from the oxide film that forms on the surface when exposed to the atmosphere. While pure aluminium melts at 660 °C, the melting temperature of the oxide is much higher at 2040 °C. This leads to welding problems in two major ways, as follows.

- **Lack of fusion defects** – Where the oxide film prevents adequate fusion to the base metal.
- **Collapse of the weldment** – Particularly where heat input is slow, such as in oxy-fuel gas welding. A considerable amount of the base metal may be melted, supported only by the surface oxide on the underside of the plate. Eventually the weight of molten aluminium may break the oxide film, leading to collapse of the weldment.
  - **Gas tungsten arc welding process** – Rapid rise in temperature enables fusion without substantial melting of the base metal.
  - **Slow heating of the base metal** – By the time the surface melts, a considerable amount of parent metal may be at the same temperature supported only by the oxide film underneath.
  - **Collapse of base metal** – Supporting oxide film breaks due to the weight of the molten aluminium base metal.
Low melting point
The low melting point of aluminium sometimes makes control of the welding process difficult.

High thermal conductivity
The high thermal conductivity leads to rapid heat loss from the weld zone. This may lead to lack of fusion defects, particularly at the start of a weld bead. Rapid freezing of the weld metal also leads to the comparatively high levels of porosity that are associated with welds in aluminium. The high thermal conductivity may also necessitate extensive use of pre-heat.

High co-efficient of expansion/hot shortness
Hot cracking is a common problem when welding aluminium alloys.
The high weld shrinkage and lack of ductility of the hot metal, combine to render the metal unable to yield to absorb shrinkage forces. Common crack types are centreline and crater cracks.

Absorption of hydrogen
In the hot condition, aluminium will dissolve large amounts of hydrogen. As the metal cools, hydrogen comes out of solution and forms gas pores in the microstructure. Levels of porosity may be extreme, causing a serious loss of cross-sectional area of the weld. It is essential that aluminium is cleaned prior to welding and that all possible sources of hydrogen via the welding process are eliminated.
Copper and its alloys

Copper is a reddish-brown coloured, corrosion resistant, highly conductive, non-magnetic metal. Its melting point is 1083 °C and its density is 8940 kg/m³. Copper is work hardenable and may be annealed by heating and quenching.

Uses
The main uses of copper are electrical, plumbing and heat exchanger applications.

Grades
- de-oxidised copper – good weldability
- tough pitch copper – limited weldability
- oxygen free copper – good weldability.

Weldability
The weldability of copper is limited by three factors.

1. The presence of oxygen results in cuprous oxide forming at the grain boundaries, leading to cracking. Fusion welding should be restricted to de-oxidised or oxygen-free copper.
2. High thermal conductivity necessitates that pre-heat be used in most cases (400 °C–700 °C).
3. Annealing of the weld zone, accompanied by a reduction in mechanical properties. Hot peening of the weld zone may be required.

Copper is commonly alloyed with other elements to produce a range of useful metals. The common alloys are:
- brasses – alloys of copper and zinc
- bronzes – alloys of copper and tin
- cupronickels – alloys of copper and nickel.

Brass
Cartridge brass – 70% Cu/30% Zn. Ideal for cold forming operations such as stamping, drawing, or spinning.
Muntz metal – 60% Cu/40% Zn. More yellow in colour than cartridge brass. Cold short.

Weldability of brass
The major problem associated with welding brass is the loss of zinc, as zinc boils at 910 °C. This leads to porosity and a loss of strength. To control this zinc loss, filler rods have small quantities of aluminium or silicon added. This forms a skin over the weld pool and helps to stop the zinc boiling off.

Formability – Brasses which contain in excess of 68% copper are hot short, while those containing less than 68% copper are cold short.
Bronze

Bronze is an alloy of copper and tin. The addition of tin to copper increases hardness, wear resistance and resistance to salt water corrosion.

Tin bronze – 1%–15% Sn. Commonly referred to as phosphor bronze because of the addition of tin, which acts as a de-oxidiser.

Aluminium bronze – 5%–11% Al. Whitish in colour. Alloys containing above 10% aluminium are heat treatable to produce high strength alloys.

Silicon bronze – up to 5% Si. The strongest of the non-heat treatable bronzes. They have good workability and are readily weldable.

Weldability of bronzes

Bronze oxidises easily. Phosphor de-oxidised filler is generally used.

Aluminium bronze tends to be hot short and is susceptible to cracking at high temperatures. PWHT may be required.

Silicon bronze has good weldability. However, rapid cooling between 800 °C and 950 °C should be facilitated, to prevent hot cracking.

Copper/nickel alloys (cupronickel)

Cupronickels are alloys of copper and nickel, in which the major portion of the alloy is copper. Cupronickels may contain up to 30% nickel. They are non-heat treatable and have excellent corrosion resistance, particularly to corrosion by salt water. The mechanical properties may be improved by cold working.

Weldability of cupronickel

Cupronickels are readily welded by the gas shielded arc welding processes and by silver brazing. They are prone to porosity as a result of contamination by O₂ and H₂ during welding. Shielding gas flow rates may need to be increased slightly when compared to other metals.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cu</th>
<th>Ni</th>
<th>Other</th>
<th>Description and uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>90/10 cupronickel</td>
<td>88</td>
<td>10</td>
<td>0.5 Mn 1.5 Fe</td>
<td>Corrosion resistant, used for coolers, tubes for salt water condensers, piping.</td>
</tr>
<tr>
<td>70/30 cupronickel</td>
<td>68</td>
<td>30</td>
<td>1.0 Mn 1.0 Fe</td>
<td>Strong resistance to corrosion and has high tensile strength. Used in tubes for salt water condensers, wire for electrical fuses.</td>
</tr>
</tbody>
</table>

Table 14.4 – Copper nickel alloys
Nickel and its alloys

Nickel

- chemical symbol: Ni
- colour: silvery-white
- melting point: 1452 °C
- density: 8800 kg/m³
- coefficient of expansion: 0.000013
- thermal conductivity: between Fe and Al
- magnetism: slightly.

Pure nickel is available in several grades between 94–99.95%.

Uses

Nickel is tough and ductile and corrosion, oxidation and creep resistant. Common applications of nickel are:

- food handling equipment
- chemical plant
- heating coils
- evaporators
- marine fabrications.

Monel

Composition:

- Ni 65%
- Cu 28%
- Mn and Fe.

Monel exhibits high resistance to corrosion by acids and salt water. It is tougher, cheaper and stronger than nickel.

Uses

- food handling equipment
- heat exchangers
- offshore structures
- turbine blades, bolts, screws, shafts.

Nimonic

Composition:

- Ni 57% or 75%
- Cr 20%
- Fe, Ti, Al, Co.

Nimonics are high strength, high temperature alloys. They have excellent resistance to corrosion, creep, oxidation and scaling at high temperatures.
Chapter 14 – Non-ferrous metals

Uses
- pumps, valves, springs
- turbine blades, aircraft engine parts
- vessels, chemical plant.

Inconel
Composition:
- Ni 32%–76%
- Cr 15%–20%
- Fe 7%–46%
- Al, Ti, Mn.

Highly resistant corrosion and oxidation, these alloys maintain strength and toughness from sub-zero to elevated temperatures.

Uses
- food and chemical plant
- heat exchangers
- furnace parts and equipment
- turbine blades
- aircraft manifolds.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Ni%</th>
<th>Cr%</th>
<th>Cu%</th>
<th>C%</th>
<th>Fe%</th>
<th>Mn%</th>
<th>Al%</th>
<th>Ti%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel 200</td>
<td>99.5</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.15</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nickel 201</td>
<td>99.5</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>0.15</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nickel 205</td>
<td>99.5</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.10</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Monel 400</td>
<td>66.0</td>
<td>-</td>
<td>31.5</td>
<td>-</td>
<td>1.35</td>
<td>0.90</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Monel 404</td>
<td>55.0</td>
<td>-</td>
<td>44.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Monel 500</td>
<td>65.0</td>
<td>-</td>
<td>29.5</td>
<td>-</td>
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<td>0.60</td>
<td>2.73</td>
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</tr>
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<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.55</td>
<td>1.30</td>
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<td>0.20</td>
<td>-</td>
<td>-</td>
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<td>20.0</td>
<td>-</td>
<td>0.04</td>
<td>46.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 14.5 – Nickel alloys
Titanium and its alloys

Titanium

- chemical symbol: Ti
- colour: silvery-grey
- melting point: 1670 °C
- density: 4500 kg/m³
- ultimate tensile strength: 315 MPa
- magnetism: non-magnetic.

Titanium is a lightweight, non-magnetic metal, which is silvery-grey in colour. It has excellent corrosion resistance and when alloyed has a high strength-to-weight ratio.

Grades

Pure titanium is relatively soft and weak. Its applications are generally restricted to those applications that take advantage of its excellent corrosion resistance, but do not have a high strength requirement.

Titanium is commonly alloyed with elements such as aluminium, chromium, zinc, iron, manganese, tin, vanadium and molybdenum. Titanium alloys exhibit high strength-to-weight ratios, good creep resistance and excellent corrosion resistance up to 250 °C.

Uses

The major uses for titanium alloys are in the chemical, marine and aerospace industries, in applications that take advantage of the strength, light weight and corrosion resistance of titanium alloys.

Weldability

Processes such as RW and GMAW may be used to weld titanium and its alloys. However, GTAW has become the most popular process. Although titanium has excellent corrosion resistance up to 250 °C, above this titanium is highly reactive with oxygen, hydrogen, nitrogen and other contaminants.

The major challenge when welding titanium and its alloys is to prevent contamination of the parent metal. The weld should be gas shielded until it has cooled to below 400 °C. To facilitate this, trail gas shielding is commonly used. An example of this for use when welding pipe is given in Fig 14.2. Sound welding procedures will result in welds with excellent mechanical properties.

![Fig 14.2 – Trailing gas shielding device](image-url)
Welding of nickel alloys

Weldability – When nickel alloys are brought into contact with sulphur at temperatures above 240 °C, they are highly susceptible to hot cracking. Cracking can also result from the presence of lead, phosphorus and other low melting point substances that are commonly found in grease, paint, crayons, cutting fluid, inks, lacquers etc. Where possible, the use of such substances should be avoided during fabrication.

It is imperative that thorough cleaning is carried out prior to welding.

Welding recommendations

- thorough cleaning
- use of jigs and fixtures
- low heat input
- close tacks
- short arc lengths.

Welding recommendations

- Thorough removal of all surface scale, grease and other surface contaminants is essential. This can be achieved by pickling, brushing with a clean stainless steel wire brush and solvent cleaning with acetone or alcohol. The weldment should be cleaned for a distance equal to ten times the plate thickness on either side of the weld, with a minimum of 25 mm.
- High purity shielding gases must be used (minimum 99.995% pure). Argon, helium, or argon/helium mixtures may be used.
- Gas shielding must completely protect the weld until it cools to below 400 °C. Trail shielding devices and welding chambers are used to facilitate this.
- Filler rods should be cleaned using a cloth wetted with alcohol or acetone and once cleaned, the filler rods and weldments should only be handled with clean cotton gloves.
- Backing gases are essential and weld support is desirable.
- Current for GTAW is DC -ve.

Amperages are similar to those used for welding stainless steel.
Chapter 15 – GTAW and equipment

Introduction

Gas tungsten arc welding (GTAW) has increased in popularity because of the relative ease with which it can be applied to difficult to weld materials, notably aluminium and stainless steel and the increased use of these materials in various industries. Thin metals, out of position work and automatic applications are well within the scope of the GTAW process and it is in these areas that it excels. Welds produced are of high quality in terms of both soundness and appearance.

In this chapter we will look at the following.

- The gas tungsten arc welding process
  - applications of the process
  - equipment
    - shielding gases
    - gas regulators and flow meters
  - gas tungsten arc welding techniques.
The gas tungsten arc welding process

The gas tungsten arc process employs an electric arc created between a non-consumable tungsten electrode and the work to heat and melt the parent metal and provide the heat required for fusion. Under normal conditions, the tungsten electrode does not melt and become part of the weld.

A separate inert gas shield is introduced around the arc zone to exclude the atmosphere and its undesirable effects. Additional weld metal may or may not be required, but can be added by dipping compatible filler rods into the weld pool.

Fig 15.1 – Gas tungsten arc welding
Applications of the process

GTAW has a wide range of applications, in particular its use on stainless steel and non-ferrous metals such as aluminium and its alloys and also copper and copper based alloys. The GTAW process is also widely used on plain carbon steel, carbon manganese steel and low and high alloy steels because of its weld finish and quality. It can be used to weld a wide variety of metal thicknesses in all types of applications, including:

- general engineering
- transport and marine industries
- sheet metal industries
- boiler and pipe welding.

Advantages of the process

Some of the advantages of the GTAW process include the following.

- An open arc, which means the weld zone is highly visible to the operator, enabling greater control of the weld pool and fusion zone.
- The arc heat is highly concentrated and produces virtually no sparks, spatter or fumes.
- The process operates in an inert atmosphere and therefore does not produce any adverse effects on the weld or weld area.
- High quality welds with a good visual appearance are able to be easily produced.
- No flux is required, therefore no slag is produced and this saves time required for post-weld clean up. Some wires do however have a flux enclosed.
- The process has a wide range of applications (nearly all the ferrous and non-ferrous materials, together with some of the more exotic materials such as nickel and titanium).

Limitations of the process

Some of the limitations of the GTAW process are as follows.

- Equipment is relatively expensive – to make full use of the process, a high degree of skill is required from the operator.
- The process is not suitable for use on dirty material and does not like a windy environment.
- It is not really suitable for thicker sections or high productivity work, although it can be mechanised to improve quality and efficiency.
- The process also has more intense arc radiation and fume safety hazards, depending on the material being welded.
Equipment

Power source

Gas tungsten arc welding power sources can be obtained to operate on domestic or industrial mains supply voltages. Most industrial machines operate on a 440 volt supply and provide current in the range 200–500 amperes with 60% duty cycle.

Any AC or DC manual metal arc welding machine (constant current) can be used to supply the current for GTAW. It is important, however, that the machine has a good current control for low amperages in order to maintain a steady arc when welding thin material. When using DC for welding, a high frequency unit is desirable for easy arc starting, but not essential. With AC, a high frequency unit is definitely required; this will be discussed later. The ideal power source for GTAW is one that has been specially designed for the process (refer to Fig 15.2). These welding machines are typically transformer rectifiers or inverters that supply both AC and DC and have a high frequency unit incorporated in them. They also usually have other controls peculiar to the GTAW process, such as:

- a selection of current ranges or digital current control to give the operator better control over the amperage
- remote current control, usually hand or foot-operated, enabling the welder to alter the amperage whilst welding
- a soft-start switch, which reduces the current when starting the arc. This is an advantage when welding aluminium or magnesium. A better GTAW power source will also provide the ability to control upslope and down slope on the main current, as well as pulsing options
- high frequency spark intensity control, which is useful when welding aluminium and magnesium
- pre and post-gas flow timer to allow the shielding gas to flow before the arc is started and then provide a gas (and water if used) flow for a set time after the arc is extinguished. This prevents atmospheric contamination of the weld pool and electrode and also assists in torch and tungsten electrode cooling.

Fig 15.2 – Equipment used in gas tungsten arc welding
Current type is important in GTAW and the choice depends mainly on the metal to be welded and its thickness, which in turn decides the current level required.

**Choice of current**

With GTAW, the operator has the choice of three types of welding current.

1. **DC(-) electrode negative.**
2. **DC(+) electrode positive.**
3. **AC(hf) AC with superimposed high frequency.**

**DC electrode negative**

In the GTAW process, two-thirds of the heat generated at the arc occurs at the positive terminal and one-third of the heat at the negative terminal. Therefore, it is beneficial (whenever possible) to connect the tungsten electrode to the negative terminal, since higher amperages can be used without the tungsten becoming overheated. Also, because most of the heat is concentrated in the parent metal, deeper penetration is obtained.

With electrode negative, the flow of electrons is from the tungsten electrode to the parent metal (from negative to positive). The shielding gas, as it passes through the arc, becomes electrically charged (ionised) and the ions of gas that are positively charged are attracted to the negative electrode (Fig 15.3). No cleaning action occurs with this polarity, but this is only needed when welding metals with a high melting point surface oxide. Electrode negative is preferred for most of the common fabrication metals, except aluminium.

GTAW with electrode negative produces deep penetration because it concentrates the heat in the joint area. No cleaning action occurs with this polarity.

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![Fig 15.3 – Direct current electrode negative](image-url)
DC electrode positive

With electrode positive, the gas ions are still positively charged but are now attracted to the negative parent metal. They bombard the plate surface, causing any oxide on the plate surface to be chipped away, exposing bare metal that is easily melted. This cleaning action is most useful when metals with a high melting point surface oxide have to be welded, eg aluminium, magnesium and titanium.

With electrode positive, the bulk of the heat is now concentrated at the tungsten electrode, which can become overheated unless a sufficiently large electrode diameter is used. The penetration is wide and shallow and the arc tends to be erratic due to the large electrode and relatively low amperage being used (Fig 15.4). Therefore, electrode positive is not recommended for GTAW.

GTAW with electrode positive produces good cleaning action, as the argon ions flowing towards the work strike with sufficient force to break up oxides on the surface of the material. Since the electrons flowing towards the electrode cause a heating effect at the electrode, weld penetration is shallow.

AC alternating current

The ideal type of welding current for metals with a high melting point surface oxide would be one that gives the good cleaning action of the electrode positive cycle and then the deep penetration, cooler electrode of the electrode negative cycle. AC is actually a combination of electrode negative and electrode positive. One half of the cycle is negative and the other half positive (Fig 15.5). The heat is equally distributed at the electrode and the work piece.
Unfortunately, the strong surface oxide on metals such as aluminium prevents the full flow of current in the reverse polarity (positive) direction of the cycle, causing the arc to become unstable. Also, as the cycle passes through the zero voltage point, the arc goes out and must re-ignite. To prevent instability or complete loss of the arc, a continuous high frequency spark is required. The high frequency current is able to jump the gap between the electrode and the parent metal during the period of arc shut down, and assists to penetrate the oxide film and form a path for the welding current to follow. Because continuous high frequency voltage is needed with AC, this type of current is usually identified as AC(hf) (Fig 15.6).

**AC square wave**

A variation on true AC is also available with modern GTAW welding equipment, where the top and bottom of the AC sine wave are flattened by electronics (Fig 15.7). With modern electronic control, the AC wave can also be altered to give more positive or negative arc time and/or current. The fact that these parameters can be changed can be used to advantage by a skilled operator to alter arc cleaning or heating time.
**Electrode current carrying capacity**

The electrode diameter required for a given amperage will vary, depending on the current type being used. A 1.6 mm tungsten on DC electrode negative will carry the same current as a 2.4 mm tungsten on AC(hf), while a 3.0 mm electrode would be required to carry the same current on DC positive.

- **Electrode cooling** is provided by the torch through the copper collet, gas diffuser and torch body.

- Direct current electrode negative is the most common type of current used for welding materials such as mild steel, stainless steel and alloy steels. Direct current electrode negative is used also to obtain narrow, deep penetrating welds.

- Direct current electrode positive may be applied to welding very thin aluminium and magnesium parts, but is not commonly used because a large diameter electrode is required to carry low current values and the arc may be unstable.

- Alternating current, with a superimposed high frequency current, is most commonly used for aluminium and magnesium, as it combines good oxide clearing when the electrode is positive with good penetration when the electrode is negative.

**Pulsed current**

Pulsed current is also available on some GTAW equipment. The welding current is set to fluctuate between a high fusion current level and a low background current, both of which are adjustable, as is the time for which each current level is effective. The number of pulses can be varied from ten per second down to about one per second.

Pulsed current, which may be AC or DC, is particularly useful for welding very thin materials, providing good penetration during the high current cycle with cooling of the molten pool and solidification during the low current cycle. In effect, pulsed current produces a series of spot welds, penetration is good, distortion is minimised and heat control is improved for difficult welding situations involving thin materials and positional welds.
Shielding gases

Generally, an inert gas is used in GTAW as the shielding medium to protect the tungsten, molten weld pool, weld zone and filler material from contamination and oxidation by the atmosphere.

Argon

Argon is the inert gas most commonly used in Australia – in preference to helium because of its lower cost and its general suitability for a wide variety of metals. Argon is an electron carrier and also exhibits better oxide removal characteristics than helium. It aids the welding operation, as heat input to the weld puddle is less affected by variations in arc length.

Helium

Helium is also an inert gas, but it is not as easily obtained and therefore is more expensive than argon. On the other hand, because it does not carry electrons as well as argon, the power source is not loaded up as well and therefore arc voltages are higher. This means more heat is available, which increases penetration and travel speeds.

Others

Oxygen is an oxidizing gas and small amounts may be introduced into the gas mixture to stir up the weld pool and increase heat in the arc. Carbon dioxide is a cheap insulator gas that may also be added in small amounts to help decrease costs and stimulate weld fusion. It should not be used on stainless steel.

Mixtures

Mixtures of the two main gases of argon and helium may prove advantageous, in some special applications. An increase in helium content will bring about increased temperature, better fusion and faster weld speeds on most materials, but there would be a corresponding increase in costs. Gas suppliers have developed numerous combinations of the various gases (brews) to suit particular situations or applications. Those seeking further information should contact the local supplier.
Gas regulators and flow meters

Fixed pressure reduction regulators are used to supply gas to the torch, together with a flow meter, to give a precise indication of the gas flow rate being used. Gas flows are adjusted between 5 and 14 litres per minute to suit the particular application. Flow rates above the recommended value may not necessarily provide better gas shielding.

Welding torches

Handheld GTA welding torches may be air cooled for low to medium amperage applications (these are also gas cooled by the gas supply). Water cooled torches are required for industrial operations involving higher amperages and longer welding periods. The electrode is held by a collet in a collet holder/gas diffuser that assists in electrode cooling and allows for removal and setting of the electrode in relation to the nozzle, or gas shroud.

Projection of the electrode should not be excessive, as this makes touching onto the work and contamination of the electrode more likely. Minimum projection of electrode consistent with good control, normally 2–5 mm, will provide good welding conditions and satisfactory gas coverage of the electrode and work. The collet is tightened by screwing in the torch back cap, which also provides insulation for the electrode.

A control knob for gas flow may be located on the torch and this often incorporates a current on/off control. Most welding torches have now removed the gas control and modern GTAW equipment provides one-touch control over pre and post-gas flow and all other welding parameters.
Gas nozzles

Gas nozzles (or gas lenses) are used to protect the tungsten electrode from the atmospheric gases and to deliver the shielding gas to the weld area. They may be made from cheap compressed and fused alumina type material. Ceramic material gas cups are able to withstand higher temperatures than the alumina type, but they are more expensive and more susceptible to damage. Metal or fused silica (glass) gas lenses are also available. The gas lens is available in a variety of sizes ranging from 8 mm to 20 mm.

The general rule for the gas lens size is four to six times the electrode diameter. This may be altered however, depending on the type of joint being welded and the material being welded. For example, an outside corner weld may require a larger gas lens size to give more shielding, while an inside corner can be achieved easily with a small gas lens because the gas will be trapped in the corner. Typically, aluminium or stainless steel may also need one step larger gas lenses to give a better gas cover.

Electrodes

Different types of tungsten electrodes are available and provide a comprehensive range for specific applications. Tungsten electrodes are identified on the tip by a colour code. This colour code should be preserved, as identification of a tungsten electrode that has lost its code can be difficult.

Pure tungsten electrodes (green tip)

Tungsten has the highest melting point of all metals, typically 3400 °C for pure tungsten. These electrodes are recommended chiefly for use with balanced wave alternating current power sources on the welding of aluminium where other electrode types are not generally used due to their emission characteristics. When used with standard power sources, they provide good stability with direct current and high frequency stabilised alternating current with argon, helium or a mixture of both as a shielding gas.

Pure tungsten electrodes have a lower current carrying capacity and poorer arc starting characteristics than other electrodes, but have a reasonably good resistance to contamination and maintain a clean balled end which is preferred for aluminium and magnesium welding. They are a general purpose electrode for less critical work.
Thoriated tungsten electrodes (red tip)

These electrodes contain 1%–2% thorium as an alloy. This gives the electrode a greater ability to resist transfer across the arc and thus help to maintain the point when using them chiefly for direct current electrode negative DC(-) work, because they offer increased life compared with that of the pure tungsten type due to their higher electron emission. They offer better arc starting, particularly at low open circuit voltages, and good arc stability. The thoriated tungsten range of electrodes have a higher current carrying capacity and greater resistance to weld pool contamination.

Thoriated tungstens are generally used when DC electrode negative is selected for welding of ferrous materials and alloys such as mild steel, alloy steel and stainless steel. They may be used on high frequency stabilised alternating current work, but difficulty can be experienced in maintaining the satisfactory balled end required for good arc stability when welding aluminium and magnesium. This condition frequently produces arc wander and tungsten emission, resulting in contamination of the weld metal.

Zirconiated tungsten electrodes (white tip)

These electrodes are treated with zirconium and are preferred for applications where tungsten contamination of the weld metal must be minimised. They are recommended for use with high frequency stabilised alternating current (AC(hf)) for the welding of aluminium and magnesium, due to the fact that they retain a clean balled end during welding and have a high resistance to contamination. They have a longer life and higher current carrying capacity than that of pure tungsten electrodes.

In recent studies related to health issues for welding operators, the thoriated and zirconiated type electrodes have been found to produce a slight amount of radiation when they are ground up. For this reason, they should be used only when special precautions are used. Because of this problem, new types of electrodes for GTAW have been developed.

Ceriated tungsten electrodes (orange tip) and lanthanated tungsten electrodes (grey tip)

These are relatively new types of non-radioactive alloy tungsten electrode. These electrodes can be used in situations where either thoriated or zirconiated tungsten electrodes would normally be used. The tip may be ground to a point when using DC -ve, or to a ball if AC(hf) is to be used and they demonstrate good welding characteristics in all applications. The only drawback is that these electrodes are more expensive to buy than the thoriated or zirconiated electrodes. However, if a welder has been instructed to use the GTAW process on a particular job but does not know what type of metal or alloy the item is made from, ceriated or lanthanated tungsten electrodes may be selected. This will ensure that a sound weld can be produced, no matter what welding current is required.
The chart below sets out general recommendations for choosing operating conditions.

<table>
<thead>
<tr>
<th>Electrode diameter</th>
<th>Gas cup size</th>
<th>AC (hf)</th>
<th>DC -ve</th>
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</thead>
<tbody>
<tr>
<td>0.5 mm</td>
<td>6 mm</td>
<td>5–15</td>
<td>5–20</td>
</tr>
<tr>
<td>1.0 mm</td>
<td>6 mm</td>
<td>15–40</td>
<td>15–70</td>
</tr>
<tr>
<td>1.2 mm</td>
<td>6 mm</td>
<td>20–60</td>
<td>40–90</td>
</tr>
<tr>
<td>1.6 mm</td>
<td>6 mm or 10 mm</td>
<td>20–90</td>
<td>65–120</td>
</tr>
<tr>
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</tr>
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<td>15 mm</td>
<td>160–340</td>
<td>300–550</td>
</tr>
<tr>
<td>6 mm</td>
<td>15 mm</td>
<td>280–470</td>
<td>500–700</td>
</tr>
</tbody>
</table>

Table 15.1 – Typical operating conditions for tungsten electrodes

Before assembling the electrode in the torch, one end should be prepared to suit the type of welding current being used. For DC -ve, it should be ground to a taper with the nose section having approximately 30° included angle; do not grind it to a sharp point, but leave approximately one-third of the electrode diameter unground as a sharp point can be lost from the electrode into the weld pool during welding. For AC welding, grind with a chamfer to provide rapid formation of the balled end necessary for AC welding.

![Fig 15.11 – Electrode tip preparation](image)

Gas tungsten arc welding techniques

Starting the arc

After a gas flow is established and providing high frequency current HF is used to initiate the arc, the electrode does not have to touch the work or starting block to effect arc initiation. The superimposed high frequency current jumps the gap between the electrode and the work or starting block and thus establishes a path for the welding current to flow. On some machines, there is facility for the current rate and rise time to be adjusted (up slope).
When DC is employed without HF, it will be necessary for the electrode to make actual contact with a starting block. At the moment of contact and when the arc is struck, the electrode should be raised 3 mm above the starting block. The torch is then moved quickly towards the work area.

To stop an arc, the current should simply be switched off and the torch held over the cooling weld to provide a protective gas shield (post-purge) whilst the electrode and work are cooling. The current may gradually be decreased (down slope) at the end of a weld pass, thus allowing the crater to be filled, instead of being finished in a concave contour.

Some care will be necessary, particularly with high-quality work and in pipe preparations when breaking the arc when a simple power source is used. In some instances, it can be advisable to run-off on to a tab or up the side of the pipe preparation when completing a pass.

**Arc wander**

Occasionally, the point from which the arc leaves the electrode can move and waver without any apparent reason. This is termed ‘arc wander’ and is generally attributed to one of the following causes:

- low electrode current density (too large an electrode for the current being employed)
- contamination of the electrode
- magnetic effects.

With AC welding, due to the fact that a ball ended electrode is used, when the current density of the electrode is of a sufficiently high level, the entire end of the electrode will be in a molten state and completely covered by the arc. When too low a current density is used, only a small area of the electrode becomes molten, resulting in an unstable arc that has poor directional characteristics and is difficult for the operator to control. Too high a current density results in excessive melting of the electrode end.

Arc wander in GTAW can be reduced by careful selection of the electrode diameter and is much less serious in DC welding, due to the fact that a tapered point is ground on the electrode.

Electrode contamination can be caused by excessive amperages or careless striking of the arc. It may be preferable to use a piece of copper for starting purposes. Carbon blocks are not recommended because of carbon pickup producing arc instability.

Contamination may also result from allowing the electrode to enter the molten pool or from being touched by the filler rod. In AC welding, contamination of the electrode can also occur when the filler material is not kept at the leading edge of the weld pool. If the electrode is allowed to wander into the arc zone then, filler may transfer to the tungsten on one half of the AC cycle. When contamination does occur, the only course of action is to remove the electrode and either replace or clean it by grinding or breaking off the contaminated end.
Performing butt welds

After the arc has been struck, the torch should be positioned at about 70° to the work. The starting point of the work is first pre-heated by moving the torch in small circles until a molten pool is formed (see Fig 15.12).

When filler metal is required to provide adequate reinforcement, the filler rod is held at about 15° to the work and about 25 mm away from the starting point. When the puddle becomes bright and fluid, move the arc to the rear of the puddle and add filler metal by quickly touching the rod to the leading edge of the puddle. As soon as the puddle is again bright, repeat the same procedure. Care should be taken to ensure the filler rod end is not permitted to leave the protection of the gas shroud during the welding process.

The rate of forward speed and amount of filler metal added will depend on the desired width and reinforcement of the weld bead. Fig 15.13 illustrates the filler rod movement.
Performing fillet welds

The torch should be held at approximately 45° to 90° to the work, with the electrode bisecting the angle between the joint members. All fillet welds require the addition of filler rod to provide the necessary build up, with the filler rod being added to the weld pool in a similar manner as described in butt welds.

After establishing the arc, the weld pool should be developed on both members of the work by using an oscillating movement, similar to that used for butt welding, before the addition of filler metal is applied. In awkward corners, it may be desirable to extend the electrode or use a smaller gas cup to provide better visibility and complete root fusion. Fig 15.14 illustrates torch and filler rod relationship to the work.

Performing pipe welds

The GTAW process is commonly used for pipe welding. High quality welds with uniform penetration may be readily made on metals such as mild and low alloy steels, stainless steels, aluminium and copper. The welds may be root passes in heavy pipe or completely welded joints with root, fill and capping passes.

In GTAW pipe welding, you can gauge the success of the process by observing the weld puddle. The shape of the puddle and its size clearly indicates the degree of penetration being achieved inside the pipe. By manipulating the torch properly, the weld puddle can be controlled at all times so that it has the correct shape for the pipe joint being welded. Thus smooth, fully penetrated porosity free welds can be produced.

Argon is recommended as a backing gas for pipe welding, since it is most effective in preventing oxidation of the back side of the weld.

The argon backing may be confined to the weld areas by paper baffles, by completely filling the pipe or by the use of a removable backing device. Joint designs include ‘V’ and ‘U’ groove preparations for horizontal and vertical applications.

The relative position of the torch and filler rod to the pipe is illustrated in Fig 15.15 through to Fig 15.19.
Fig 15.15 – Relative position of torch and filler rod to pipe

Fig 15.16 – Welding sequence of pipe in the fixed horizontal position
Fig 15.17 – Vertical joint torch and filler rod relationship

Fig 15.18 – Overhead joint torch and filler rod relationship

Fig 15.19 – Horizontal joint torch position
Weld backup

On many GTA welding applications, the joint should be backed up, particularly on light gauge material. Backing is usually used to protect the underside of the weld from atmospheric contamination resulting in possible weld porosity or poor surface appearance. In addition to these functions, weld backup prevents the weld puddle from dropping through by drawing some of the heat generated by the intense arc away from the work and can also physically support the weld puddle.

A weld can be backed up by:

- metal backing bars
- introducing an inert gas atmosphere on the weld underside, or
- a combination of both methods.

Weld backing bars may be of a temporary or permanent type. The former does not form part of the welded joint and can be copper, stainless steel, mild steel, etc, depending on the material to be welded and may be removed on completion of the weld. The latter is usually of the same composition as the material to be welded and becomes part of the welded joint as illustrated in Fig 15.20. They are generally used where access does not allow the removal of the temporary type.

A type of temporary backing bar commonly used is that shown in Fig 15.21, where the surface is cut or machined out directly below the joint. A bar of this type will protect the bottom of the weld from excessive contamination by the atmosphere, as well as draw heat away from the weld zone.
On applications where the final weld composition must conform to extremely rigid specifications, extra care must be taken to exclude all atmospheric oxygen from the weld underside using temporary backing bars that will trap gas on the underside. A supply of inert gas can also be offered up to the underside. Nitrogen may be used for the stainless steel. Argon should be used for aluminium, magnesium and other metals that oxidise readily or react with nitrogen at high temperatures.
Chapter 16 – GMAW/FCAW and equipment

Introduction

Since its introduction in the 1940s, gas metal arc welding (GMAW) has become a very popular welding process in the metal fabrication and welding industries. The flux-cored arc welding (FCAW) process has also become very popular since new gas shielded wires have been developed.

The GMAW solid wire process is suited to a wide range of light and general fabrication applications. Gas metal arc welding is a semi-automatic process where the wire is automatically fed into the weld pool. This produces higher deposition rates and greater efficiency over the manual metal arc welding process.

In this chapter we will look at the following.

- **Gas metal arc welding (GMAW) principles**
  - applications of the process
  - specific safety related to gas metal arc welding
  - wire feed systems
  - metal transfer
  - classification of consumables
  - gas metal arc welding variables
  - gas metal arc welding defects

- **Flux-cored arc welding**
  - equipment
  - techniques for gas-shielded flux-cored arc welding
  - effects of the operating variables with flux-cored arc welding
  - flux-cored arc welding consumables classification
  - safety recommendations with flux-cored arc welding.
Gas metal arc welding (GMAW) principles

Gas metal arc welding is an arc welding process where the necessary heat for fusion is produced by an electric arc that is created and maintained between a continuously fed wire electrode and the part to be welded. The parent metal and heated weld zone, the molten weld metal and the consumable electrode end are shielded from the effects of atmospheric gases by a shroud of inert or slightly reactive gas, fed through the welding torch.

Applications of the process

The GMAW solid wire process can be applied to a wide range of materials, because a fairly good range of filler material is now available. Some of the welding machine suppliers provide welding machines that specialise in either thin or thick materials, however all good welding machines will adapt to a wide range of thicknesses in the hands of a good operator. The process is applicable to either fillet or butt weld joints in the flat or various welding positions.

Typical industrial uses are automotive repairs and vehicle body building, sheet metal work, mining support industries, transport and marine industries, heavy fabrication and general engineering work.

Advantages of the process

The major advantage of the GMAW process is its high deposition rate compared with the manual metal arc and gas tungsten arc welding processes. This is brought about by the automatic wire feed, the high ratio of current to wire diameter and the elimination of the need for the operator to stop to change electrodes, chip slag etc.
The advantages of this are summarised as follows:

- high deposition rates when compared to manual metal arc welding
- high operating factor (duty cycle)
- no wastage from electrode stubs
- elimination of slag removal
- less operator skill required
- has a wide range of applications
- low hydrogen deposit
- reduced distortion on thin materials.

Limitations of the process

Whilst GMAW is a popular and versatile welding process offering the advantages already listed, it is also limited by the following:

- high initial equipment cost
- high maintenance requirements
- it cannot be used in windy conditions, making the process generally unsuited to site work
- lack of fusion defects can be a major problem under some circumstances.

Specific safety related to GMAW

Darker welding filters

The primary concern in regard to safety when using the GMAW plant is the open arc and high arc intensity, which is much greater than that associated with MMAW electrodes. Thus a darker welding filter than is normally used will be required for GMAW. A filter one shade darker than that used for welding at the same amperage with the MMAW process is required, ie:

- up to 200 Amps: a shade 11 is recommended
- 200–300 Amps: a shade 12 is recommended.

Clear safety glasses must be worn at all times, as the higher current density and emission of UV radiation results in increased risk of arc flash and more severe arc flashes if safety is ignored.

Body protection

This same arc intensity will also require the operator to ensure his/her body is completely covered with protective clothing. Even extraneous light from the arc (ie UV radiation bouncing from a reflecting wall) can result in a rather uncomfortable ‘ray burn’.

Experience has shown that cotton materials have a lesser degree of resistance to UV rays than woollen materials. Cotton and particularly synthetics, will quickly break down and eventually disintegrate. Consequently, it is preferable to wear leather or woollen materials.
Ventilation

When using GMAW, a toxic gas called ozone (O₃) is given off in the vicinity of the arc. Processes that employ higher current densities produce more ozone. Although ozone is not normally dangerous under most conditions, it is advisable to use exhaust extraction when working in confined spaces where ventilation is restricted. Natural ventilation and exhaust fans can also be advantageous. Any ventilation system used must not interfere with the gas shielding of the weld zone.

Equipment required

The major equipment items that make up a GMAW plant are the:

- power source
- wire feeder
- cable assembly and welding gun
- gas supply system
- inter-connecting cables.

Fig 16.2 – Gas metal arc welding equipment
Power source

A constant voltage (constant potential) power source with a high duty cycle rating is required for GMAW. This is commonly a transformer/rectifier or an inverter. The output requirement is for direct current with a constant voltage type characteristic, but this may be varied to suit different applications. All solid wires for GMAW run on DC electrode positive (DC +ve).

The GMAW process is intolerant of any variations in arc voltage and the constant voltage type output provided by the power source ensures that the arc length is self-adjusting and the wire burn off rate remains constant, despite uneven torch movement and variations in arc length.

![Fig 16.3 – Gas metal arc welding power source](image)

Wire feed unit

The primary function of the wire feed unit is to feed wire to the arc. The unit houses a reel of wire and a DC motor to which feed rollers are attached. The feed rollers feed wire to the arc down through a hollow steel conduit to the torch. The speed of the drive motor is governed by a potentiometer (the wire feed control). Increasing the wire speed rate usually increases amperage, because the increased wire feed rate effectively decreases the arc length slightly; this loads up the arc voltage and the machine will then increase welding current to compensate.

Incorporated into the wire feed unit are the shielding gas supply and connections, gas control solenoid and water connections (in the case of a water-cooled torch). Most wire feed units also have a gas purge control so that the gas flow can be set without any current or wire flow and a wire inch control so that wire may be fed through without the welding current being turned on. Some wire feeders may also have a pre-gas and post-gas flow timer (useful for aluminium and stainless steel). Some wire feeders may also incorporate spot welding timers and controls.
Cable assembly and welding gun

The cable assembly and welding gun is the medium by which wire, current and shielding gas are conveyed to the welding arc. It connects to the wire feeder and terminates with the ‘gun’ or ‘torch’.

The electrode wire generally travels through the steel wire conduit or ‘liner’, which runs through the centre of the gun cable. Welding current is carried through the cable assembly by a heavy copper lead incorporated within the cable assembly.

Shielding gas is also carried through the cable and is distributed at the weld via the gas diffuser and gas nozzle.
Welding is commenced by depressing the torch trigger. This initiates three separate functions, as follows.

1. The gas solenoid valve opens and allows shielding gas to flow through to the gas nozzle.
2. The welding current contactor is ‘pulled in’ (closed) and welding current becomes available. Welding current is transferred to the wire through the wire feeder, the cable assembly and from the contact tip.
3. The wire feed motor starts up and feeds wire at the pre-set constant speed through the torch conduit.

Because of the heat generated in the weld pool and the heat generated through electrical resistance at the contact tip, torches have to be efficiently cooled. The majority of torches are gas-cooled; however, water-cooled torches may be required when high amperages are used on a continuous basis.

Welding guns are usually provided with a bent neck to improve operator comfort, but some guns may have a straight neck, which allows better wire feed.

Gas supply system

Shielding gases for GMAW are usually supplied from a single cylinder; however, large consumers may use two cylinders or manifolded systems. The components of the gas supply system are a:

- cylinder of gas CO₂ or Argon/CO₂ mixtures for carbon steels
- regulator to reduce cylinder pressure
- flow meter to accurately control shielding gas flow rate
- heater – when CO₂ is used as a shielding gas, a heater is fitted between the cylinder and the regulator to prevent freezing at the regulator
- gas diffuser to distribute gas evenly and prevent turbulence
- gas nozzle to surround the welding wire and provide shielding gas around the weld zone.
Interconnecting cables

These consist of:

- the work return lead and work clamp
- the welding current cable from the power source to the contact tip via the wire feeder and cable assembly
- the control cables from the activation switch to the wire feeder and from the wire feeder to the power source.

Wire feed systems

There are three basic types of GMAW wire feeding systems, each requiring different welding guns.

The push system

The push system is by far the most popular wire feed system. The wire feed unit pushes the electrode wire from the drive rolls along the cable conduit, through the gun and contact tip and to the weld pool. Push systems are generally robust, lightweight and very functional (also the least expensive). The system works very well with hard wires (steel, stainless steel, etc). Wire on spools of 15 kg or larger are usually used with this system. This keeps costs down and increases convenience.

The major disadvantage of the push system is the unreliability of wire feeding over anything other than short cable assembly distances. This unreliability is caused by a number of factors, such as friction which may cause dust to accumulate in the conduit. Wires may also become kinked over long distances due to internal friction; this is a particular problem when feeding soft wires such as aluminium. Nylon or Teflon® liners are used to try to reduce this problem when aluminium wires are being pushed.

Because the conduit in most wire feed systems is live (connected to the wire feeder and/or the contact tip), the conduit may experience internal arcing and wire feed problems caused by dust, or a faulty or dirty contact tip. Any wire feed rate problem caused by dust, a dirty contact tip and/or faulty wire feed will reflect itself in altered or changing weld parameters (voltage/amperage).

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![Diagram of the push system](image-url)
The pull system

The pull system is sometimes known as spool on gun and is ideally suited to feeding soft wires such as aluminium, or where welding is to be carried out at a location remote from the power source. The drive motor and drive rollers are built into the handle of the gun. This offers a short, direct wire travel, with little friction through the conduit.

The drawbacks of this system are the high initial cost of equipment and the welding gun is delicate and susceptible to damage. Consumable wire on small spools is also more expensive. The size of the assembly and weight of wire carried on the gun can also be a disadvantage. Though this system is mainly used for aluminium work, mild steel and stainless steel wires can also be used.

![Diagram of pull systems](image-url)
The push/pull system

As the name implies, both the push motor at the wire feeder and a pull motor at the torch are employed. In the best brands the motors are synchronised to feed the wire at the same speed, although there are some cheaper brands on the market that allow the torch motor to only apply a set tension to the wire feed whilst all the speed control is maintained at the main wire feeder.

The push/pull wire feed system enables the feeding of both hard and soft wires up to ten metres from the welding machine and still offers the economy of 15 kg (or larger) spools of wire. The push/pull system is a versatile system, particularly suited to aluminium but may also be used for hard wires as well. Obviously there is a greater initial purchase penalty and higher maintenance costs.

Fig 16.9 – Push/pull systems (a) and (b)
Drive rollers

Friction, caused by pressure applied to the welding wire as it passes through the rotating drive rolls, is the mechanism by which the wire is fed. Resistance in the gun cable may cause the wire to slip as it passes through the drive rolls. Increasing the pressure of the top roller increases friction and prevents this slippage. However, excessive pressure can deform the wire, making it more difficult to feed (Fig 16.10).

![Fig 16.10 – Deformation caused by excessive roll pressure](image)

Wire feeders use either a two or four-roller drive system. Two-roll systems are cheaper to manufacture and purchase and are best suited to feeding hard wires such as carbon and stainless steels through short gun cables. Most two-roll wire feeders have the two rolls geared to drive together, however some cheap machines have only one roll driven and this will inevitably give trouble and should be avoided.

Four-roll feeders (especially the all-geared type) allow positive drive between the rollers and the wire with less roller pressure, giving a smoother feed with less slippage and less distortion of the wire.

The four-roll system offers advantages for:

- feeding soft wires such as aluminium
- feeding wires through longer cable assemblies
- use with cored wires.
The cross sectional shape of the rollers used with any particular wire feeder, for any particular application, varies according to the manufacturer.
Common configurations/sections of drive rolls and their uses are as follows.

<table>
<thead>
<tr>
<th>Top</th>
<th>Bottom</th>
<th>Drive rolls</th>
<th>Description</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Fig 16.13 – (a)" /></td>
<td><img src="image" alt="Fig 16.13 – (a)" /></td>
<td></td>
<td>Flat top roll/'V' bottom roll (three point universal system)</td>
<td>General purpose feeding of hard wires such as steel and stainless steel</td>
</tr>
<tr>
<td><img src="image" alt="Fig 16.13 – (b)" /></td>
<td><img src="image" alt="Fig 16.13 – (b)" /></td>
<td></td>
<td>Flat top roll/'U' bottom roll (contour system) (the rolls must suit wire size)</td>
<td>Mainly for aluminium wires. The 'U' profile reduces deformation of the soft wire</td>
</tr>
<tr>
<td><img src="image" alt="Fig 16.13 – (c)" /></td>
<td><img src="image" alt="Fig 16.13 – (c)" /></td>
<td></td>
<td>Top and bottom rolls have serrated vee grooves</td>
<td>Used for cored wires and large diameter solid wires</td>
</tr>
</tbody>
</table>

This list is not exhaustive, but these are the ones in the most common use.
Wire conduit (liner)

The liner is used to guide the wire through the gun cable to the torch and through to the contact tip. The liner is made of spiral steel wound wire for feeding hard wires such as carbon and stainless steels and of nylon or Teflon® for feeding aluminium wire. To ensure reliable wire feeding, it is imperative that the liner is cut to the correct length and properly fitted into the cable assembly at the wire feed end and the gas diffuser at the gun end. Additionally, the cable assembly and conduit should be kept free of dust and as straight as possible when in use.

Contact tip

The contact tip serves two functions, to:

- guide the wire to the arc
- transfer welding current to the wire.

The contact tip is the most important component of the welding torch. It is here that the filler-wire is energised or ‘picks-up’ the welding current. The contact tip is usually made from copper and is, via the gas diffuser and torch body, directly attached to the power lead and power source. Contact tips are matched to each wire size.

It is important that the contact tip is maintained in a clean condition, free from spatter on the end and with a smooth internal bore. Worn contact tips reduce the efficiency with which current is transferred to the wire and contribute to uneven wire feeding. They should be replaced when worn.

Metal transfer

With most of the commonly used welding processes, the operator has little control over the way metal is transferred across the arc. With GMAW, the operator can select and control the type of metal transfer. This is done essentially by a combination of arc voltage selection, wire feed rate and shielding gas type being used. Wire type and size being used will also influence the effect these parameters have on the final metal transfer mode.

The metal transfer mode determines the welding characteristics of the GMAW process. The operator must select the most appropriate mode of transfer and set the machine according to a specific application prior to commencing welding.

Apart from the pulsed transfer mode, which requires sophisticated power sources, the welding operator can select from three transfer modes, which are:

- dip (or short arc) transfer
- globular transfer
- spray transfer.

Dip transfer

Dip transfer is also known as short arc transfer (short for short circuiting arc). In the dip transfer mode, low voltage and wire feed settings are used. The low voltage employed is easily overcome by electrical resistance across the arc, preventing continuous current flow as arc length increases.
Dip transfer can occur anywhere from 12–20 volts and 50–170 amps when using 0.9 mm steel wire and argon/15% CO₂ shielding gas.

When welding commences, the tip of the electrode wire contacts the plate and a short circuit occurs, causing a rapid rise in current from the constant voltage power source. If this rate of current rise is too rapid, the wire can simply explode or vaporise much the same way as a fuse wire does when exposed to excessive current. The rate of current rise is controlled by fixed or variable inductance that can sometimes be altered (pinch control). The rapid current rise leads to a temperature rise in the wire (caused by the short circuit current flowing through to the work) and the end of the electrode wire is heated and melted off. An arc is immediately formed between the tip of the wire and the parent metal, creating heating and a weld pool. The arc is maintained by the electrical circuit for a short time. The electrode wire continues to feed at a rate greater than burn off, until the decreasing arc gap causes the arc to be extinguished.

The wire tip once again dips into the pool and the cycle is repeated. This sequence of events is repeated at a frequency of up to 200 times per second. It produces sufficient heat for fusion and to keep the weld pool fluid.

This method is suitable for positional welding, due to rapid freezing of the weld pool and has the advantage that the heat input to the work is kept to a minimum. This limits distortion and enables thin sheet material to be welded. However, on thicker material, the low heat input tends to give rise to lack of fusion defects on material above 5 mm in thickness if care is not taken with machine adjustment and technique.

**Fig 16.14 – Schematic diagram of short arc transfer**

1. Trigger depressed wire starts to feed.
2. Wire contacts; the work piece heats up due to electrical resistance and starts to melt.
3. Wire melts off and an arc is established.
4. Arc length decreases as the end of the wire melts and wire feed continues.
5. Arcing ceases due to the low arc voltage being unable to overcome the electrical resistance across the arc gap.
6. Wire is fed into the weld pool that has been created and the cycle begins again.
Features of dip transfer

- low currents are used
- low heat input
- low penetration
- moderate spatter
- low deposition rate
- relatively cold weld pool
- ideal for thin materials
- used for positional welding
- suffers from lack of fusion defects, particularly when plate thickness exceeds 5 mm.

Globular transfer

Globular transfer can occur anywhere from 18–23 volts and 100–175 amps when using 0.9 mm steel wire and argon/15% CO₂ shielding gas.

Globular transfer occurs at voltage and current levels between those used for dip and spray transfer. Voltages are high enough to ensure a constant arc, but amperage is set below the threshold current that produces spray transfer. The result is that the wire melts in the arc and a molten globule forms on the end of the wire.

As melting continues, the size of the globule grows until its own weight causes detachment of the droplet due to gravitational forces. This droplet detachment is erratic and, along with the influence of arc forces repelling the droplet away from the wire, high spatter levels result. Droplet size is considerably larger than the wire diameter.
The features of globular transfer include:

- moderate amperages are used (medium heat)
- low/moderate penetration
- moderate/high spatter levels
- coarse appearance
- metal droplets are detached by gravitational forces
- largely unsuitable for positional welding
- occurs even at high amperages when the shielding gas contains in excess of approximately 23% CO₂.

**Spray transfer**

Spray transfer can occur anywhere above 23 volts and over 170 amps when using 0.9 mm steel wire and argon/15% CO₂ shielding gas.

Unlike dip transfer, where the low arc voltage used precludes the use of a continuous arc, spray transfer employs an arc that burns continuously. To achieve this, the arc voltage when welding steel must be above approximately 23 V, depending on wire size and shielding gas composition.

Additionally, the amperage used must be above the ‘threshold current’, which is the current above which tiny droplets are pinched off and projected axially across the arc gap. Below the threshold current, droplet detachment is brought about by the molten droplet of wire growing in size until it is heavy enough to be detached by gravitational forces.

![Spray transfer](image)

**Fig 16.16 – Spray transfer**

Spray transfer offers greatly increased deposition rates compared to dip transfer and minimal spatter and is not accompanied by the lack of fusion defects sometimes associated with dip transfer. Because of the hot, fluid weld pool associated with spray transfer, it is only suitable for use on plates above approximately 5 mm thick and in the downhand (flat) position.
Features of spray transfer

- high currents are used
- high heat input
- moderate/deep penetration
- high deposition rates
- low spatter
- good appearance
- fluid weld pool
- unsuitable for positional welding
- requires a shielding gas with high argon content.

Fig 16.17 – Volt/amp ranges for GMAW

Volatages and currents shown are due to the graph applying to 1.2 mm steel wire and argon/15% CO₂ shielding gas.
Pulsed current

Pulsed current may be available on some GMAW power sources. The welding current is set to fluctuate between a high peak current level for fusion and deposition and then a low background current level for weld pool solidification and cooling. The peak and background currents are adjustable and the time for each current level can also be adjusted. On some GMAW welding power sources, the number of pulses per second can be varied from ten per second (or higher) down to about one per second, depending on the time set for the peak and background current.

Pulsed current is particularly useful for welding very thin materials, providing good penetration during the high current cycle with cooling of the molten pool during the low current cycle. In effect, pulsed current produces a series of spot welds, penetration is good, distortion is minimised and control is improved for difficult welding situations involving thin materials and positional welds.

A number of machine manufacturers are now providing a droplet transfer option. In this mode, the variables related to background current, pulse frequency and pulse current are controlled to provide a cool/heat cycle that produces sufficient current and voltage to melt off a droplet of wire at each pulse cycle. Refer to Figs 16.18 and 16.19.

![Pulsed current terms graphic](image-url)
Fig 16.19 – Increasing pulse rate increases average amperage
Classification of consumables

There are many different types of solid electrode wires commercially available. They are classified according to a particular standard, which makes it possible to identify and select the most suitable type of wire for a job. It is important to understand these classification systems and the information they represent.

Consumable classification systems list a number of essential features about the consumable; for example, consumables are classified in terms of electrode construction, filler metal composition, shielding method, mechanical strength of the weld deposit and so on.

Solid wire electrodes classification system

AS/NZS 2717.1 classifies solid wire electrodes under three groups of elements, separated by hyphens. Each group consists of a number of letters or letters and numbers.

An example of the full classification system is shown below.

eg AS/NZS 2717.1 ES2-GM-W502H


Represents the code for ferritic steel electrodes.

Group 1 (ES2)

The first group of letters relates to the filler metal. ES stands for ‘electrode solid’. After ES, a number indicates the chemical composition of the wire. From the following chart, you can see that a wire ES2 contains 0.07% carbon and 0.9 to 1.4% manganese.
Electrodes can also contain very small additions of copper, titanium, zirconium and aluminium.

**Group 2 (GM)**

The second group relates to the shielding method. G represents gas shielded and then two letters that indicate the type of shielding gas used during qualification tests and the welding current required, for example:

- **C** = shielded with carbon dioxide (CO₂)
- **M** = shielding with a mixture of gases
- **I** = shielded with an inert gas

For example, **GM** indicates that the wire is to be shielded by use of mixed gas.

**Group 3 (W502H)**

The third group relates to deposited weld. W means weld metal followed by a three-digit number. The first two numericals refer to one-tenth of the minimum strength of the deposited weld, which is measured in megapascals (MPa). The third numerical refers to the minimum impact test or value. The letter H generally completes the classification, which indicates that the process is hydrogen-controlled.

- **W** = weld metal properties
- **50** = 500 MPa (minimum specified tensile) strength
- **2** = degree of impact test
- **H** = hydrogen-controlled

For example, **W502H** indicates the weld strength is 500 MPa, impact tested to achieve a minimum 47J @ 0 °C and low in hydrogen content.
Typical minimum Charpy impact test values expressed in joules (J) are as follows.

<table>
<thead>
<tr>
<th>Weld metal designation (designer's requirements)</th>
<th>Required minimum average Charpy V-notch impact energy value J</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon steel electrodes</strong></td>
<td></td>
</tr>
<tr>
<td>W50ZHX-X</td>
<td>Not required</td>
</tr>
<tr>
<td>W50AXH-X</td>
<td>47 at +20 °C</td>
</tr>
<tr>
<td>W500XH-X</td>
<td>47 at 0 °C</td>
</tr>
<tr>
<td>W502XH-X</td>
<td>47 at -20 °C</td>
</tr>
<tr>
<td>W503XH-X</td>
<td>47 at -30 °C</td>
</tr>
<tr>
<td>W504XH-X</td>
<td>47 at -40 °C</td>
</tr>
<tr>
<td>W505XH-X</td>
<td>47 at -50 °C</td>
</tr>
<tr>
<td>W506XH-X</td>
<td>47 at -60 °C</td>
</tr>
</tbody>
</table>

Here are some examples of the system.

**ES2-GM-W502H**
A plain carbon steel wire electrode.

The chemical composition can be found in the previous chart. When deposited with an Ar/CO₂ gas shield, the weld metal will have a minimum tensile strength of 500 MPa and an impact value 47J @ 0 °C. The weld is hydrogen-controlled.

**ES4-GC-W503H**
A plain carbon steel wire electrode.

The chemical composition can be found in the previous chart. When deposited with CO₂ shielding gas, the weld metal will have a minimum tensile strength of 500 MPa and an impact value of 47J @ -20 °C. The weld is hydrogen-controlled.

Filler wires for welding of steels are de-oxidised with manganese and silicon and are generally copper coated (nickel is sometimes used). The copper coating of the wire serves three purposes:
- prevents corrosion of the wire
- improves current pickup
- improves feeding characteristics.

Common wire sizes for GMAW of steels are as follows.
Gas metal arc welding variables

The variables affecting the GMAW process are as follows:

- arc voltage
- wire speed/amperage
- travel speed
- electrical stick-out
- torch angle
- shielding gases and flow rate.

Arc voltage

Arc voltage determines the mode of metal transfer, arc length (and therefore width) and also the weld shape when GMA welding. At low arc voltages, resistance across the arc causes extinguishment of the arc, which results in short circuiting (dip transfer). Higher arc voltages may be enough to maintain an open arc by overcoming the electrical resistance.

As the arc voltage is increased, arc length is increased. This enables more wire to be melted off without ‘stubbing’ as sometimes occurs when high wire feed speeds and low arc voltages are used. Increased arc length also increases the width of the weld bead.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>1.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Fig 16.20 – Effect of arc voltage

It can be seen therefore that if arc voltage is increased without changing the wire speed or travel speed, a wider, flatter bead will result.

Wire speed/amperage
Wire speed and amperage are controlled by the same control at the wire feeder on a GMAW plant. Consequently, these variables cannot be adjusted independently of each other.

As the wire feed rate increases, the wire is driven closer to the work and the arc voltage is loaded up. This produces a current rise as the constant voltage power source responds to the voltage drop. The current density in the wire increases and the melt-off rate of the wire increases. Amperage is the most important factor when determining heat input into the metal being welded.

As previously explained, voltage and wire feed rate are linked together to produce the various modes of metal transfer. A minor change in one may have an insignificant effect on the weld characteristics. More commonly, a change in any parameter may require the operator to also adjust another variable to compensate.

Increasing wire speed/amperage control will:

- increase the wire feed rate
- reduce arc voltage slightly (C/V machine will compensate)
- increase amperage
- increase deposition rate
- increase penetration
- increase heat input
- for a given travel speed, increase the size of the weld bead.

Decreasing wire speed will have the opposite effect.

**Fig 16.21 – Effect of amperage**
As travel speed is increased, the weld bead becomes smaller and stringy in appearance due to the lesser amount of filler wire being deposited in the same place. Heat input is also reduced, due to the fact that the arc does not remain above any particular point for very long. A decrease in travel rate will have the opposite effect and produce a larger more convex weld shape. In GMAW, the travel rate can also affect penetration, due to the effect that the arc has on the parent metal.

For example, an operator may actually get better penetration by increasing the travel rate, because this action allows the arc to directly heat the parent metal. Conversely, an operator who slows the travel rate down (and thus allows the weld metal to build up under the arc) may in fact produce lack of fusion in a weld.

**Electrical stick-out**

When discussing GMAW, two types of stick-out are referred to.

1. **Visible stick-out** – The distance that the electrode protrudes beyond the gas nozzle.
2. **Electrical stick-out** – The distance that the electrode protrudes from the contact tip.
Visible stick-out has little effect upon welding conditions except that, if excessive, shielding efficiency will be reduced. However, electrical stick-out is an important consideration. Welding current is transferred to the wire via the contact tip. The wire between the end of the contact tip and the arc offers electrical resistance. As the electrical stick-out is increased, so is the electrical resistance (Fig 16.24).

The effect of this increased resistance is:
- reduced amperage
- reduced penetration
- reduced heat input
- higher deposition rate.

The increased deposition rate is brought about by:
- pre-heating of the wire
- the wire feed rate being adjusted to compensate.

As the increased electrical resistance due to the increase in electrical stick-out pre-heats the wire, it tends to melt off sooner. This has the effect of increasing the arc length, which in turn tends to increase arc voltage. Because of the power source characteristics (constant voltage), the current reduces and thus compensates. If the drive motor speed is now increased, there will be an increase in wire deposition rates.

A good operator can also use arc length to control heat, because when the operator increases arc length there will be an increase in arc length and voltage. This has the effect of reducing the heat, because the CV power source compensates for the voltage increase by reducing current.
Torch angle

As with any welding process, the angle of approach must be adjusted to distribute the weld metal evenly in the joint. The torch should typically dissect the angle between the two parts to be joined. The theoretical torch angle may be varied to compensate for the various heat sink paths of different joint configurations (Fig 16.25).

Angle of travel

The angle of the gun is maintained such that it is ‘pushed’ in the direction of travel (Fig 16.26).

The exception to this is when making heavy welds in spray transfer where the gun is ‘dragged’. This is done to direct shielding gas over the solidifying/cooling weld metal, which remains hot for an extended period of time.

The operator determines the actual angle of travel used by seeking the best compromise between good visibility and efficient shielding.

As the torch angle is lowered, shielding efficiency is reduced due to the venturi effect, which draws air into the gas shield.
Shielding gases

In Australia, GMAW was also commonly known as ‘MIG welding’ (metal inert gas). This is in fact misleading, as it suggests that the shielding gas is inert. All GMAW of carbon and low alloy steels employs the use of an active shielding gas, ie there is a reaction between the shielding gas and the metal droplets as they travel across the arc. Inert shielding gases are used for welding stainless steels and non-ferrous metals. To achieve the desired arc stability when welding carbon and low alloy steels, some oxidising action is required in the arc. This can be achieved in one of two ways, using:

- CO₂ (carbon dioxide) as a shielding gas, or
- Ar (argon) as the base with the addition of CO₂ and/or O₂ (oxygen).

Carbon dioxide

CO₂ is easily produced and large quantities can be stored in a gas cylinder, because the gas liquifies at low pressures. CO₂ is therefore cheap when used as a shielding gas. CO₂ gas breaks down into carbon monoxide and oxygen in the arc and this produces a highly reactive arc. CO₂ promotes the following characteristics to the welding arc:

- deep penetration
- high spatter levels
- high deposition rates
- high heat input.

However, true spray transfer cannot be achieved.

CO₂ is best suited to the making of welds using dip transfer or for production-type welds on mild steel. The additional heat of CO₂ helps to overcome the tendency towards lack of fusion and increases deposition rates. CO₂ tends to produce a convex bead shape, with a rough appearance and high spatter levels. Typically, CO₂ requires a dedicated flow meter and higher flow rates, because the gas has different density and flow characteristics when compared to argon.

Note: Angle varies with direction of travel drag or push.
Argon

Argon is a true inert gas that is often used to weld non-ferrous metals. Argon ionises easily to promote electron flow, however argon is more expensive than CO₂ and is rarely used by itself to weld carbon and low alloy steels. When used to weld mild steel, argon produces arc characteristics that have the following features:

- smoother arc
- lower penetration
- lower heat input
- lower spatter
- improved bead shape
- promotes spray transfer.

However, costs will increase.

Oxygen

Oxygen is an oxidising gas and when used in small quantities in the GMAW of steel will improve weld finish and arc transfer characteristics.

Gas mixtures

Gas mixtures for welding steel employ the use of argon as a base to promote a smooth arc, combined with differing levels of CO₂ and/or O₂ to achieve desirable arc characteristics.

The greater the CO₂ addition, the lower the cost and the more the arc characteristics align to the characteristics of CO₂. The lower the addition of CO₂, the more the arc aligns toward characteristics produced by argon shielding gas.

<table>
<thead>
<tr>
<th>Shielding gas</th>
<th>Chemical behaviour</th>
<th>Effect/uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>inert</td>
<td>for welding all metals (mainly non-ferrous)</td>
</tr>
<tr>
<td>CO₂</td>
<td>oxidising</td>
<td>produces high spatter and deep penetration used with de-oxidised wire on carbon steels</td>
</tr>
<tr>
<td>argon/CO₂</td>
<td>oxidising</td>
<td>for welding carbon and low alloy steels produces low spatter and moderate penetration</td>
</tr>
<tr>
<td>argon/CO₂O₂</td>
<td>oxidising</td>
<td>additional oxygen increases penetration and improves finish used with de-oxidised wire to weld carbon and low alloy steels</td>
</tr>
</tbody>
</table>

Each gas company will supply mixtures of their own formulation. However, as a rough guide for welding carbon and low-alloy steels, uses for mixtures approximating the following compositions are as follows.
<table>
<thead>
<tr>
<th>Gas</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Cheap reliable production welds using globular transfer particularly on thicker plates, or positional welds using dip transfer.</td>
</tr>
<tr>
<td>Ar + 25% CO₂</td>
<td>General use in dip transfer up to 5 mm in thickness or positional welds.</td>
</tr>
<tr>
<td>Ar + 15% CO₂</td>
<td>Multi-purpose for dip and spray transfer.</td>
</tr>
<tr>
<td>Ar + 5% CO₂</td>
<td>Quality welds using spray transfer in the flat position.</td>
</tr>
</tbody>
</table>

The choice of shielding gas influences bead shape, as well as the amount of penetration obtained. The effect of shielding gas upon bead shape can be seen in Figs 16.28 (a) and (b).

![Diagram](image)

**Fig 16.28 – (a) Effect of a change from argon to helium and (b) effect of various shielding gases on bead shape**

**Flow rates**
Gas flow rates should be set so as to provide adequate shielding.

- The recommended rate of flow for argon/CO₂ mixtures = 12–14 litres/min.
- The recommended rate of flow for CO₂ mixtures = 18–20 litres/min.

It should be kept in mind that excessively high flow rates cause turbulence and increase the venturi effect, which will in fact drag in atmospheric gases when torch angles are too low.

**Other machine controls**

**Spot timer**
Spot timers allow the weld time and reset time to be preset as a means of making consistent weld sizes for spot welding. The timer is activated when the gun trigger is depressed.
Burnback control
Enables wire to feed for a small amount of time after current flow is terminated when the torch trigger is released. This can be adjusted to prevent the wire fusing to the contact tip, or to stop it sticking to the weld pool when welding is terminated.

Pre and post-gas purge control
Pre-gas timers allow the gas to flow before the arc is started and a post-gas timer allows the gas to flow for a set time after the arc is finished. Used to protect the end of wire, particularly when welding aluminium and steel.

Spool brake
The wire spool carrier employs a braking device to prevent over-run of the wire due to the inertia of the spool of wire. It should be adjusted to provide enough braking to prevent over-run, but with no unnecessary drag that would cause slippage of the wire at the drive rollers.

Joint design for gas metal arc welding
Pre-qualified joint preparation for GMAW of steel structures can be found in AS/NZS 1554.1. It can be seen that joint design is similar to that used for MMAW butt welds in steels, but with the following variations.

- Included angles of butt welds are reduced by 10°. This is because the thinner electrode and lack of flux provides easier access to the root of the joint.
- The root face for butt welds is decreased when dip transfer is used, due to the fact that penetration is limited and increased when spray transfer is used as a means of preventing burn-through.

GMAW defects
Apart from slag inclusions (silicon can be trapped in the weld), all the common weld defects that occur with other processes may also occur with GMAW. Defects such as porosity and lack of fusion can be a particular problem with GMAW.

The defects commonly encountered in GMAW are:

- porosity
- cold lap/lack of fusion
- lack of root penetration
- excessive penetration
- contour defects
- undercut
- weld cracking
- excessive spatter
- stray arcing.
Porosity
Defined as a pore or group of gas pores in the weld metal, porosity may be conveniently differentiated according to size and distribution. A number of different terms are used, related to size.

- **Gas pore** – A cavity (usually spherical), formed by entrapped gas during the solidification of molten metal.
- **Wormhole** – An elongated or tubular cavity in the weld metal, caused by entrapped gas being forced away from the solidifying weld metal.
- **Cluster** – A group of pores in close proximity to each other.

As is the case with other welding processes, porosity may be caused by moisture, or by surface contaminants on the plate. The GMAW process has no hydrogen source itself but is particularly susceptible to contamination and the parent metal and filler must be clean. By far the greatest cause of porosity is due to inadequate gas shielding.

This may be due to:

- flow rate set too low
- flow rate set too high
- no gas flow at all
- excessive wind or air movement at the gun
- contaminated shielding gas
- stick-out length too long
- gun angle too low.

Lack of fusion
Defined as portions of the weld deposit which do not fuse to the surface of the metal or edge of the weld joint. With GMAW, lack of fusion is commonly referred to as ‘cold lapping’, as it usually takes the form of lack of sidewall fusion over an extensive part of the joint.

Cold lapping is common when welding in the dip transfer mode, particularly when the plate thickness exceeds 5 mm. Welding downhill, or with high wire speed and low arc voltage settings, further increases the risk of occurrence. Plates that are dirty or heavily scaled further exacerbate the problem.

Cold lapping does not generally occur when welding in the spray transfer mode. Therefore, to minimise the likelihood of cold lapping, one or more of the following should be employed:

- weld in the spray transfer mode
- clean plates
- if in doubt, set the arc voltage slightly high
- set enough amperage to ensure sufficient heat for fusion
- keep the electrical stick-out short
- use CO₂ shielding gas or a mixed gas high in CO₂.
Lack of root penetration

Defined as the failure of the weld metal to completely fill the root of the joint. Root runs in butt welds are normally made in the dip transfer mode, except for those in heavy plate, in which case spray transfer would be used. The dip transfer mode is inherently ‘cold’, employing low amperages and voltages. This means that root penetration is limited in this mode.

The solution to overcoming lack of root fusion is to use thinner root faces on butt welds than would be the case with other processes, i.e. typically in the range of ½ to 1 mm.

In fillet welds, the solution is to use comparatively high amperage settings when in the dip transfer mode. Additionally, CO₂ or a gas mixture high in CO₂ will help.

Excessive penetration

Defined as excess weld metal protruding through the root of a butt weld, this defect normally only occurs on thin (sheet) materials or when excessive heat (current) is used. Adjustment of wire speed, arc voltage or travel speed will usually overcome this problem with relative ease.

Another form of this defect is electrode wire protruding through the root of the butt in the form of ‘spikes’ or ‘icicles’. This is caused when arcing to the root face of the butt weld momentarily ceases, a small amount of wire penetrates the butt and the arc is re-established when the wire contacts the parent metal.

The solution to this problem is to limit the width of the root gap and/or to increase the arc voltage, which results in a wider spread of the arc so that arcing to one or both sides of the weld is always present.

Contour defects

Contour defects may be in the form of overroll or overlap, excessive convexity or concavity of the bead, or simply rough, uneven appearance.

Travel speed and torch angle adjustments may fix many of these problems, but the GMAW operator has an advantage in that he/she can control weld profile by adjusting the arc voltage.

Excessive convexity may be remedied by increasing arc voltage. Beads that are too wide or too concave may be remedied by decreasing arc voltage.

Undercut

Defined as a groove or channel in the parent metal, occurring continuously or intermittently along the toes or edge of a weld.

Undercut is not a common problem in GMAW; however, it is likely to be encountered in two situations.

1. When fillet welding in spray transfer – This is normally caused by setting the arc voltage too high, causing a long arc length that results in undercutting of the toe of the weld of the vertical plate. The solution to this is quite simple and is good practice for all welds in spray transfer: set a smooth spray transfer mode using the lowest arc voltage that will facilitate this.
2. Vertical-up welds – Solid wires are largely unsuitable for making stringer beads in the vertical-up position. Convex beads with some undercut generally result. When a weave technique is used, a bead that is convex in the middle with undercut toes may result. The solution is to:

a) reduce the arc voltage, or
b) reduce the overall heat of the welding, or
c) pause longer at the toes.

**Cracking**

Defined as discontinuities produced either by tearing of the metal in the plastic condition (hot cracks) or by fracturing when cold (cold cracks), cracking in GMAW is not common but may be related to parent metal susceptibility or stress. Cracking is considered to be a serious defect and rarely is any amount of cracking tolerated.

Hot cracks are common in materials with high coefficients of expansion and/or which suffer from hot shortness. Hot cracking occurs at elevated temperatures soon after solidification. This mode of cracking is common in aluminium and stainless steel.

Cold cracking is most common in hardenable materials, particularly when cooling rates are rapid.

Cracks may also be described depending on how, when and where they occur, eg longitudinal, transverse, crater, centre line, hot, cold, toe and underbead. Cracks may occur in either the parent metal, usually as fusion or HAZ cracks, or in the weld metal.

**Crater cracks**

These come from hot shrinkage. The crater solidifies from all sides toward the centre, leading to a high concentration of stress at the centre. If the metal lacks ductility, or the hollow crater cannot accommodate the shrinkage, cracking may result. Crater cracks may, under stress, propagate from the crater and lead to failure of the weldment.

Cracking in GMA welds is not generally a major problem due to the following factors.

- GMAW is a ‘low-hydrogen’ process.
- Hollow craters are not usually a characteristic of GMA welds.
- The inherent low heat input is ideal for stainless steels and other metals that are prone to hot cracking.

**Stray arcing**

Stray arcing is defined as damage on the parent metal resulting from the accidental striking of an arc away from the weld. Stray arcing is not a major problem associated with GMAW, as the electrode is usually only live when the gun trigger is depressed. Care should be taken that the gun is not put down with the weight resting on the trigger and also that arcing does not occur between the job and the work return lead connection.
Chapter 16 – GMAW/FCAW and equipment

Excessive spatter

Defined as the metal particles expelled onto the surface of the parent metal or weld during welding and not forming part of the weld.

This usually occurs due to one of the following factors:

- shielding gas or plate contaminated with moisture
- high levels of CO₂ or O₂ in the shielding gas
- excessive arc voltage in the dip transfer mode
- welding in the globular transfer mode.

Spatter is not usually present in the spray transfer mode.

Trouble shooting/equipment malfunction

Compared to the manual welding processes, GMAW requires higher levels of care and maintenance. Major sources of frustration are the problems associated with feeding of the electrode wire. This is a particular problem when welding with aluminium wire, feeding wire through long gun cables, or when using a gun cable that has been poorly maintained.

Equipment malfunctions with GMAW fall into two main categories:

1. electrical
2. mechanical.

The main problems with regard to electrical malfunctions and their likely causes are as follows.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Likely cause</th>
<th>Rectification</th>
</tr>
</thead>
<tbody>
<tr>
<td>No power at machine</td>
<td>mains switch off</td>
<td>check switches and fuses. If intact, call electricians</td>
</tr>
<tr>
<td></td>
<td>machine switched off</td>
<td></td>
</tr>
<tr>
<td></td>
<td>blown fuse</td>
<td></td>
</tr>
<tr>
<td>Mains power on but no welding</td>
<td>trigger switch not working</td>
<td>check − if trigger is working, wire feeder will operate, wire will feed</td>
</tr>
<tr>
<td>power</td>
<td>wire feeder not connected</td>
<td></td>
</tr>
<tr>
<td>Wire feeds, but no arc</td>
<td>work return not connected</td>
<td>check work return</td>
</tr>
<tr>
<td></td>
<td>blown fuse</td>
<td>check fuses</td>
</tr>
</tbody>
</table>
Mechanical problems manifest themselves in the form of wire feeding problems. Common wire feeding problems and their likely causes are as follows.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Likely cause</th>
<th>Rectification</th>
</tr>
</thead>
<tbody>
<tr>
<td>No wire feed at all</td>
<td>spool brake excessively tight</td>
<td>check tension on spool brake</td>
</tr>
<tr>
<td></td>
<td>no friction at drive rolls</td>
<td>check drive rolls and adjust as necessary</td>
</tr>
<tr>
<td></td>
<td>wire jammed at drive rolls or in gun cable</td>
<td>check guide tubes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>check wire conduit</td>
</tr>
<tr>
<td>Uneven wire feed</td>
<td>dirty or damaged liner</td>
<td>clean or replace</td>
</tr>
<tr>
<td></td>
<td>slippage at drive rolls</td>
<td>increase pressure</td>
</tr>
<tr>
<td></td>
<td>liner cut too short</td>
<td>replace</td>
</tr>
<tr>
<td></td>
<td>kinks in gun cable</td>
<td>keep as straight as possible</td>
</tr>
<tr>
<td></td>
<td>insufficient roll pressure</td>
<td>tighten drive rolls</td>
</tr>
<tr>
<td></td>
<td>wire distorted due to excessive roll pressure</td>
<td>reduce roll pressure</td>
</tr>
<tr>
<td></td>
<td>wire is kinked or twisted</td>
<td>misalignment of drive rolls</td>
</tr>
<tr>
<td></td>
<td>contact tip worn or dirty</td>
<td>damaged liner</td>
</tr>
<tr>
<td></td>
<td>spool brake excessively tight</td>
<td>inspect and replace</td>
</tr>
<tr>
<td></td>
<td></td>
<td>check tension on spool brake</td>
</tr>
<tr>
<td>Spool overrun</td>
<td>spool brake too loose</td>
<td>tighten</td>
</tr>
<tr>
<td>Wire fused to contact tip</td>
<td>excessive arc voltage</td>
<td>reduce arc voltage</td>
</tr>
<tr>
<td></td>
<td>excessive burnback time</td>
<td>reduce burnback time</td>
</tr>
<tr>
<td></td>
<td>intermittent wire feed</td>
<td>see above</td>
</tr>
</tbody>
</table>

GMAW equipment requires a regular inspection and maintenance schedule, such as:
- contact tips inspected at least daily
- liners, drive rolls and spool brake inspected weekly
- gas and electrical connections inspected monthly.
Flux-cored arc welding

The introduction of flux-cored wires (creating the process of flux-cored arc welding) extended the range of work carried out by hand-held semi-automatic welding. Flux-cored welding brought with it the advantages of greater penetration, higher welding speeds, site-welding capability, and its ability to be applied to a greater range of plate thicknesses. Modern flux-cored wires have reduced lack of fusion faults and also have improved weld finish.

Principles

As the name implies, the FCAW process employs an electrode which is essentially a hollow formed steel sheath containing a core of flux. The flux-cored electrode has been described as a ‘stick’ electrode turned inside out and made into a continuous wire.

There are two distinct types of FCAW welding.

- Self-shielding FCAW process in which all of the shielding is provided by the decomposition of the flux-core.
- Gas-shielded FCAW, which uses additional shielding gas to assist or take over the role of shielding the arc from the atmosphere.

Self-shielding wire has the advantage that it is suitable for use in windy conditions and is therefore ideally suited to site work. Further to this, no shielding gas system is required.

Gas-shielded wires have the disadvantage of requiring a shielding gas system, but they produce lower levels of fume.
A major advantage of both FCAW processes is that high current densities are used. This means that the mode of metal transfer across the arc is always spray transfer.

The advantages of this when compared to GMAW are:

- higher deposition rates
- deeper penetration
- excellent fusion to the base metal.

The downside of this for the operator is:

- higher emission of UV
- higher fume levels
- more heat is generated.

The flux-core also serves as a medium to introduce deoxidants and other alloying elements into the weld. The flux is low in hydrogen and the process is therefore suitable for welding hardenable steels and other carbon and low alloy steels.

Due to the limitations of the manufacturing technology available at the time, early flux-cored wires were produced by applying the flux to a strip of metal and then forming it into a tube. Wires smaller than about 2 mm to 2.4 mm diameter could not easily be produced by this method. This meant that when low welding currents were required, the current density in the wire was relatively low and the metal transfer across the arc was relatively coarse and rough.

Currently, flux-cored wires are produced in a number of configurations designed to improve burn-off, as shown in Fig 16.30. They are also being manufactured by filling a tube with flux and drawing the wire to produce a seamless electrode in sizes down to 0.9 mm diameter. This is a major advantage in that even though welding current used may be low, the current density is high enough to ensure ideal transfer characteristics across the range.

![Fig 16.30 – Flux-cored wire](image-url)
Advantages of the process

Penetration
Compared with other processes, the depth of penetration is much greater. This makes it possible to reduce the fillet leg length without decreasing the strength of the weld (Fig 16.31).

![Fig 16.31 – Comparison of penetration](image)

Deposition rate
Compared with manual metal arc electrodes, the deposition rate is very high.

Slag detachability
Providing that the operating conditions are correct, the slag is virtually self-detaching. In a deep groove, the slag is removed easily when the weld has cooled.

Appearance
Providing the operating conditions are correct, the weld appearance is bright and neatly rippled with a good ‘wash’ into the parent metal at the toes. Fillet welds tend to be mitre or slightly concave rather than convex.

Weld quality
The weld deposit is low in hydrogen content and has good mechanical properties. Sound radiographic quality welds can be achieved.

Low spatter
Assuming the correct operating conditions have been selected, spatter should be minimal.

Visibility
Because of its high deposition and high penetration characteristics, gas shielded FCAW is often compared with submerged arc welding, which can offer similar advantages. With the FCAW process, however, the operator can see the arc and be in a position to allow for variations in the joint fit-up.
Limitations of the process

Limited applications
The range of FCAW consumables currently available is limited to ferrous-based alloys such as steel. Constant development means there is potential for a much greater range of materials that may be welded with FCAW in the future.

Loss of gas shielding
The gas-shielded FCAW is only suitable for sheltered conditions away from any wind that will interfere with the gas shielding. For this reason, the process is not usually suitable for outdoor work unless adequate steps are taken to screen the arc from the wind. Loss of gas shielding can cause severe porosity in the weld.

Self-shielding wires do not suffer from this problem.

Operator fatigue
With the smaller diameter of all positional wires, operator fatigue is no greater than that experienced with GMAW. However, when used as a high deposition process, the welding gun and cables must be robust enough to withstand the heat generated and are usually rather heavy. This, together with the hot conditions, makes operator fatigue a significant factor. This problem can be overcome by mechanising the process.

Fumes
Many FCAW wires (particularly self-shielding wires) emit a substantial volume of fumes that can add to the discomfort of the welder. Special precautions may be required to eliminate these fumes, such as the use of fume extractor nozzles fitted to the gun. In confined spaces, fume extraction units will be needed to remove fumes from the work area into filter banks or outside the workshop.

Equipment
The equipment required is essentially the same as that used for GMAW, however the component parts may be heavier duty. Electrode positive is generally required for gas assisted wires, whilst most of the self-shielding wires use electrode negative.

A constant voltage DC power source is generally used, however there are some newer wire feeders that incorporate a wire feed rate compensating circuit. These will operate successfully on constant current power supplies.

The wire feed unit used for GMAW can usually be adapted for FCAW. The wire reel holder may need to be changed to carry the spool of flux-core wire, which is usually supplied in 30 kg reels. The wire drive rolls may be serrated or have a 15° vee groove. Care must be taken to minimise the pressure on the feed rolls so that the wire is not squeezed out of round.

The welding torch is the preferred pistol type where the wire is kept straight as it passes through the torch. Goose-necked torches with a small radius bend tend to create a ‘drag’ on the wire, thus giving rise to wire feed problems.

Because of the high amperages employed, heat radiation is intense and therefore the welding torch is sometimes fitted with a heat shield at the handle.
Techniques for gas-shielded flux-cored arc welding

A welding operator with a reasonable degree of skill in MMAW or GMAW can readily adapt to gas-shielded FCAW; however, a few factors need attention.

Electrode stick-out

Recommended stick-out lengths must be adhered to; they tend to be greater than the stick-out lengths used with GMAW. Stick-out is the length of the wire from the end of the contact tip to the surface of the work piece. A shorter stick-out could result in a poorly shaped weld, due to an increase in amps and a decrease in voltage. A longer stick-out could give rise to excessive spatter and porosity in the weld due to poor gas-shielding when using gas-shielded wires.

Direction of travel

The direction of travel (whether pushing the torch or dragging it) is usually a matter of personal preference on the part of the operator. However, where the work is to be of a particularly high quality, the backhand or drag method is regarded as superior.
Position of torch and angle of torch

As already mentioned, it is preferable to push the arc with gas-assisted wires and most self-shielded wires should be dragged (although not always essential). Fig 16.33 shows the recommended angle of the torch in relation to the direction of travel.

In the flat position, the torch is angled at 90° to the plate (Fig 16.34).
Self-shielding FCAW

This is probably best regarded as a semi-automatic version of the MMAW process. Like MMAW, the flux-cored wire generates sufficient vaporised gases around the arc to completely protect the arc from the atmosphere.

Advantages of self-shielding FCAW

- No external shielding gas or flux is required; therefore the process can easily be used outdoors, even in draughty conditions.
- All positional wires, hard facing and stainless steel wires are available.
- Deposition rates are high when compared with MMA welding.
- Slag is easily detachable, except where tacks have been made with cellulose or rutile electrodes.
- The weld deposit is low hydrogen and resists cracking in many crack-sensitive applications.
- Poor fit-ups (gaps) can be handled easily by increasing wire stick-out.

Limitations of self-shielding FCAW

- Penetration is not as great as the gas-shielded FCAW process. It is more akin to that achieved with MMA low hydrogen electrodes.
- Slag removal is difficult when welding over tacks or a previous weld made with cellulose or general purpose electrodes. The use of low silicon cellulose electrodes or certain low hydrogen electrodes can overcome this problem.
- Fumes can also be a problem and the precautions outlined previously for gas-shielded FCAW may be necessary.

Techniques for self-shielding FCAW

Welding techniques are similar to those employed with hydrogen-controlled MMAW electrodes; however, a few additional factors should be considered.

Electrode stick-out

For all-positional self-shielding electrode wires, the recommended electrode stick-out is usually 18–20 mm. If with these wires no gas nozzle is used, the electrode stick-out is visible from the contact tip to the work (Fig 16.36). Even though no gas-shielding is employed, a nozzle is commonly used to give the operator the feel of ‘normal’ electrical stick-out. When no nozzle is used, the tendency is for the operator to reduce the stick-out so as to provide the visible stick-out that the operator is used to (Fig 16.35).
Fig 16.35 – Electrode stick-out is visible

Some self-shielding electrode wires are designed to give high deposition rates in the downhand positions by employing long electrical stick-out (Fig 16.36).

A long electrical stick-out is used to increase the deposition rate by pre-heating the wire before it is melted at the arc. The recommended electrical stick-out varies, depending on the type and size of wire. The wire manufacturer’s recommendations should be observed. To assist the operator in maintaining the correct electrical stick-out for these wires, the welding gun can be fitted with a nozzle incorporating an insulated extension guide.
Electrode angles

When welding with self-shielding flux-cored wires, the electrode angles are much the same as for MMAW electrodes, as shown in Fig 16.37.

Fig 16.37 – Self-shielding wires are dragged similar to MMAW electrodes
For horizontal-vertical welds, the wire is pointed directly into the root of the joint at an approach of 40° (Fig 16.38).

Vertical welding
Most all-positional self-shielding wires can be used vertical-down or vertical-up. Vertical-down is usually preferred for welds in thinner sections, or for the first pass in a butt weld. The gun is tilted to a drag angle of 10–15° from the horizontal so that the arc force helps hold the molten metal in the joint (Fig 16.39).

Techniques for welding vertical-upwards are the same as for low hydrogen MMAW electrodes. Vertical-up welding is recommended for welds in thick sections. The first pass in a vertical-up fillet or butt is best made using a triangular weave technique and subsequent passes are made with a side-to-side weave.

Welding procedures for FCAW
There are wide varieties of flux-cored electrode wires for both the gas-shielded and self-shielding processes. Each wire has its own set of optimum operating conditions and procedures and therefore it is best to consult the wire manufacturer’s tables to obtain the recommended welding procedure for a particular wire. However, the following discussion on the effects of the operating variables associated with the FCAW process may help to refine the set procedures.
Effects of the operating variables with flux-cored arc welding

With FCAW there are five major operating variables:

- polarity
- arc voltage
- current (wire feed speed)
- travel speed
- electrode stick-out.

Polarity

Whereas all solid wires for GMAW run on direct current electrode positive DC +ve, some flux-cored wires are designed to run on negative polarity.

Arc voltage

If the other variables are held constant, arc voltage variations have the following effect.

- Higher arc voltage gives a wider and flatter bead shape.
- Excessive arc voltage can cause porosity.
- Low voltage causes a convex, ropey bead shape.
- Extremely low voltage will cause the electrode wire to stub on the parent metal.
- The arc voltage should be set according to the wire manufacturer’s recommendations and, if necessary, be fine-tuned to give the desired bead shape.

Current (wire feed speed)

In setting critical procedures, wire feed speed is a better measure than the welding current. The wire feed speed is constant, whereas the current reading at the ammeter tends to fluctuate.

If the other variables are held constant, current variations have the following major effects.

- Increasing the current increases penetration and deposition rate.
- Excessive current produces convex, ropey bead shapes.
- Current that is too low gives a large droplet transfer and may give porosity.

As the current (WFS) is increased or decreased, the arc voltage must be increased or decreased to maintain the proper bead shape. The correct current range should be obtained from the wire manufacturer’s tables.
Travel speed
If the other variables are held constant, travel speed variations have the following effects.

- Too high a travel speed increases the convexity of the bead and causes uneven edges.
- Too slow a travel speed results in slag interference, possible slag inclusions and a rough, uneven bead shape.

Electrode stick-out
If the other variables are held constant, variations in stick-out have the following effects.

- Increasing stick-out decreases the welding current.
- Decreasing stick-out increases the welding current.
- With self-shielding wires, the stick-out can be increased to reduce the penetration, thereby allowing poor fit-ups to be bridged.
- Decreasing stick-out can lead to spatter build-up on the contact tip or overheating of the contact tip.

Flux-cored wire electrodes
Early electrode wires developed for gas-shielded FCAW used a basic type flux with low hydrogen content and required electrode positive polarity. This type of flux-cored wire electrode is still popular today.

More recent developments have led to the availability of electrode wires with a rutile flux suitable for more general purpose work. Many of these rutile flux-cored wires perform better with electrode negative polarity.

Virtually all flux-cored wires, whether gas-shielded or gasless, require a constant voltage power source; however, there are a few types that can operate satisfactorily with constant current power sources.

Because of all the variables stated, it became necessary to provide a system of classification for flux-cored electrode wires, an outline of which follows.

FCAW consumables classification
There are many different types of flux-cored electrode wires commercially available. They are classified to a particular standard, which makes it possible to identify and select the most suitable type of wire for a job. It is important to understand classification systems and the information they represent.

Consumable classification systems list a number of essential features about the consumable; for example, consumables are classified in construction, filler metal composition, shielding method, mechanical strength of the weld deposit and so on.

ISO 17632:2004 classifies flux-cored electrodes within this standard as ISO 17632-A or ISO 17632-B, ie there are two classifications within the standard. Reference should also be made to ISO 17634 and ISO 18276.

Please refer to Appendices 7, 8, 9 and 10 at the back of this book for further information.
Safety recommendations with FCAW

- Because of the greater arc intensity, particularly with the gas-shielded FCAW process, a welding lens one or even two shades darker than for MMAW should be used.
- A heat shield fitted to the torch handle is desirable to protect the operator’s hand from radiated heat. Reflective-backed leather gloves are recommended.
- Additional care should be taken regarding clothing and protective leathers. Dark woollen clothing is most desirable and leather gloves, apron, jacket, spats, etc should be worn.
- Attention should be given to ensuring adequate ventilation. If natural ventilation is inadequate, exhaust fans and respirators should be used.

Flux-cored arc welding faults
The defects commonly encountered in FCAW are:

- weld cracking
- porosity
- slag inclusions
- lack of fusion
- insufficient or excessive penetration
- contour faults
- undercut
- excessive spatter
- stray arcing.

Cracking
Cracks may be described depending on how, when and where they occur, eg longitudinal, transverse, crater, centre line, hot, cold, toe and underbead. Cracks may occur in either the parent metal, usually as fusion or HAZ cracks, or in the weld metal. Cracking is considered to be a serious weld fault and rarely is any amount of cracking tolerated.

Crater cracks occur when the weld solidifies from all sides toward the centre, leading to a high concentration of stress at the centre of the crater. If the metal lacks ductility, or the hollow crater cannot accommodate the shrinkage, cracking may result. Crater cracks may, under stress, propagate from the crater and lead to failure of the weld.

Cracking in FCAW welds on mild steel is not generally a major problem.

Porosity
Porosity in FCAW welds may be the result of welding on a parent metal that is susceptible, such as steel that contains high amounts of dissolved gases or sulphur. Porosity may also be caused by welding on dirty material or material contaminated with moisture, oil, paint or grease. The electrode may have been contaminated, or too much voltage or current has been used. The shielding gas may not be the correct type to suit the wire. The gas flow may be set incorrectly or be affected by wind, or too long an arc length may have been used.
Slag inclusions
Slag inclusions are not generally a problem in FCAW due to the high heat input. If they do occur in FCAW, they can occur at the weld root, between weld runs, or on the weld surface. They may occur as a result of low voltage or amperage, or poor electrode manipulation. Slag inclusions can occur when incorrect joint preparations are used, or when material is dirty or contaminated.

Lack of fusion/lack of root penetration
With FCAW, lack of fusion or lack of root penetration is not normally a problem, but may be caused by working with incorrect joint configuration, low amperage, working on dirty or contaminated material or using wrong electrode angles or travel rate.

Excessive penetration
Excess weld metal protruding through the root of a butt weld may occur in FCAW because of incorrect joint preparation, wrong electrode choice, excessive amperage or incorrect variables.

Contour defects
Contour defects may be in the form of insufficient or excessive leg size, overroll or overlap, excessive convexity or excessive concavity of the bead, or simply rough, uneven appearance.

These are mainly caused by the operator, but using the correct electrode, voltage, amperage, travel speed and electrode angle adjustments may fix many of these problems.

Undercut
Undercut in FCAW is defined as a groove or channel in the parent metal, occurring continuously or intermittently along the toes or edge of a weld.

Undercut is a common problem in FCAW and may be caused by excessive voltage or amperage, too long an arc length, wrong electrode angles, or wrong travel rate.

Excessive spatter
Spatter is a normal part of welding and FCAW does not normally produce excessive spatter.

Stray arcing
Defined as damage to the parent metal resulting from the accidental striking of an arc away from the weld.

Even though stray arcing is not usually a major problem associated with the FCAW of mild steel, it is good practice to take precautions against accidental arc of the electrode anywhere other than in the weld zone.

Stray arcing can lead to serious weld failure in a material that is crack sensitive, or that is going to be put into a stressed situation.
Chapter 17 – Oxy-fuel gas welding

Introduction

Given the efficiency and advantages of other modern welding processes, there would be few welding applications for which the oxy-acetylene flame is considered to be the most efficient production process. The gas welding process is characterised by low heat input, with slow travel speeds and high heat transfer into the parent metal.

However, a competent operator can use the gas welding processes to fuse weld or repair nearly any material. The gas welding process remains as an occasional back-up process for situations where other processes are not available, or where portability of other equipment is a problem.

In the maintenance industries (and for the occasional welding of thin materials and the welding of small bore pipe), the oxy-acetylene fusion welding process is still a viable alternative to some other welding processes.

In this chapter we will look at the following.

- Oxy-fuel gas welding (OFGW) principles
  - oxygen
  - acetylene
  - gases – oxy-acetylene
- Oxy-welding techniques
  - braze welding
  - bronze
  - galvanised iron
  - silver brazing.
The oxy-fuel gas arc welding (OFGW) principles

The combination of oxygen and acetylene in near equal proportions produces a flame that has the intense heat (3000 °C) required to melt most metals. The oxy-acetylene gas combination is the only oxygen/fuel gas combination that burns completely, to produce a non-reactive secondary flame or envelope suitable for fusion welds. This secondary flame does not influence the weld pool and also acts as a neutral shield that protects the weld and weld area from the effects of atmospheric gases such as oxygen and nitrogen.

If the adjacent edges of two compatible materials are melted and protected by the flame envelope, then the edges may fuse together. A suitable filler may or may not be required. Other fuel gases such as LPG or propane produce a reactive secondary flame that interferes with the molten metal and are therefore unsuitable for fusion welding.

Applications
- flux-free fusion welding of plain carbon and alloy steel
- fusion welds of pure aluminium and some alloys (flux required)
- fusion welds of some stainless steels (flux required)
- fusion welds of copper and copper based alloys (flux required)
- fusion welds of other metals (requires great skill)
- general repairs
- braze or bronze welding (not fusion welds)
- silver soldering.

Advantages
- equipment set up is simple
- equipment is readily available and portable
- wide range of applications
- cheap consumables
- low skill level required.

Limitations
- large HAZ (distortion)
- slow output
- more suitable processes are available.
Oxygen

Oxygen is a colourless, odourless, tasteless gas. Oxygen itself does not burn, but supports combustion. Oxygen is used in welding to make the fuel gases used burn hotter.

<table>
<thead>
<tr>
<th>Chemical symbol</th>
<th>$O_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can be liquified at</td>
<td>$-183 , ^\circ C$</td>
</tr>
<tr>
<td>Density:</td>
<td></td>
</tr>
<tr>
<td>Gas at $150 , ^\circ C$ and $100 , kPa$</td>
<td>$1.337 , kg/m^3$</td>
</tr>
<tr>
<td>Liquid at B.pt</td>
<td>$1.141 , kg/L$</td>
</tr>
</tbody>
</table>

Oxygen production

Oxygen is distilled from the air around us. Air consists of one-fifth oxygen, the remainder being mainly nitrogen, with some carbon dioxide, water vapour and traces of other rare gases.

The air is compressed in stages. Between each compression stage, the heat generated is extracted in coolers, resulting in a fall in temperature of the air. The air is compressed and super cooled until it liquifies.

The liquid air is then distilled (nitrogen allowed to boil off) to separate the nitrogen from the oxygen. Nitrogen forms as a vapour, at the top of the distillation tower. The oxygen, still in liquid form, collects at the base of the tower.

This oxygen is virtually pure and is drawn off and contained under pressure in large storage vessels. The oxygen is then distributed either in cylinders as a compressed gas, or in insulated containers in liquid form.

Oxygen cylinders

An oxygen cylinder is a hollow container of sufficient wall thickness and strength to withstand much more than the filling pressure (safety factor). Into this container a cylinder valve is screwed, to which a regulator may be attached.

Oxygen gas is compressed and forced into the cylinder to produce a pressure to a maximum of $17500 \, kPa$ at $15 \, ^\circ C$. One size of cylinder (G) commonly used will hold in excess of $8.9 \, m^3$ ($8900 \, L$) of gas under pressure, but if water was to be poured into it when empty it would hold only 47 litres. It will be seen that oxygen when compressed will occupy much less space than it does at normal atmospheric pressure. It is squeezed into the cylinder and reduced in volume approximately 140 times. Oxygen cylinders are therefore very dangerous and are fitted with bursting discs that are designed to vent off any excessive increases in cylinder pressure.
Acetylene

Acetylene is composed of carbon and hydrogen ($\text{C}_2\text{H}_2$). Acetylene is a colourless gas with a distinctive odour and is readily soluble in acetone. It is a popular fuel gas for cutting and welding as it produces a hotter flame than any other fuel gas.

<table>
<thead>
<tr>
<th>Chemical symbol</th>
<th>$\text{C}_2\text{H}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 0 °C and 1 atm</td>
<td>1.1709 kg/m$^3$</td>
</tr>
<tr>
<td>Solubility of acetylene in acetone</td>
<td>300:1 by volume 175 kPa gauge</td>
</tr>
</tbody>
</table>

Flammability

Acetylene burns in air with a yellow hot and smoky flame. The ignition temperature of acetylene (335 °C) is much lower than the majority of fuel gases.

Acetylene, when mixed with air, has a very wide flammable and explosive range, from about 3% acetylene and 97% air to 81% acetylene and 19% air. When submitted to a pressure exceeding 175 kPa, acetylene becomes unstable; if subjected to a slight shock, friction or heat, it is likely to explode with great violence. Consequently, the maximum safe working pressure for acetylene is 150 kPa.

Acetylene production

In contrast to oxygen production, impure acetylene is relatively easy to make but because of its unstable nature stringent safety precautions must be maintained.

Acetylene gas is produced by feeding solid calcium carbide into water; acetylene is given off as a gas and the slaked slime remains with the water to form a sludge.

\[ \text{CaC}_2 + 2\text{H}_2\text{O} = \text{C}_2\text{H}_2 + \text{Ca(OH)}_2 \]

Calcium carbide + water = acetylene + slaked lime.

The acetylene gas given off is washed in water, purified, dried and passed onto the acetylene compressor.

A characteristic of acetylene is its effect on copper. When acetylene and copper come into contact, a highly explosive compound (copper acetylide) is formed on the surface of the copper. This compound may cause an explosion if subjected to heat, friction or a sharp blow. For this reason, copper tubing should never be used to join welding hoses – use approved type joiners only.

Acetylene cylinders

An acetylene cylinder is rather different from an oxygen cylinder; the cylinder is not hollow because acetylene is extremely unstable when compressed in a free area. The cylinder is filled with a porous material saturated with liquid acetone. Whilst the porous mass is used to break up the area inside the cylinder into a great number of very fine holes capable of absorbing the acetone in a similar manner to a sponge absorbing water, use is made of the established fact that acetone is soluble and acetylene gas can be absorbed into this liquid. The presence of the porous mass prevents large gas areas forming and limits any possible explosion to the size of the microscopic pore.
The outside shell of the container is not required to be very strong, as the pressures involved are not very high. Fusible plugs are provided in acetylene cylinders to vent off acetylene should any overheating occur (increased temperature would increase pressure).

When acetylene is forced into the cylinder, it comes in contact with and is absorbed by the acetone. Heat is produced and as the acetylene dissolves better in acetone at lower temperatures, the cylinders are sprayed with water while being filled. As acetone has the property of absorbing many times its own volume of acetylene, it permits the storage of a greater quantity of acetylene than could normally be accommodated. The acetylene gas is not present in a free space (which would be dangerous at the pressures required) but is dissolved into the acetone inside the cylinder at a pressure of approximately 1500 kPa at 15 °C.

As acetylene is drawn from the cylinder, a reaction similar to the opening of a soft-drink bottle occurs – you have seen the gas bubbling out from soft drinks when the pressure is reduced by removing the bottle top. When the acetylene cylinder valve is opened, the pressure in the cylinder falls and the gas comes away from the acetone. If the rate of flow from the cylinder is too great, the gas will not have time to separate out from the liquid and liquid acetone will flow out from the cylinder.

For this reason, on long jobs or continuous work the allowable discharge rate of acetylene is one-seventh the volume of a full cylinder per hour, eg if a cylinder containing 7000 litres is used, the maximum draw-off in any one hour would be 1000 litres.

Where it is not possible to obtain sufficient acetylene from a single cylinder without exceeding the recommended flow rate, several cylinders should be joined together with a manifold.

Acetone can also be discharged from an acetylene cylinder if the cylinder is operated whilst lying on its side – therefore, always store and operate an acetylene cylinder in the upright position.

The passing of acetone into welding or cutting equipment is extremely dangerous, as it will continue to liberate acetylene and pressures may become excessive. It also reduces the flame temperature and therefore increases the cost of carrying out the work.

Gases – oxy-acetylene

Oxygen and fuel gas combined

At the end of the nineteenth century, a discovery was made which was to have a big effect on the metal fabrication industry in general. The flame produced by burning acetylene with oxygen was hotter than any previously known. The flame was quickly adapted to heat and weld metal.

Today, the system is in wide use where welding and cutting operations use oxygen and acetylene or other fuel gases in a great variety of equipment.

Table 17.1 sets out the flame temperatures of various fuel gases. From this it can be seen that acetylene is the hottest of all flames in commercial use.
Table 17.1 – Fuel gases – temperatures

<table>
<thead>
<tr>
<th>Fuel gas</th>
<th>Maximum flame with air °C</th>
<th>Temperature with oxygen °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetylene</td>
<td>2630</td>
<td>3130</td>
</tr>
<tr>
<td>hydrogen</td>
<td>2210</td>
<td>2660</td>
</tr>
<tr>
<td>coal gas</td>
<td>1920</td>
<td>2450</td>
</tr>
<tr>
<td>propane</td>
<td>1925</td>
<td>2700</td>
</tr>
</tbody>
</table>

Gas welding equipment

Fusion welding operations require a cylinder of compressed oxygen and acetylene, correct regulators for both gases, flashback arrestors, correct couplings and hoses, welding blowpipe, mixer and welding tips.

Oxygen and acetylene gases are generally set at equal pressures of approximately 50 to 75 kPa.

Typical welding equipment required, such as cylinders, regulators, arrestors, hoses, welding blowpipe, mixer and swaged welding tip are shown in Fig 17.1. The swaged tip provides smooth gas flow and a soft, quiet neutral flame for all welding purposes.

Fig 17.1 – Gas welding equipment
Oxy-acetylene flames

Characteristics of the oxy-acetylene flame

Oxygen and acetylene blowpipes utilise the Bunsen burner principle of mixing gases together before they reach the point at which combustion is to take place. This prior mixing of the gases produces a much hotter and shorter flame than when fuel gases are simply allowed to flow out into the air and burn.

For example, acetylene when pre-mixed and burnt with pure oxygen produces the highest temperature gas flame known to man that is safe and convenient for welding.

Theoretically, it requires two volumes of oxygen to burn one volume of acetylene, but the blowpipe is designed to only supply the oxygen necessary to form the luminous or incandescent cone for which the volume is 1:1. When the flame is adjusted to neutral (see Fig 17.2) – the extra volumes of oxygen are obtained from the atmosphere.

Chemistry of the oxy-acetylene flame

The maximum temperature obtainable from the oxy-acetylene flame is approximately 3300 °C, (oxy/coal gas flame: 2000 °C, oxy/hydrogen flame: 2300 °C, air/acetylene: 2400 °C, air/liquid petroleum gas: 2700 °C), and the heat concentration is 1–2 mm in front of the extreme tip of the inner cone. Combustion is recognised as taking place in two main stages.

1. Oxygen and acetylene (O\textsubscript{2} and C\textsubscript{2}H\textsubscript{2}), in a 1:1 ratio, burn in the inner white cone. In the inner cone, two separate reactions take place; the oxygen combines with the carbon of the acetylene to form carbon monoxide (CO), while hydrogen (H\textsubscript{2}) is liberated.

2. Two more separate reactions take place in the outer envelope to complete combustion. The carbon monoxide takes up oxygen from the atmosphere to form carbon dioxide (CO\textsubscript{2}) and the hydrogen burns with oxygen, also from the atmosphere, to form water vapour (H\textsubscript{2}O).

Flame adjustment

Three types of flame adjustment can be obtained when using the oxy-acetylene gas welding plant:

1. neutral
2. carburising
3. oxidising.

It is essential that the operator learns to recognise the three types of flame, because incorrect flame setting could lead to weld problems or failure of the weld.

Neutral flame

A neutral flame is produced when acetylene and oxygen burn in the proper proportions, i.e., equal volumes. It is made up of a distinct and clearly defined incandescent cone or jet, surrounded by a faint secondary flame or envelope. The length of the inner cone should be between three to five times its own width. The flame desired is what may be termed as a gentle or soft flame, not a harsh flame. A harsh flame increases the agitation of the molten metal and causes metal to be forced over unfused areas.
Temperature 3000 °C – Uses

- Fusion welding of:
  - mild steel and alloys
  - cast iron
  - aluminium and alloys
  - stainless steel
  - chrome-nickel alloys
  - copper and alloys
  - lead.
- All heating applications and cutting pre-heating flames.

Carburising flame

This flame is produced when there is an excess of acetylene and can be readily recognised by a luminous intermediate cone or ‘feather’ around the inner cone; caused by unburnt particles of carbon that are burnt and disappear as they reach the outer edge of the feather.

The carburising flame has an excess of carbon and will add carbon to the surface of the material. It is also sometimes referred to as a ‘reducing flame’. A reducing flame is one that, because of its need for oxygen, will reduce oxides such as iron oxide.

The temperature of the carburising flame is lower than that of the neutral flame. It causes mild steel to seemingly sweat or look greasy. This is brought about by the unburnt particles of carbon in the flame reacting on the steel’s surface and lowering the melting point of the steel before it melts to any depth.

Temperature 2800 °C – Uses

- fusion welding high carbon steels
- hard surfacing operations.
Oxidising flame

This flame is produced when there is an excess of oxygen in the flame and is so named because of its oxidising effect on the molten metal. The effect of too much oxygen is to decrease the length and width of the outer envelope and to shorten the inner core.

An oxidising flame is very harmful in certain welding applications, such as in the welding of mild steel, aluminium and stainless steels.

When welding mild steel, excess oxygen can be detected by the intense sparking of the melted metal and the appearance of a whitish scum.

Temperature 3000 °C – Uses

- fusion welding of:
  - brass
  - bronze
  - zinc die castings
- bronze welding of:
  - cast iron
  - galvanised iron
  - mild steel.
Oxy-welding techniques

Forehand welding technique

The definition of forehand welding is welding with the blowpipe flame pointing in the direction in which the weld progresses, ie towards the unfilled seam, where the blowpipe follows the filler rod (see Fig 17.5).

This technique is the most commonly used for mild steel and alloy steels on butt weld and fillet weld joints, flanged edges, unbevelled plates up to 3 mm and bevelled plates up to 5 mm. It is also the technique adopted for cast iron and non-ferrous metals.

Backhand welding mild steel

The definition for backhand welding is welding with the blowpipe flame pointing in the reverse of the direction in which the weld progresses, ie towards the filled seam, where the blowpipe is ahead of the weld and filler rod (see Fig 17.6).

This technique requires great skill and is the most common method used for full fusion root welds on pipe.
**Fig 17.6 – Backhand welding**

**Tip sizes**
Welding tip sizes are designated in tenths of a mm, ie:
- size 8 = 8/10 = 0.8 mm
- size 20 = 2 mm.

<table>
<thead>
<tr>
<th>Tip sizes</th>
<th>Filler rod diameter (mm)</th>
<th>Thickness of mild steel</th>
<th>Pressure* kPa oxygen</th>
<th>Pressure* kPa acetylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1.6</td>
<td>0.8 mm</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>8–10</td>
<td>1.6</td>
<td>1.6 mm</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>10–12</td>
<td>1.6</td>
<td>2.4 mm</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>12–15</td>
<td>2.4</td>
<td>3 mm</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

*These pressures apply only to equal pressure blowpipes, when you can adjust both regulators.*
Filler rods

Filler rods are available to enable oxy-acetylene fusion welding of a wide range of materials and these are identified by colour codes or markings in accordance with the AS 1167.2 Fusion Filler wire code, which contains details of filler specifications in various tables as shown in the examples that follow.

For example, a steel wire would be shown in AS1167 part 2 in Table 3 as RG and an alloy steel wire as R1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Marking (eg)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>none AS/NZS 1167.2-3RG</td>
<td>Free running, high ductility mild steel and wrought iron, no flux required but susceptible to oxide inclusion.</td>
</tr>
<tr>
<td>High test</td>
<td>copper coating as above</td>
<td>High quality rod for flux-free fusion welding of mild steel where better mechanical properties and some de-oxidising is required.</td>
</tr>
<tr>
<td>Super steel</td>
<td>copper coat blue tip as above</td>
<td>Low alloy steel containing balanced quantities of si and mn (double de-oxidised), produces flux-free quality fusion welds of high strength and suitable for many low alloy steels.</td>
</tr>
<tr>
<td>Alloy steel</td>
<td>AS/NZS 1167.2-3R1</td>
<td>A range of fusion welding rods for flux free fusion welding of carbon/moly, chrome/moly and nickel low alloy steels.</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>AS/NZS 1167.2-4R308</td>
<td>A range of fusion welding wires, for austenitic stainless steel. May need flux to assist in de-oxidisation of surface.</td>
</tr>
<tr>
<td>Copper and alloy</td>
<td>AS/NZS 1167.2-5CuSnA</td>
<td>Fillers are available for fusion welding of pure copper (de-oxidised). Example is bronze filler for fusion welding of bronze. May need flux to assist in de-oxidisation of surface.</td>
</tr>
<tr>
<td>Aluminium and alloys</td>
<td>AS/NZS 1167.2-R1000 (pure)</td>
<td>Fillers are available for fusion and braze welding of aluminium and alloys. May need flux to assist in de-oxidisation of surface.</td>
</tr>
</tbody>
</table>

Table 17.3 – Filler rod selection chart

Requirements for fusion welding

1. **Flame**: a neutral flame is required for the welding of mild steel.
2. **Flux**: not required for steel because oxides melt at a lower temperature than the melting point, but flux may be required when fusion welding on metals such as stainless steel or aluminium that have a surface oxide layer that is promoted by heat or has a higher melt point than the parent metal.
3. **Filler rods**: a filler rod of the same composition as the base metal is mostly used. The diameter of the rod should be selected to enable easy control of the weld pool and filler rod melt off.
Preparation – tacking and gap

Tack welding is the term given to small welds that are used to maintain the correct joint gap and alignment of parts and to control distortion during the welding process. The tack weld is made by producing a small molten puddle across the seam to produce local fusion of the joint faces. A small circular motion of the tip may be used and filler rod introduced to assist in making a strong tack weld.

The distance between tack welds should ensure that the joint is stable during welding operations. On thin plate, eg 1.6 mm thick material, the recommended distance between tacks should be no greater than 40 mm; this is to stop the plate edges from distorting between the tacks as the welding heat is applied. Usually one edge rises and the other drops down, resulting in uneven joint faces.

As the plate thickness increases, so then does the distance between the tack welds. In many instances, it is wise to make some allowance for expansion and contraction when tacking up the joint.

Methods in common use are (see Fig 17.7):

- allowing a slightly larger joint gap than normal
- setting the gap wider at one end of the joint where welding is to commence
- combined with the above, plates are usually overset to allow for and use contraction forces to align the welded plates and reduce distortion.

![Fig 17.7 – Common methods of tacking](image-url)
Joint gap (refer Table 17.4) sets out the correct edge preparation and accompanying joint gap for forehand welding in the flat position.

<table>
<thead>
<tr>
<th>Metal thickness mm (in)</th>
<th>Filler rod diameter mm (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2 t</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>1/2 t</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
</tr>
</tbody>
</table>

**Table 17.4 – Joint gap examples**

Table 17.4 should be used as a starting point, but minor adjustments can be made to allow for expansion and contraction forces produced during welding. However, depending on the type and grade of material, thickness and length of weld, the allowance may vary and only by using experience can the operator decide the most suitable joint set-up.

A sound weld is produced by the correct employment of such factors as flame setting, flame control, tip angle, filler rod angle and feed. The operator should choose a comfortable position and, as the result of experience through practice, be able to coordinate and control all factors to produce consistently good welds. Welding should take place with the operator welding across the face of the body. In case of a right-handed person, from right to left.

1. The flame – The inner core is brought to within 2 mm of the metal surface and directed at a point to melt the metal and form a molten pool. The flame is kept in a direct line of the weld joint, maintaining recommended angles – Fig 17.8.

2. The molten pool – Should extend from the top surface of the plate through to the underside edges of the seam. Welding takes place when the two molten faces fuse, the forward movement of the blowpipe makes this a continuous process.

3. The filler rod is held in the outer envelope to raise and keep it at a welding temperature. For the correct angle see Fig 17.8.
Welding technique

The flame is directed at a point to form a molten weld pool. The filler rod is held within the outer envelope to raise it to a welding temperature. On formation of the weld pool, the filler rod is lowered into the centre of the molten pool in a constant dipping action, regulated by the amount of filler metal required.

Do not allow the molten metal from the rod to drop into the weld pool. Keep the flame on the line of the weld moving forward, without an excessive weaving motion sideways.

Increased angle of the blowpipe slows progress and increases the size of the molten pool.

It is important that the filler rod be withdrawn from the molten pool, so that the heat build-up can occur to re-establish the correct pool depth for full penetration.

Care should be taken to keep the end of the filler rod within the envelope to restrict the formation of oxides that would be detrimental to the weld.

Operator control

Accurate control of the welding rod requires great operator skill. The filler metal should be deposited at an even rate to form a sound joint with adequate weld reinforcement. Operator control is also needed to prevent the rod from sticking. If the rod should stick to the parent metal, simply melt it loose using the welding flame.

When the weld is completed, or in the case of an intermediate stop, the molten pool should be allowed to slowly solidify inside the flame envelope so that oxides are not formed and gases are not trapped within the weld.
Gas welding of small diameter pipes

Oxy-acetylene welding of pipe is accomplished by one of three techniques:

- single-pass or multi-pass forehand technique
- single-pass or multi-pass backhand technique
- two-pass technique using a backhand first run and forehand capping run.

Forehand technique

Pipe welds using the forehand technique are started at the bottom or '6 o'clock' position and welded upwards to the top or '12 o'clock' position. The welding flame points towards the direction of welding with the filler rod leading the blowpipe (see Fig 17.9).

Pipe should be pre-heated before welding commences, particularly on pipe over 6 mm thick.

The forehand method is a slow process that involves movement of the flame from one side of the joint to the other. The filler rod is also moved from side to side, alternating with the flame. If build-up is required, the rod is stopped momentarily in the middle of the molten pool to melt off more filler metal.

Backhand technique

The backhand technique is illustrated in Fig 17.10. It involves the welding of pipe from top to bottom, when the pipe is in the fixed horizontal position. The flame is directed back into the molten pool and the rod is held behind the welding flame.
Backhand is faster than the forehand technique. The flame is directed into the root opening, until both pipe edges are melted to form a molten eye, or ‘key hole’. As the molten eye forms, the rod is moved towards the forward edge of the pool.

**General notes**

As gas welding is slower than other processes, it allows more time for change of operator position when welding small bore pipes. Welds are normally sound and no grinding or slag removal is required on completion.

Normalising of mild steel is often required. The slow process tends to promote heat transfer into the parent metal, which causes slow cooling and a relatively coarse grain structure. Any post-weld heat treatment should be carried out strictly in accordance with the specifications for the material.

**Trade terms**

There are four terms used in the oxy-acetylene welding trade that are frequently confused. The terms must be understood and correctly used at all times. These are:

- braze welding
- brazing
- bronze welding
- bronze surfacing.

**Braze welding**

The joining of metals using a technique similar to fusion welding (fillet weld external to parts to be joined or butt weld that extends to cover the surface). The parent metal is not melted and the low temperature filler material bonds to the grain structure from the surface only, but without melting the parent metal (see Fig 17.11).
Brazing
A process of joining metals in which, during or after heating the parent material, molten filler metal is drawn by capillary attraction into the space between closely adjacent surfaces of the parts to be joined. In general, the melting point of the filler metal is above 500 °C, but always below the melting temperature of the parent metal (see Fig 17.12).

Bronze welding
A form of braze welding in which copper-rich filler metal is used.

Bronze surfacing
The deposition of bronze filler metal over an area of a metal surface, to impart certain wear resistant properties or build-up of worn parts.

These processes may seem similar in their low temperatures required and in the method of bonding, however there are differences in the filler material, joint design and flame type required.
Summary

<table>
<thead>
<tr>
<th>Bronze welding – braze welding</th>
<th>Brazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature above 500 °C</td>
<td>below parent metal melt point</td>
</tr>
<tr>
<td>filler material type</td>
<td>copper/zinc alloy</td>
</tr>
<tr>
<td>joint design required</td>
<td>weld build-up</td>
</tr>
<tr>
<td>bonding method (filler to metal)</td>
<td>intergranular</td>
</tr>
<tr>
<td>flux type (borax base)</td>
<td>bronze GP</td>
</tr>
<tr>
<td>flame type required</td>
<td>neutral – slightly oxidising</td>
</tr>
</tbody>
</table>

Table 17.5 – Similarities/differences between braze welding and brazing

Intergranular penetration

The molten filler metal permeates into the parent metal, around the grains and ‘hooks’ itself in the parent metal. For this reason, the parent metal must be hot (but not molten) to expand the gaps in the grain. A flux is used to clean out the gaps and help the filler metal to flow between the grains.

![Intergranular penetration](image)

Capillary attraction

This is the final term requiring definition. It describes where molten filler metal flows between closely fitted surfaces of a joint, which will even occur against the pull of gravity.

Uses of braze welding (with bronze filler)

Bronze welding may be employed on cast irons, mild and alloy steels and galvanised iron. It has a number of advantages over fusion welding for these materials but it also has some limitations.
Advantages

- much faster than fusion welding
- lower heat input will not destroy the properties of the parent metal
- resultant weld is ductile.

Limitations

Bronze welding is not to be used in the following instances:

- on joints under stress, as tensile strength of the joint is lower than that of the parent metal
- in conditions where the operating temperature is above 260 °C, as bronze loses strength rapidly at elevated temperatures
- when the joint comes in contact with ammonia gas
- when a colour match with the parent metal is required.

Braze welding techniques

Mild steel and galvanised Iron

Galvanised iron consists of mild steel, coated with zinc. Braze welding is especially recommended for joining galvanised plate or pipe, as the low heat input (compared with fusion welding) does not appreciably affect the zinc coating. The braze welded joint is also itself resistant to corrosion and it alloys with the zinc coating to form a continuous protective layer (bronze consists of copper and zinc).

Precautions

As can be seen from the previous chart, extra care must be taken to prevent the zinc from vaporising (becoming a gas). Zinc forms an oxide, from atmospheric oxygen, which is poisonous. On mild steel, only the zinc in the bronze filler can vaporise; with galvanised iron, the zinc coating can also vaporise. By using the correct flame (slightly oxidising), this problem can be minimised; but for all braze welding, the operator must avoid breathing the fumes given off.

This can be achieved by:

- using a fume extractor (exhaust fan)
- wearing a personal respirator
- working in the open air or near a draught (open the doors and windows in the workshop).

Preparation of materials

The surface of parts to be joined must be absolutely clean, mechanical cleaning and a corrosive flux being required for most applications.

The base metal must be ‘tinned’ before depositing the bulk of the filler material.
Mild steel
Fillet welds: joint edges should be straight and close fitting. Because of the viscous and fast freezing nature of molten bronze, a certain degree of poor fit-up may be tolerated.

Butt welds: preparation of butt joints for braze welding is similar to that of fusion welding of the same thickness, except that a 90° vee is generally employed.

Parts should be held firmly in alignment with tackwelds or clamps and jigs etc.

Galvanised iron
It is not necessary to grind off the zinc coating, but a light rub over the joint surfaces with emery cloth will remove any grease or oxides prior to joining.

Filler material
A range of filler material is available for various applications. Examples are given from the BOC Gases range.

<table>
<thead>
<tr>
<th>Filler Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tobin Bronze</td>
<td>A low cost copper zinc alloy for fusion weld of brass and bronze.</td>
</tr>
<tr>
<td>Manganese Bronze 411</td>
<td>A free-flowing manganese bronze from producing high bond strength on steel and cast iron.</td>
</tr>
<tr>
<td>Blue Tip</td>
<td></td>
</tr>
<tr>
<td>Nickel Bronze 904</td>
<td>Produces maximum bond strength in braze welds on steel and cast iron. Has excellent hardness and wear-resistant properties.</td>
</tr>
<tr>
<td>Imperial Brown</td>
<td></td>
</tr>
</tbody>
</table>

Some of these above examples are also available in a pre flux-coated rod.

Filler material is manufactured in a range of rod diameters to suit various applications.

Fluxes
In general, a flux should be used to remove any contamination from the surface (oxides) and to help to protect the surface from the effects of the atmosphere. Most fluxes are slightly acidic and will etch the surface of the material when heated. Fluxes may be based on resins, borax, sodium or fluorides. There is a particular flux blend to suit each application.

<table>
<thead>
<tr>
<th>Flux Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>General purpose flux</td>
<td>Braze welding of mild steel and galvanised iron.</td>
</tr>
<tr>
<td>Bronze flux</td>
<td>Braze welding of cast iron.</td>
</tr>
<tr>
<td>Bronze tinning flux</td>
<td>Specially designed for difficult tinning situations – use bronze flux to complete.</td>
</tr>
</tbody>
</table>

Tip size
Generally, a tip one size smaller than would be appropriate for a similar joint, if fusion welding were employed, is used for braze welding.

Flame setting
The flame adjustment for braze (bronze) welding is slightly oxidising; this creates an oxide film over the puddle and prevents the zinc from dissipating (fuming).
Chapter 17 – Oxy-fuel gas welding

Reinforced pieces for pipe

If flux is correctly applied the braze will flow between the plates

Lap fillet

‘Tee’ fillet

Fig 17.14 – Some typical braze welded joints

Method

With the joint edges properly prepared and the equipment set up correctly, the surface is brought to the correct temperature; this will generally be a dull red colour. The correct temperature can be ascertained from the fact that if too cold, the filler material will tend to ‘ball up’ on the surface and not flow out or ‘tin’. Overheating will cause the filler material to boil, characterised by a spitting and popping sound; zinc fumes will be given off in large amounts and black, oxidised areas may appear in the weld.

The forehand technique is generally employed, as the backhand method usually results in overheating. The inner cone should be maintained at approximately 6 mm from the surface of the metal and the tip and the filler rod should be held at 45° to the surface.

If an uncoated rod is being used, this must be heated and dipped into the flux; some flux will then adhere to the rod and be introduced to the joint. This procedure is repeated as the fluxed rod is consumed.
As an alternative, flux powder may be mixed with water to form a paste, this being painted on the surface of the joint prior to welding.

**Flux removal**

On completion of the weld, the weld area will be coated with flux residue, a hard glassy substance; this must be removed by mechanical methods or acid pickling to prevent any corrosion when the part is put into service.

**Silver brazing**

**Definition**

A process of joining metals in which, during or after heating, molten filler metal is drawn by capillary action into the space between closely adjacent surfaces of the parts to be joined. In general, the melting point of the filler metal is above 500 °C, but always below the melting point of the parent metal.

The process involves using an alloy filler rod consisting largely of silver and copper, with additions of other elements. The materials that can be silver brazed include nickel, monel, nickel-silver, copper, brass, bronze, stainless steel, carbon steel, alloy steel and tungsten carbide tool tips.
The process

Silver brazing is extremely easy if a few basic rules are strictly observed. Successful brazing depends upon:

- joint design
- choice of brazing alloy
- preparation of surfaces
- technique.

Joint design

Joints must allow for sufficient surface areas to be in close contact – large gaps do not allow capillary action to take place. Generally, a gap of 0.05 to 0.03 mm is required.

Some of the more common joints are shown in Fig 17.16.
Choice of brazing alloy

There is a large range of alloys to choose from, using from 2% to 72% silver. Silver is expensive, so the correct alloy must be chosen for each job and only the amount required for a sound joint used. Don’t build-up on the joint with alloy, as it is not only wasteful but it may also harm the joint.

Silver brazing alloys (SBA) are classified into groups according to their uses and silver content is also indicated.

Group 1 SBA

These are used primarily for the brazing of copper to copper, without flux. They should be used with flux on copper alloys. They should not be used on ferrous or nickel-base alloys, as this forms nickel-phosphide, causing severe embrittlement of the weld. These alloys contain silver-copper-phosphorous.

Group 2 SBA

This group is the most commonly used alloy in industry for the low temperature brazing of all ferrous and non-ferrous metals. This group should not be used on food handling equipment, however, particularly where the equipment is subject to high temperature.

The alloys in this group contain silver-copper-cadmium-zinc.

AS/NZS 1167.1-A8 contains 50% silver and 4% nickel. It has been specially developed for brazing tungsten carbide tool tips. An example is BOC Gases’ ProSilver 494.

Group 3 SBA

These are used for intermediate temperature brazing of all metals and are particularly useful in the silversmith’s trade. These should be used in the food handling industry.

These alloys are cadmium-free; they contain silver-copper-zinc.

Group 4 SBA

These are used on vacuum units and where high electrical conductivity is necessary. They are best used on copper, but may also be used on stainless steel, copper alloys and nickel alloys.

These alloys contain very high proportions of silver (for electrical conductivity), the rest being copper.

The silver brazing alloys (Table 17.6) for selecting silver brazing alloys has been included for future reference. Welders need to select the SBA carefully.
<table>
<thead>
<tr>
<th>Grade</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS/NZS 1167.1</td>
<td>Alloy designation ‘B’</td>
<td>AS/NZS 1167.1</td>
<td>Alloy designation ‘A’</td>
<td>AS/NZS 1167.1</td>
</tr>
<tr>
<td>Alloys used</td>
<td>copper/silver/ phosphorus</td>
<td>copper/silver/ cadmium</td>
<td>copper/silver</td>
<td>copper/high silver</td>
</tr>
<tr>
<td>Temperature</td>
<td>700 °C</td>
<td>Av 650 °C</td>
<td>Av 750 °C</td>
<td>780 °C</td>
</tr>
<tr>
<td>Applications</td>
<td>used for flux free joints on copper and for joining copper alloys such as brass and bronze</td>
<td>used for low cost general purpose jointing of steel, stainless steel, copper, copper alloys and dissimilar metals by low temperature</td>
<td>used for general purpose and in joints where cadmium would be hazardous (weld temperature is slightly higher than group 2)</td>
<td>used for joints requiring better colour match, such as silver or stainless and/or high conductivity on copper</td>
</tr>
<tr>
<td>Not recommended</td>
<td>must not be used on ferrous materials such as steel or stainless steel because a brittle joint may be formed</td>
<td>not to be used for food or water utensils because of cadmium</td>
<td>not suitable for some nickel alloys</td>
<td>more costly</td>
</tr>
<tr>
<td>Flux required</td>
<td>none required on clean copper (phosphorus acts as de-oxidiser and flux agent) flux may be beneficial on alloys</td>
<td>requires a general purpose flux on most materials</td>
<td>requires a general purpose flux on most materials</td>
<td>requires an aggressive flux on most materials</td>
</tr>
</tbody>
</table>

Table 17.6 – Silver brazing alloys comparison chart
Special hazards associated with braze welding/brazing

It can be seen that metal fumes may be produced by the vaporisation of metals at high temperatures.

- Braze welding or brazing on most base metals will not cause parent metal vaporisation and fuming at the low temperatures involved.
- Coatings used on materials such as zinc and aluminium (used on galvanised iron or coated sheet metal) may fume if overheated.
- The copper, zinc, or cadmium used in the filler material will certainly smoke and cause dangerous fumes if overheated.
- Solvents and degreasers should also not be used on materials to be heated.

The fluxes used can also generate dangerous or toxic fumes when heated. Avoid breathing any fumes at all, always use correct fume extraction methods or proper ventilation procedures.

Most of the fluxes that are use in oxy-acetylene welding operations are based on borax, fluorides, or other caustic materials. Avoid contamination of the hands by using gloves or applying flux with disposable items. After using any flux, always wash your hands thoroughly before eating.
Chapter 18 – Automatic welding

Introduction

The principles of submerged arc and electro-slag welding processes are similar, to the extent that they are ideally suited to joints in very heavy materials. Both processes make use of a continuously fed filler wire and a granular flux. Deposition rates are high and weld quality is excellent, providing very economical welded joints.

The basic difference between the two processes is that submerged arc is applied to joints in the flat position and electro-slag to joints in the vertical position.

In this chapter we will look at the following.

- Submerged arc welding principles
  - the effect of welding variables
  - submerged arc welding consumables classification
  - process requirements
- Electro-slag welding.
Submerged arc welding (SAW) principles

Submerged arc welding is defined as the process where the heat required for welding is produced from an electric arc (or arcs) created between a bare metal electrode (or electrodes) and the work piece. The weld area is completely shielded from the effects of atmospheric gases by a blanket of finely crushed flux, making the arc invisible; hence the term ‘submerged arc’ (see Fig 18.1).

During the welding operations, the flux in the vicinity of the arc interacts with the parent metal and filler wire and melts and fuses to form an airtight slag to protect the molten metal from oxygen and nitrogen in the atmosphere and to slow down the cooling rate. As welding progresses, there is no visible arc and a complete absence of spatter. The fused flux is easily removed when cool; the unfused flux is recovered for re-use.

The process was developed primarily for the production of high quality butt welds at increased welding rates. Briefly, SAW can be performed using a handheld gun which makes the process flexible for repetition work where complicated shapes make fixturing too difficult. The operation is more usually carried out by a unit that moves at a controlled speed along the joint to be welded. For circumferential joints, the work piece is rotated beneath a stationary welding head.

The process

The process is particularly suited to welding heavy plate and up to 75 mm thick plate can be welded in one pass. With smaller filler rod and low amperages, SAW can be used successfully on material as light as 2.6 mm. High welding currents can be used on heavy sections and in some cases this can be as high as 4000 amps. This allows faster weld deposits to be made with very deep penetration.

Plates up to 12.5 mm thick can be welded without edge preparation. On thicker plate, a relatively small narrow preparation is used, permitting the use of smaller amounts of deposited metal.
Submerged arc welding can be carried out using two or three wires simultaneously, with welding speeds as high as 2.5 metres per minute. It is a fast and economical method of welding when large diameter rod and high amps are used.

Absence of spatter and easy slag removal facilitates post-cleaning. Completed welds are of high quality with uniform appearance. Parameters such as voltage and current are easy to maintain and this, combined with predetermined or constant travel speeds and arc length, enables high quality welds.

Typical applications for SAW include:

- mechanised fillet welding of web to flange connections on fabricated beams and columns
- butt welding of longitudinal and circumference welds on cylinders and pressure vessels
- hand fillet welds on structural fabrications
- mechanised welds on material handling equipment
- re-facing or hard facing of material.

The metals that are weldable are:

- low and medium carbon steels
- low alloy, high strength steels
- quenched and tempered steels
- many types of stainless steels.

Copper and nickel alloys have been welded experimentally.

**Process advantages**

The SAW process is capable of high productivity rates, because of its automatically fed filler wire and subsequent high deposition rate. The process also has a high duty cycle because of its easily mechanised nature. Welds completed by the submerged arc welding process typically have controlled penetration or are deep penetrating in nature. Deposited welds display uniform bead width and height with no spatter and are thus high quality in appearance. Welds produced by the process have good mechanical properties.

Welding operators like the process because it is mechanised and thus requires less effort than other processes. The arc is hidden, low levels of radiation and fumes are emitted and the slag is easy to remove. Additionally, the flux blanket prevents any rapid escape of heat and the submerged arc welding process produces less distortion than some of the other weld processes.

Multiple electrodes can be used (ie tandem or twin arcs) and thick materials can be welded with less passes and less filler metal being required than with other processes. Small preparations only are required on thin materials.

**Process limitations**

The major limitations of SAW are the high initial cost of equipment and the inability of the process to cope with positional welding and poor fit-up or dirty joints.

There is a limited selection of consumables; almost exclusively mild and low alloy high strength steels.
The high heat input and slow cooling cycle of submerged arc welding can be a problem when fine grained welds are required, or when welding quenched and tempered steels. The heat input limitations of the Q and T steel must be strictly adhered to when using SAW. This may require the making of multi-pass welds, where a single-pass weld would be acceptable in mild steel. In some cases, the economics may be reduced to the point where flux-cored arc welding or some other process should be considered.

In semi-automatic submerged arc welding, the inability to see the arc and puddle can be a disadvantage in reaching the root of a groove weld and properly filling or sizing. Seam tracking can also be a problem and the operator can only see the completed weld once all the slag and unused flux is removed from the surface.

**Power source**

The power source for submerged arc welding can be either constant voltage or constant current type. Constant voltage is often used with small wire sizes, where the self-adjusting arc properties are most useful. Constant current type power sources are generally used on larger wires and these require feedback circuits that change the wire feed rate to compensate for any arc length or wire burn off variations.

Machines can be either generator, inverter or transformer rectifier power sources. The rectifier type machines are the most common and modern versions are efficient and quiet. The machines range in capacity from 300–1500 amperes and must be rated for a 100% duty cycle; they may also be connected in parallel to provide extra power for high current applications. Both AC or DC current can be used. Multiple electrode systems require specialised types of circuits, especially when AC is employed.
Current selection – AC or DC

The difference in arcing and operating characteristics obtained from AC and DC welding supply with the submerged arc welding process has a slight bearing upon the suitability for a particular application. Generally, the majority of applications can be carried out equally effectively with either AC or DC, but there are definite advantages at the extremities of the application range for each current choice.

When selecting the most suitable welding supply, direct current (DC) gives the operator polarity choice and therefore greater control over bead shape and penetration. Direct current electrode negative (DC-ve) has a slight advantage in regard to deposition rate (this is the reverse of GMAW), whilst direct current electrode positive (DC+ve) has a slight advantage where deep penetration is required. Light gauge applications around 3 mm are best carried out with DC welding power. Weld starting is more positive with DC and the arc is more stable at the lower currents used. Increased travel speeds can be obtained.

Square-edge, prepared edge butt welds and standing and positioned fillet welds from 5 mm and upwards may be carried out with either type of supply with equal results. Arc blow or magnetic disturbance may cause deposit deformation when welding inside circular vessels with a DC supply.

Arc blow is more likely to occur at higher currents with DC, especially on applications such as heavy wall thickness, circular vessels of comparatively small dimensions, and also geometrically complex weldments.

Multiple electrode techniques such as twin (side-by-side wire electrodes) or tandem arc (where one automatic welding head and wire follows another in a common molten pool) are used for higher productivity rates. Where more than one power supply is used, one of the electrodes is often connected to an AC welding supply to cancel any magnetic effects and help arc stability. Both electrodes can be operated from an AC welding supply, but higher welding speeds are possible with an AC/DC combination.

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Fig 18.3 – Twin/tandem arc/strip
Control box/head unit

The head unit consists of a control box that provides adjustment of arc voltage, amperage and travel rate. It may have additional functions such as wire inch, start current, and adjustable rise rate, end current and decline rate and/or crater fill. The welding head also houses a large reel of wire that is lightly covered with copper to improve its transport and electrical properties. A wire straightener and a heavy duty wire feed unit are also incorporated. A flux feed hopper and delivery system is also provided to deposit the dry, finely divided, free flowing flux automatically along the weld joint. The unit may also have a travel motor that can allow the unit to travel at a predetermined speed (forward or reverse) along a weld joint and arc length and seam tracking adjustments.

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Fig 18.4 – Head unit

Submerged arc welding variables

The effect of welding variables

The major variables that affect the weld involve heat input derived from the arc voltage, the welding current and the travel speed. The quality of the finished weld depends almost entirely upon these parameters and their proper selection and control.

The variables (in the approximate order of importance) that must be set and maintained during welding are:

- voltage
- the current
- weld travel speed
- electrical stick-out
- arc length and width
- flux depth.
Table 1 Current ranges for SAW electrodes

<table>
<thead>
<tr>
<th>Electrode Dia. (mm)</th>
<th>Current range (amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>200 - 500</td>
</tr>
<tr>
<td>2.4</td>
<td>230 - 600</td>
</tr>
<tr>
<td>3.2</td>
<td>300 - 750</td>
</tr>
<tr>
<td>4.0</td>
<td>400 - 900</td>
</tr>
<tr>
<td>4.8</td>
<td>500 - 1050</td>
</tr>
</tbody>
</table>

Fig 18.5 – Welding variables – Current ranges for SAW electrodes

Arc voltage

As the arc voltage is reduced, the tip of the welding wires will operate at a lower height level, giving a narrower weld with deeper penetration than a higher arc voltage would give under the same current and speed condition. With high arc voltage, the wire tip operates at a higher height level, allowing the metal to spread out and giving a wider weld with less penetration. It also allows the fusing of slightly more flux than in the former case.

An extremely low arc voltage for a given current setting, with the tip of the welding wire operating at a lower level (which could be well below the surface of plate in a narrow vee preparation), will cause the molten deposited metal to be forced up around the sides and the rear of the crater. The resultant bead will be rough, irregular, comparatively high and narrow, with visible gas holes sometimes occurring in the crater. With an excessively high arc voltage under the same current conditions, the tip of the welding wire being rather high above the plate surface will mean that the covering flux will tend to extinguish the arc. The resultant bead will again tend to be rough and irregular, but in this case comparatively flat and wide.

For this example:
4.0 mm electrode
600 amps
500 mm/min

Fig 18.6 – Effects of voltage
Wire feed control (amperage)

This may be by either constant speed wire feed or voltage controlled systems.

Constant speed wire feed controls the wire speed (once it is pre-set), by means of some form of either mechanical or electrical governor. This type of control is usually used with constant potential power sources, because the constant voltage type power source will alter the output current to compensate for any arc voltage variation and thus provide the self-adjusting parameters necessary to maintain an open arc. The desired arc length (from arc voltage) is selected by setting the constant voltage power source output voltage at a value suited to the maintenance of an open arc.

Voltage-controlled or voltage-sensing wire feed motors are generally used for constant current type power sources; the control used may be a 'series control', which is essentially an electric motor that is highly responsive to arc voltage variations, or it could be an electronic device that senses arc voltage variations and promotes motor response to these changes as they occur.

In this system, if for any short period of time the welding current melts off filler wire at a faster rate than it is being fed, the increased distance between the wire and the work will increase the arc voltage. This increase in arc voltage speeds results in a speed up of the wire speed motor and restores the wire tip-to-work relationship as previously established.

With either control system the most critical variables, arc voltage and arc current, are maintained at constant levels.

Typically, any increase in wire feed rate will increase amperage, penetration and deposition rate.

For this example:
4.0 mm electrode
34 volts
600 mm/min

Fig 18.7 – Effects of amperage
Travel rate

Weld size and shape are affected by travel speed. Any increase in travel speed will reduce weld size and produce a narrower weld bead. Penetration is also affected by travel speed; an increase over normal settings will give a proportionate decrease in depth of penetration.

![Travel rate diagram](image)

For this example:
- 4.0 mm electrode
- 600 amps
- 33 volts

**Fig 18.8 – Effects of travel rate**

Stick-out

The electrical stick-out must be set correctly, because this will affect arc voltage and welding current. On a constant voltage power source, any increase in stick-out will produce a voltage rise and therefore require the power source to reduce amperage to compensate.

Flux

Submerged arc welding flux shields the arc, and the molten weld metal, from the harmful effect of atmospheric oxygen and nitrogen. The flux contains deoxidisers and scavengers, which help to remove impurities from the molten weld metal. The welding flux also provides a means of introducing alloys into the weld metal. As this molten flux cools to a glassy slag, it forms a covering that protects the surface of the weld.

The non-melted portion of the flux does not change its form, its properties are not affected, and it can be recovered and reused. The flux that does melt and forms the slag covering must be removed from the weld bead. This is easily done after the weld has cooled and in many cases will actually peel without requiring special effort for removal. In groove welds, the solidified slag may have to be removed by a chipping hammer.

Fluxes are available in various types similar to MMAW; namely rutile, acid, or basic type fluxes (hydrogen-controlled). These fluxes are formulated for specific applications and for specific types of weld deposits. Because a large part of the flux can interact with the molten weld pool, another method is often used to differentiate between various types of submerged arc fluxes. A neutral flux has no effect on the finished weld, in spite of any variable change.
Chapter 18 – Automatic welding

Active fluxes contain elements such as manganese and/or silicon and these can be picked up in the arc and thus contribute to the weld metal properties. The flux/wire combination must be carefully selected and is often critical in predicting weld metal properties. Submerged arc welding fluxes are also available in different particle sizes and methods of manufacturing.

**Vertical displacement**

When circumference welds are carried out, the molten weld pool must be kept as near to the flat position as possible while it solidifies. Some allowance can therefore be made to deposit the weld before the flat position, to allow liquid weld to cool and solidify as it travels though the ideal position. Too much lead distance may allow flux loss and the weld will tend to run back onto itself before the cylinder turns to the ideal position. Not enough lead distance may allow the molten weld insufficient time to freeze before the weld goes through the ideal position and the flux spills off.

The best lead angle should be determined by trial runs.

![Diagram of vertical displacement on cylinders](image)

**Submerged arc welding consumables classification**

There are many different types of electrode wires commercially available for mild steel and alloy steels, but limited choice of stainless steel wires and copper alloy wires. Some hard facing wires are also available. Solid wires are classified to a particular standard, which makes it possible to identify and select the most suitable type of wire for a job. It is important to understand classification systems and the information they represent.

Consumable classification systems list a number of essential features about the consumable; for example, consumables are classified based on filler metal composition, flux type and method and deposited weld properties.
AS1858.1 classifies solid wire electrodes under three groups of elements separated by hyphens. Each group consists of a number of letters or letters and numbers.

For example, EL12K – FMM – W504.

**Group 1 (EL12K)**
The first group of letters relates to the filler material and denotes a solid electrode and indicates:

- **E** = electrode
- **L** = little or no increase in manganese (H = high manganese silicon, M = moderate manganese silicon)
- **12** = 0.12% carbon, 8, 12, 13, 14 (a number indicating % carbon)
- **K** = killed (double de-oxidised).

**Group 2 (FMM)**
The second group relates to the shielding medium used and consists of **F** for flux shield and then two letters that indicate the type of flux and contribution to weld metal:

- **F** = flux shield
- **M** = multi run (S = single run, B = basic flux, G = general flux)
- **M** = moderate increase in manganese, (L = little or no increase, H = high increase).

**Group 3**
The third group relates to the weld deposit and involves a letter **W** followed by a three-digit number. W stands for weld metal. The following two digits refer to the minimum strength of the deposited weld, which is measured in megapascals. The third digit refers to the minimum impact value:

- **W** = weld metal properties
- **50** = 500 MPa strength
- **3** = degree of impact test.

**Process requirements**
The successful application of the process of submerged arc welding depends on the following.

- **Welding conditions and preparation to suit the work.**

  Correct voltage, welding current and travel rate create the necessary bead width, weld contour and penetration. The joint often contains more of the base metal (from 50 to 70%) than applied filler metal, hence the composition of the base metal plays an important part in this process. Base metal composition and thickness go hand-in-hand in determining the mechanical properties of the joint.
Correct selection of welding wire and flux combination to suit the base metal to be welded.
The wire and its manganese contribution, combined with flux manganese and alloy contribution, should be matched to the parent metal and expected weld metal properties. The depth of flux covering applied should be no greater than is required to obtain a quiet action and an absence of porosity in the finished weld. If too deep a layer is used, the rough and uneven surface that results is due to the entrapment of gases generated during the welding process which cannot escape through the thick layer of flux. Too shallow a flux results in porosity and 'open arcing' occurring.

Plate surface preparation other than joint preparation.
It is important that no foreign material is picked up during flux reclamation and, to prevent this, a suitable width of plate on either side of the joint is cleared prior to welding. It is essential that the plate and joint surfaces are clean and dry. Oil, grease, paint and other gas producing mediums remaining in the joint area will cause porosity. Even a crayon mark on the joint surface can ruin an otherwise good weld.

Heat treatment prior to, during and after welding has been completed
Calculation of pre-heat temperatures and the requirements of post-weld heat treatment is extremely important. For most plain carbon and alloy steels, only pre-heat is needed, if any treatment is required at all.

Weld backing
Due to the large volume of molten metal that remains fluid for an appreciable time, it is essential to provide support to contain the weld until solidification is effected.

Methods used are:
- non-fusible backing, for example copper backing strip
- weld backing – this is the most widely used method of applying support.

Some further points to consider on weld backing are as follows.
- In a ‘root backed’ joint, the root face should be thick enough to support the incompletely penetrated first pass of weld. It is most important that the joint edges are tightly butted.
- Manual welds are sometimes used as backing when it is not convenient to use other backing methods because of inaccessibility, poor joint preparation of fitting, or difficulty in positioning the job.
- The manual weld may become part of the complete joint or it may be removed and replaced.
- E4312 and E4313 electrodes are not recommended as backing welds, as they tend to cause porosity in the finished weld.
- Preparation is provided to aid weld penetration and control the amount of weld reinforcement. Preparation is usually provided in accordance with the quality of the weld metal required in the finished weld.
Causes of porosity

The principal causes of porosity when submerged arc welding are as follows.

<table>
<thead>
<tr>
<th>Causes</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contamination</td>
<td>dirty parent metal, rust, oil, paint, grease</td>
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<tr>
<td>Flux cover</td>
<td>too thin, contaminated</td>
</tr>
<tr>
<td>Voltage</td>
<td>voltage too high, causing long arc</td>
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</table>

Causes of cracking

The principal causes of cracking when submerged arc welding are as follows.

<table>
<thead>
<tr>
<th>Causes</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>Hardness</td>
<td>poor parent metal/wire/flux combination</td>
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<tr>
<td>Rigidity</td>
<td>caused by thick plates or reinforced/braced structures</td>
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<tr>
<td>Low ambient temperatures and fast cooling rates</td>
<td>cause an increase in quench rates that might be detrimental on susceptible material</td>
</tr>
<tr>
<td>Steels of low weldability</td>
<td>high alloy content, high carbon equivalent or large mass can all contribute to poor weldability</td>
</tr>
<tr>
<td>Polarity</td>
<td>if cracking is due to plate composition, electrode positive polarity is recommended. The 20% to 30% better burn-off will help to build up an adequate cross section of weld with a proper convex bead which resists cracking</td>
</tr>
<tr>
<td>Manual first pass weld backing</td>
<td>use only recommended hydrogen-controlled electrode types for this function</td>
</tr>
<tr>
<td>Bead shape and dimensions</td>
<td>particularly the ratio between the width and depth of deposit (ratio 3 width to 2 depth or better)</td>
</tr>
<tr>
<td>Internal shrinkage</td>
<td>to prevent internal shrinkage cracking, the bead surface must be flat to slightly convex and the width of the weld must not be greater than penetration depth</td>
</tr>
<tr>
<td>Electrode stick-out</td>
<td>this determines the burn-off rate; a high burn-off rate gives less penetration and weld dilution and reduces cracking, but bead shape is hard to control</td>
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All operating factors are important. With adequate supervision, SAW will provide the most consistent and trouble-free welding of all production processes.
Electro-slag welding

The electro-slag process was first developed for vertical welding of tank seams on site, but the process potential for single-pass welds on heavy materials in the vertical position was soon realised. A unique feature of the process is the absence of an open arc, because once the molten pool is established, welding heat is developed by resistance heating as the current passes through the molten slag.

Preparation of plate edges is minimised, since square oxy-cut edges can safely be welded, but the advantages of this feature are limited to some extent by the need to provide substantial clamping arrangements to secure the parts during welding.

The slag has no metallurgical function, because very limited amounts of flux are used in comparison with other processes. Its function is to develop and distribute welding heat and to protect the molten pool of weld metal from the atmosphere.

In the electro-slag process, the guide and contact tube for the continuously fed electrode wire is mounted just above the weld pool and mechanically raised as the weld progresses. An adaptation of this process employs a continuous guide from top to bottom of the weld, passing down the centre of the joint. This process is referred to as 'consumable guide welding' because the guide is melted into the weld pool as it rises. The advantage of a consumable guide is that it can be set up before welding commences, including the wire feed mechanism which remains static, and joints that change direction and slope away from the vertical can be better catered for.

![Diagram of Electro-slag arrangement](image-url)
Preparation

A gap is required between square plate edges of between 25 mm and 50 mm, depending on the thickness of the material. The gap is often set to increase from bottom to top, in order to cope with the considerable contraction forces as the weld progresses. ‘Strong backs’ or shaped plates are usually welded on to hold joint plates in the position required and to maintain good alignment across the face of the joint.

These strong backs must be cut out to provide free passage for the copper shoes and the vertical drive gear (see Fig 18.11).

Preparation also requires the provision of run-on and run-off plates at the beginning and end of joints. These short extensions of joint plates, approximately 75 mm, allow full size and full strength welds to be maintained throughout. They can be seen on the sketch of the consumable guide arrangement in Fig 18.12.

Copper mould

Copper moulds, or shoes, contain the molten metal and slag and are moved forward as the weld proceeds. Copper is a good conductor of heat and the moulds tend to cool the weld quickly. The moulds are water cooled internally and form a solidified flux coating against the weld face, which also serves to protect the copper. Reinforcement of the weld is created by the shape of the moulds. They are held in close contact with the joint faces to prevent leakage from the molten pool and are moved upwards as welding progresses. The molten metal solidifies and becomes self-supporting before the bottom of the mould moves forward. An alternative to continuously moving shoes is the stepping of moulds as indicated in Fig 18.12.

Flux

Flux is similar to submerged arc fluxes but has additional amounts of:

- calcium fluoride – to prevent arcing
- manganese and aluminium silicates – to raise boiling point
- fluorspar and magnesia – to improve conductivity and ionisation.
Flux is added as necessary to compensate for losses and the level of molten slag is maintained between 38 mm and 50 mm. The flux is a non-conductor of electricity when cold, but in the molten state it becomes highly conductive.

Molten slag that is too deep may trap gas or slag and if too shallow may allow metal to run out or cause unstable current flow. Steel wool is often used to assist with starting of the arc.

The molten slag maintains a temperature between 1700°C and 2400°C, which melts the filler wire and the plate edges. The actual melting point of flux is much lower than the melting point of steel, which is designed to prevent slag being trapped. The molten slag must not be allowed to boil.
Wires

Standard wires are used (as in SAW), but since flux cannot be used to add elements to the weld, these must be added via the wires and/or the consumable guide when it is used. Wire oscillation can be arranged to ensure even heat and metal distribution.

Power source

Ordinary arc welding transformers or generators that have high output can be used, but the duty cycle must be very high. Constant potential machines give better control of weld conditions than constant current machines. Alternating or direct current can be used, but alternating is preferred. Welding current is relatively high, depending on the size of joint and the number and size of electrodes; for example, three wire feeds may require 3000 amps at 40 to 55 volts.

Metallurgical aspects

Owing to prolonged heating and slow solidification, the welds produced have a very coarse grain structure and a wide HAZ, often returning low impact values. However, normalising can give the necessary grain refinement and a resulting improvement in mechanical properties.

Summary

Advantages:

- single-pass only required
- square edge preparation
- no visible arc and little heat given off
- excellent on heavy material
- no angular distortion
- more metal is deposited per unit of electric power than other processes
- flux consumption is very low compared to submerged arc welding.

Limitations:

- high cost of equipment
- can only weld vertical
- setting up may be difficult – strongbacks must be used
- heat treatment is often required.
Appendices
## Appendix 1

### Metals and fabrication competency mapping

#### Arc Welding 3

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3. Codes and regulations

© VET (WA) Ministerial Corporation 2010 – ENG1769
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12. MMAW, arc conditions and electrodes

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### Competency title
- **Welding alloy steels**
- **Welding non-ferrous metals**

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|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Weld using manual metal arc welding process | Weld using gas tungsten arc welding process | Perform advanced welding using MMAW process | Perform advanced welding using GTAW process | Weld using gas metal arc welding process | Perform advanced welding using GMAW process | Perform welds to code standards using MMAW process | Perform welds to code standards using GTAW process | Perform welds to code standards using GMAW process | Perform welds to code standards using FCAW process | Weld using submerged arc welding process | Select welding principles | Weld using gas tungsten arc welding process | Perform advanced welding using GTAW process | Perform welds to code standards using FCAW process | Weld using gas tungsten arc welding process | Perform advanced welding using GTAW process | Perform welds to code standards using FCAW process | Weld using gas metal arc welding process | Perform advanced welding using GTAW process | Perform welds to code standards using FCAW process |

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Advanced welding

This resource is specifically designed to provide basic underpinning knowledge related to a number of competency units used in the Certificate IV in Engineering Welding pathway across TAFE WA from January 2007. This pathway was specifically designed to meet the needs of the metal fabrication and welding industry after industry consultation, WTIA involvement and TAFE WA moderation sessions held in 2006. This pathway is also designed to be common across all colleges of TAFE WA (customisation to suit local conditions is however encouraged). The pathway meets the requirements of AS1796 and guidelines of the MEM05 Training Package.

Context of assessment

Assessors are reminded the individual units may be assessed on the job, off the job or a combination of both on and off the job. Where assessment occurs off the job, that is the candidate is not in productive work, then an appropriate simulation must be used where the range of conditions reflects realistic workplace situations.

Project work, integration

These units could be assessed in conjunction with mandatory units addressing the safety, quality, communication, mathematics etc. Units may also be assessed with other units requiring the exercise of the skills and knowledge.

Method of assessment

Assessors should gather a range of evidence that is valid, sufficient, current and authentic. Evidence can be gathered through a variety of ways including direct observation, supervisor's reports, project work, samples and questioning. Questioning should not require language, literacy and numeracy skills beyond those required in this unit. The candidate must have access to all tools, equipment, materials and documentation required. The candidate must be permitted to refer to any relevant workplace procedures, product and manufacturing specifications, codes, standards, manuals and reference materials.

Consistency of performance

Assessors must be satisfied that the candidate can competently and consistently perform all elements of the units as specified by the criteria, including required knowledge and be capable of applying the competency in new and different situations and contexts.
# Appendix 2

## Hot-work permit (example)

**TYPICAL FORM FOR A HOT-WORK PERMIT**

(Informative)

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<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>Site location</td>
<td>Date</td>
</tr>
<tr>
<td>2</td>
<td>The hot work that is covered by this permit</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>The location of the hot work</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>The equipment to be used</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>The firefighting equipment to be laid out at the worksite</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Whether the following checks been made: (Note: All questions are to be answered and initialled by the issuing responsible officer. ‘N.a.’ means ‘not applicable’).</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Have drains, pits and depressions been checked, isolated and sealed?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.2</td>
<td>Have combustible materials been removed from the work area or made safe?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.3</td>
<td>Have tanks, valves, vents and pipelines been blanked off or effectively isolated?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.5</td>
<td>Are spark and flash screens in place?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.6</td>
<td>Have leaks from valve and pump glands, flanges and the like been controlled?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.7</td>
<td>Have pressure relief valves been vented to safe areas?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.8</td>
<td>Has contaminated ground been covered?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.9</td>
<td>Is the fire equipment checked and laid out ready for use?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.10</td>
<td>Is the fire pump or fire brigade on standby?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.11</td>
<td>Is a firewatch required?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.12</td>
<td>If required, has a firewatch been organised?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.13</td>
<td>Is the wind direction satisfactory for hot work to be done?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.14</td>
<td>Has product movement been stopped in the area of hot work?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.15</td>
<td>Has the site of the hot work been isolated and roped off?</td>
<td>Yes / N.a.</td>
</tr>
<tr>
<td>6.16</td>
<td>GAS TESTING:</td>
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<td>Equipment make and model</td>
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<td>Serial No.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Date of last equipment check</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Date of test</td>
<td></td>
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<td></td>
<td>Time of test</td>
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</table>
Results of test __________________________________________________________

Percentage L.E.L. ______________________________________________________

Is hot-work safe to proceed? ____________________________________________

Initials of tester ______________________________________________________

The following conditions and precautions were observed:

____________________________________________________________________

This permit is valid from______ am/pm on___/___/___ to ______ am/pm on ___/___/___

Name of contractor performing the work_________________ Order or contract no. ______

Name and signature of firewatch (where required) ______________________________

Permit received by:

(print name) ____________________________ (signature)

Person in charge of location:

(print name) ____________________________ (signature)

Responsible Officer:

(print name) ____________________________ (signature)

Return permit:

This permit was returned/cancelled by:

(print name) ____________________________ (signature)

to:

(print name) ____________________________ (signature)

at______ am/pm ___/___/___

The worksite has been inspected by me at the expiry/cancellation of this hot-work permit and declared safe for normal operations to resume.

(print name) ____________________________ R.O. ____________________________

THIS HOT-WORK PERMIT SHOULD BE PROMINENTLY DISPLAYED ON THE WORKSITE
Appendix 3

Compulsory classification designators

This text has been removed. It was reproduced from page 20 of AS/NZS 4855:2007 ISO 2560:2002.
Appendix 4

Compulsory classification designators

This text has been removed. It was reproduced from page 21 of AS/NZS 4855:2007 ISO 2560:2002.
Appendix 5

Classification systems – Creep resistant steels

A.1 ISO 3580-A

The ISO 3580 Classification system for covered electrodes based upon chemical composition is shown in Figure A.1.

A.2 ISO 3580-B

The ISO 3580 Classification system for covered electrodes based upon tensile strength and chemical composition is shown in Figure A.2.
Appendix 6

Classification systems – High strength steels
from AS/NZS 4857

A.1 ISO 18275-A
The ISO 18275-A classification system for covered electrodes for high-tensile steels, based upon yield strength and 47 J minimum impact energy, is shown in Figure A.1.

A.2 ISO 18275-B
The ISO 18275-B classification system for covered electrodes for high-tensile steels, based upon tensile strength and 27 J minimum impact energy, is shown in Figure A.2.
Appendix 7

Scope for ISO 17632:2006, MOD

This International Standard specifies requirements for classification of tubular cored electrodes with or without a gas shield for metal arc welding of non-alloy and fine grain steels in the as-welded condition or in the post-weld heat-treated condition with a minimum yield strength of up to 500 MPa or a minimum tensile strength of up to 570 MPa. One tubular cored electrode can be tested and classified with different shielding gases, if any.

This International Standard is a combined specification providing classification utilizing a system based upon the yield strength and the average impact energy of 47 J of all-weld metal, or utilizing a system based upon the tensile strength and the average impact energy of 27 J of all-weld metal.

1) Paragraphs and tables which carry the suffix letter “A” are applicable only to tubular cored electrodes classified to the system based upon the yield strength and the average impact energy of 47 J of all-weld metal in accordance with this International Standard.

2) Paragraphs and tables which carry the suffix letter “B” are applicable only to tubular cored electrodes classified to the system based upon the tensile strength and the average impact energy of 27 J of all-weld metal in accordance with this International Standard.

3) Paragraphs and tables which have neither the suffix letter “A” nor the suffix letter “B” are applicable to all tubular cored electrodes classified in accordance with this International Standard.

It is recognized that the operating characteristics of tubular cored electrodes can be modified by the use of pulsed current, but for the purposes of this International Standard, pulsed current is not permitted for determining the electrode classification.
Appendix 8

Classification from ISO 17632:2006

This text has been removed. It was reproduced from pages 2, 3 and 4 of AS/NZS ISO 17632:2006.
Appendix 9

Classification systems from ISO 17632:2004

A.1 ISO 17632-A
The ISO 17632 classification system for tubular cored electrodes based upon yield strength and 47 J minimum impact strength is shown in Figure A.1.

A.2 ISO 17632-B
The ISO 17632 classification system for tubular cored electrodes based upon tensile strength and 27 J minimum impact strength is shown in Figure A.2.

This text has been removed. It was reproduced from pages 20, 21 and 22 of AS/NZS 17632:2006.
Appendix 10

Examples of designation

This text has been removed. It was reproduced from pages 18 and 19 of AS/NZS 17632:2006.
METALS AND FABRICATION
ARC WELDING 3
Advanced Arc Welding Information Book

Learner’s Guide

DESCRIPTION
This resource supports learners to develop advanced-level skills and knowledge relating to a number of competency units used in the Engineering Tradesperson Fabrication learning pathway.
Topics covered include the following.
• Distortion
• Welding safety
• Codes and regulations
• Welding terms and symbols
• Welding plain carbon steel
• Heat treatment
• Weld testing
• Weld preparation and set up
• Weld procedures
• Metal cutting and gouging
• Elementary electrical terms
• MMAW, arc conditions and electrodes
• Welding alloy steels
• Ferrous metals
• GTAW and equipment
• GMAW/FCAW and equipment
• Oxy-fuel gas welding
• Automatic welding

Detailed graphics, technical drawings and photographs are provided throughout the book to support learners. As the content within this book is of a higher level and is more technical in nature, it aligns with a range of Australian Standards, and includes extracts from some Standards documents as references for students.

EDITION
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CATEGORY
Metals and Engineering

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• MEM05