ENG094

Arc Welding 2
Intermediate Arc Welding
Information Book

Learning Resource
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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
Chapter 1 – Distortion

- Contra-heating
  - advantages of the process
  - principles of flame straightening
  - cooling procedure
  - application to plates
  - 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).

Fig 1.5 – Transverse distortion

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.
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).

Warping, bowing or buckling

Longitudinal, transverse, and angular contraction occurring together can produce some complex distortion problems. This is most common in thin plates. The simple example in Fig 1.7 illustrates the warping and bowing effect created by the presence of all three contraction forces.

Correction of warping such as this can be very difficult when multi-pass welds are involved. Successive beads are deposited on metal that is already distorted, tending to compound the total distortion.
Chapter 1 – Distortion

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.

Fig 1.8 – Backstep technique

Incorrect  Correct

Fig 1.9 – Number of runs

Fig 1.10 – Intermittent fillet welds
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.

![Fig 1.13 – Balanced welds](image)

Pre-setting parts

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

![Fig 1.14 – Pre-setting](image)

Cambering

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

![Fig 1.15 – Pre-cambering](image)
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.

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 1.19 – Proportion of the heating wedge

Fig 1.20 (a)

ANGLE
(Heat legs in order indicated)

CHANNEL
(Heat web first then flange)

(Heat both flanges at the same time, then web)
Fig 1.20 (b)

Fig 1.20 (c)

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.

Fig 1.21 – Equipment for providing an atomised spray for quenching

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.

Fig 1.22 – Spot heating shrinks excessive metal on the convex side of the buckle
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 – Weld defects

Introduction

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

A weld defect is a discontinuity that exceeds acceptable standards.

The question to be answered is, ‘when does a discontinuity become a defect?’

Example


G.P. category welds are suitable for low stress applications and static loaded structures. S.P. category welds are designed for dynamic loads and higher stress loadings, therefore a better quality of weld is demanded. Table 6.2.2 of AS/NZS 1554.1 sets out 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.

This table has been removed. It was reproduced from Table 6.2.2 on page 61 of AS/NZS 1554.1.
In this chapter we will look at the following.

- Weld quality
- Types of weld defect
- Internal/external defects.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>cracks</td>
<td>discontinuities produced either by tearing of the metal in the plastic condition (hot cracks) or by fracturing when cold (cold cracks)</td>
</tr>
<tr>
<td>porosity</td>
<td>a pore or group of gas pores in the weld metal</td>
</tr>
<tr>
<td>inclusions</td>
<td>metal oxides and other solid compounds which occur as irregular or globular inclusions in weld metal</td>
</tr>
<tr>
<td>stray arcing</td>
<td>the damage on the parent metal resulting from the accidental striking of an arc away from the weld</td>
</tr>
<tr>
<td>underfill</td>
<td>a longitudinal continuous or intermittent channel in the surface of a butt weld due to insufficient deposition of weld metal</td>
</tr>
<tr>
<td>over-roll or overlap</td>
<td>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</td>
</tr>
<tr>
<td>lack of fusion</td>
<td>portions of the weld run which do not fuse to the surface of the metal or edge of the joint</td>
</tr>
<tr>
<td>excessive spatter</td>
<td>the metal particles expelled onto the surface of the parent metal or weld during welding, and not forming part of the weld</td>
</tr>
<tr>
<td>misalignment</td>
<td>an unnecessary variation in the alignment of the parts being welded</td>
</tr>
<tr>
<td>lack of root penetration</td>
<td>the failure of the weld metal to completely fill the root of the joint</td>
</tr>
<tr>
<td>excessive penetration</td>
<td>excess weld metal protruding through the root of a butt weld</td>
</tr>
<tr>
<td>(burn through)</td>
<td></td>
</tr>
<tr>
<td>undercut</td>
<td>a groove or channel in the parent metal occurring continuously or intermittently along the toes or edge of a weld</td>
</tr>
<tr>
<td>edge of plate melt-off</td>
<td>an imperfection in a welded joint due to a free edge of plate being melted off</td>
</tr>
</tbody>
</table>
Weld quality

Weld quality is hard to define but generally a quality weld is ‘fit for purpose’, in other words it can do the job required of it. 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.

Types of weld defect

Different types of weld defects include:

- cracks
- cavities (porosity)
- inclusions
- incorrect size or profile (over-roll or overlap)
- lack of fusion/lack of root penetration
- others, such as:
  - excessive penetration
  - undercut
  - edge of plate melt-off
  - misalignment
  - stray arcing
  - excessive spatter.

The following is a brief outline of how defects occur. Each defect is discussed in terms of cause, effect and correction.

Weld defects are commonly classified according to their location in the weld.
Cracks

Cracks are discontinuities produced either by tearing of the metal in the plastic condition (hot cracks) or by fracturing when cold (cold cracks). 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. Cracking is considered to be a serious defect and rarely is any amount of cracking tolerated.

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 heat affected zone (HAZ) cracks, or in the weld metal.

![Crack types](image)

**Hot cracking**

Usually occurs in metals that are hot short and/or have high rates of thermal expansion. Hot cracking most commonly occurs in the weld metal; longitudinal cracks, and crater cracks being the most common examples.

**Cold cracking**

Most commonly occurs in the base metal adjacent to the fusion zone. The most common example of this is underbead cracking in hardenable steels.

**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.
Causes of crater cracks include:

- the base metal is of poor weldability
- improper preparation of the weld joints
- incorrect welding procedure
- the weld joint is too rigid
- undersized welds
- unfilled craters
- stray arcing
- incompatible filler metal
- contaminated weldments.

**Correction**

Cracks should preferably be removed in their entirety, and rewelding of the joint carried out. Care must be taken to ensure that no portion of the crack remains. Failure to do this may result in further cracking.

**Underbead cracks**

The factor that 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.

The three major factors contributing to underbead cracking are:

- 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 constructional steels having tensile strengths of 680 MPa and higher. Low grade structural steels do not present a problem in this regard as they have insufficient carbon for hardening to occur.

**Rapid cooling**

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

**Hydrogen**

Hydrogen that 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.
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 heat affected zone that 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.

Fig 2.2 – Underbead crack
Porosity

This relates to 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.

![Gas pores](Image) ![Wormholes](Image) ![Cluster](Image)

**Fig 2.3 (a) – Porosity (types)**

**Causes**

- **Moisture** – A major cause of porosity is moisture on the metal surface or in welding consumables.
- **Excessive amperage** – Causing the electrode to overheat and the breakdown of the flux coating.
- **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.
- **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.

**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 is considered to be more serious, as it concentrates 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 rewelded.
Inclusions

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

Causes
- 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 inter-run 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 reweld.

Fig 2.3 (b) – Slag inclusions
Incorrect weld size, shape, weld profile
These defects are similar and often occur together. The terms are self explanatory.

Causes
- 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.

Underfill (incompletely filled groove)
A longitudinal continuous or intermittent channel in the surface of a butt weld due to insufficient deposition of weld metal.

![Fig 2.4 – Underfill](image)

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.
Chapter 2 – Weld defects

Over-roll or overlap
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 2.5 – Over-roll/overlap](image)

Causes
- Insufficient heat – causing weld metal to lie on top of the parent metal.
- Contaminated parent metal surfaces.
- Incorrect electrode angles.
- Travel speed too slow.

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.

Lack of fusion
Portions of the weld run that do not fuse to the surface of the metal or edge of the joint.

![Fig 2.6 – Lack of sidewall fusion](image)
Causes
- Amperage too low.
- 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
Any area that is unfused must lower the total strength of the weld. It is the same as leaving that portion unwelded.

Correction
Lack of fusion can only be rectified by removing the defective portion of the weld and rewelding.

It is important that sufficient weld metal is removed to permit proper manipulation of the electrode and full penetration at the walls of the joint.

Lack of root penetration
The failure of the weld metal to completely fill the root of the joint.

Causes
- 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 too fast.

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.
Chapter 2 – Weld defects

Incomplete penetration

Fig 2.7 – Lack of penetration

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 rewelded. 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, as these welds are difficult to x-ray. The welder must depend on maintaining approved procedures.

Excessive penetration (burn through)
Excess weld metal protruding through the root of a butt weld. Note: This occurs in butt welds only.

Fig 2.8 – Excessive penetration

Causes
Excessive penetration is essentially the opposite of insufficient penetration, as are the causes:

- root face too small
- root gap too big
- amperage too high
- travel speed too slow.
Effect
This is two-fold: firstly, there is excessive reinforcement (or overwelding) 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 which can erode the pipe wall downstream, particularly if the fluid is abrasive.

Correction
In butt welds that 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 rewelded. This can prove difficult, especially in pipes, and the whole joint may have to be removed.

Undercut
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 too fast
- 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 that are dynamically loaded, undercut is regarded as much more serious and may ultimately cause failure due to the stress concentration produced.

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.

Edge of plate melt-off
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 2.10 – Edge of plate melt-off

Causes
- 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 the corner and lap joints respectively.

Note: 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.

Misalignment
An unnecessary variation in the alignment of the parts being welded.

![Fig 2.11 – Misalignment](image)

Cause
Poor assembly of the parts to be welded, in the initial stage of the work. This is usually caused by faulty or insufficient tack welds, poor assembly techniques, or inefficient alignment clamps.

Effect
The main effect on butt welded joints is to produce poor root penetration. This is very serious when butt welding small diameter pipes without the use of backing rings. Lack of full penetration will result in 'notching' under service stresses, and could cause failure. When misalignment occurs, welds of specified size are unlikely to be achieved.

Correction
If slight misalignment is not critical, the joint should be ground or otherwise shaped to the correct alignment and weld metal deposited in the deficient sections. If joint misalignment is critical, the whole weld may have to be removed and the joint correctly aligned.

![Fig 2.12 – Correction of misalignment](image)
**Stray arcing**

The damage on the parent metal resulting from the accidental striking of an arc away from the weld.

![Stress concentration](image)

**Fig 2.13 – Stray arcing**

**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)
- the electrode holder and the work
- 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.
Excessive spatter

The metal particles expelled onto the surface of the parent metal or weld during welding, and not forming part of the weld.

![Excessive spatter](image)

**Fig 2.14 – Excessive spatter**

**Causes**
- 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 the parent metal are caused.
Chapter 2 – Weld defects

Internal/external defects

Some of the defects previously mentioned, marked below with an (*), may occur either as internal or external defects and are sometimes classified as internal/external defects.

Remember – An imperfection or discontinuity only becomes a defect when it exceeds the limits set down in the acceptable standard.

Internal defects

Weld metal defects which do not extend to the plate surface are:

- cracks*
- porosity*
- lack of fusion*
- lack of penetration*
- slag inclusions*.

External defects

Those which can be identified by visual examination are:

- undercut
- underfill
- profile defects
- misalignment
- stray arcing
- cracks*
- porosity*
- lack of fusion*
- lack of penetration*
- slag inclusions*. 
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:

- procedure qualification – to ensure that the welding procedure is capable of delivering welds which 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
- product inspection – to ensure that the completed weldment meets specifications and is fit for purpose.

Weld testing procedures are divided into two major categories; non-destructive testing (NDT) and destructive testing (DT).

In this chapter we will look at the following.

- Destructive and non-destructive testing.
Destructive and non-destructive testing

Non-destructive testing (NDT)
NDT is carried out by various processes that 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 DT methods are usually not suitable as a means of product inspection, as all the products produced would be destroyed in testing. DT 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.

Production inspection is usually carried out by NDT methods. It can 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 defect-free. Where strength of the weld is critical (eg in the case of pressure vessels), proof tests are usually carried out. These usually take the form of pneumatic or hydrostatic pressure tests, and give a direct indication that the weldment is capable of meeting service requirements.

If testing of welds is to be successful, it is essential that the technician carrying out the test knows:

- what defects are likely to occur
- the likely location of these defects within or adjacent to the weld
- the test method/s that will best disclose these defects.

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 to which they are made. The most common discontinuity types and their likely location are:

- cracks
- cavities (porosity)
- inclusions
- incomplete fusion (lack of fusion)
- inadequate penetration (lack of penetration)
- contour defects
- undercut
- underfill
- misalignment
- lamellar tearing.
**Lamellar tear**

This defect occurs in the heat affected zone of welds in heavy rolled sections, and appears as a crack or tear running in the direction of rolling.

![Lamellar tear](image)

**Laminations and de-laminations**

Laminations occur in the parent metal during manufacture, producing a 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.

![Lamination opening under load](image)

**Selection of a testing method**

The testing procedure and the costs associated form part of the overall cost of the product. The testing procedure must be cost-effective if overall fabrication costs are to be kept within budget.

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, therefore 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 non-compliance by radiographic examination.
Non destructive test methods

There are six NDT methods that we will examine:

- visual inspection
- penetrant inspection
- magnetic particle inspection
- ultrasonic inspection
- radiographic testing
- 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.

Visual inspection should be applied in the following ways.

Prior to welding – check:

- 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 jigging, bracing, or cambering.

During welding – check:

- 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 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.
Aides to visual inspection are devices such as a torch, fillet gauges, callipers, other measuring devices, and a low powered (up to 10x) magnifying glass.

The major limitation of visual inspection is that it will disclose only surface defects, and only defects that can be seen by the naked eye. Fine surface cracks may not be readily apparent by visual inspection, but may be easily 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.

![Diagram of penetrant testing process]

**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 (chemical) 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 that may be present.

The steps involved in this method of inspection are:

- 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 ‘blotter’ and to draw the fluorescent penetrant back from the defects.

After processing, the surfaces are viewed while illuminated with high-intensity ultra violet 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.
- Ability to disclose fine 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.

For further information about penetrant testing, you may like to look at the ‘Penetrant Testing’ DVD (also available with supporting Learning Guide and Workbook), which can be ordered through WestOne Services. Refer product code ENG508 at http://wpc.westone.wa.gov.au.
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 3.4)

Fig 3.4 – The magnetic field surrounding a bar magnet

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 3.5).

Fig 3.5 – Concentration of iron filings where lines of force meet

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 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, as per Fig 3.6 (a).

![Fig 3.6 (a) – Magnetic flux at 50° or greater to crack](image)

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, as shown in Fig 3.6 (b).

![Fig 3.6 (b) – Magnetic flux at less than 50° to crack](image)

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, usually in the frequency 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 that generates the electrical oscillations, a cathode ray tube on which pulse and echo can be seen, and probes that 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 of the plate and the probe is slid over this surface.

Three types of probe are available.

- A single probe that acts as both transmitter and receiver, the same ‘piezo-electric’ 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, is quite separate electrically and ultrasonically so that there is no trouble from interference with 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 segregations etc. 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 and 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 it 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 3.10).

The radiation that passes through the specimen strikes the film behind. The radiation darkens 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.
Chapter 3 – Testing of welds

X-rays
X-rays are produced in an electrical apparatus (see Fig 3.11) 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.

![Fig 3.11 – Production of x-rays](image)

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. Generally in the testing of welds, artificial radioactive elements called ‘isotopes’ are used. Gamma rays are electromagnetic radiation of very short wave-length 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 ‘gammaphotographs’ 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 field and shop 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 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 characterise 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 dosimeters. Film badges are supplied by a special service that 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 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 3.1 on the following pages.
<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, weld size gauge, pocket rule, straight edge, workmanship standards</td>
<td>External defects: cracks, porosity, slag, unfilled craters, slag inclusions, warpage, under-welding, over welding, poorly formed beads, misalignment, improper fit-up</td>
<td>Low cost, can be applied while work is in progress, permitting correction of faults, gives indication of incorrect procedure</td>
<td>Only surface defects are detectable, cannot be used effectively on hot assemblies</td>
<td>Should always be the primary method of inspection, no matter what other techniques are required</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></td>
</tr>
<tr>
<td>Magnetic particle</td>
<td>special commercial equipment, magnetic powders – dry or wet form</td>
<td>External defects: surface discontinuities – especially surface cracks</td>
<td>Un erosible, low cost method</td>
<td>Requires skill in interpretation of indications and recognition of irrelevant patterns</td>
<td>Requires skill in interpretation of indications and recognition of irrelevant patterns</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>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------</td>
<td>----------------------</td>
<td>------------</td>
<td>-------------</td>
<td>---------</td>
</tr>
</tbody>
</table>
| Pressure          | • water pumps or air compressors  
|                   | • pressure gauges and piping  
|                   | • water/air tightness leaks through weldments in tanks, boilers, etc | • low cost  
|                   |                   | • sensitive | • can only be applied in last stages of fabrication | • care should be applied when carrying out pneumatic testing. All air must be excluded when hydro-static testing |
| Ultrasonic        | • special commercial equipment either of the pulse-echo or transmission type  
|                   | • standard reference pattern for interpretation of RF or video pattern | 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 | • very sensitive  
|                   |                   | • permits probing of joints inaccessible to radiography | • requires high degree of skill in interpreting pulse-echo patterns  
|                   |                   | • permanent record is not easily obtained | • pulse-echo equipment is highly developed for weld inspection purposes  
|                   |                   |                   | • the transmission-type equipment simplifies pattern interpretation where it is applicable |
| Radiographic      | • x-ray equipment or gamma radiation source  
|                   | • facilities for processing and viewing of radiographs | • 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 | • when the indications are recorded on film, gives a permanent record | • requires skill in choosing angles of exposure, operating equipment and interpreting indication  
|                   |                   |                   | • requires safety precautions  
|                   |                   |                   | • not generally suitable for fillet weld inspection | • 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 |

Table 3.1 (cont) – 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. These can be easily carried out in most workshops as no sophisticated equipment is required.

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 that 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**  
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 are not to be confused. Ductility is the ability to permanently deform without breaking.

**Tenacity**  
The ability of a metal to resist a force which is acting directly to pull it apart (tensile strength).

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 3.14).

A tensile test will disclose information about the test specimen regarding:

- ultimate tensile strength (UTS)
- yield strength
- elasticity
- ductility.
Ultimate tensile strength (UTS)
The ultimate tensile strength 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
- % 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’.

---

**Fig 3.15 – Tensile test specimens**
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 3.15). These two distances are used to calculate ductility using one of the following formulas.

- \( \% \text{ elongation} = \frac{\text{increase in length}}{\text{original length}} \times 100 \)
- \( \% \text{ reduction of area} = \frac{\text{decrease in cross sectional area}}{\text{original cross sectional area}} \times 100 \)

**Example 1**

Consider a test piece of a gauge length of 50 mm which stretched 12 mm prior to failure.

\[
\% \text{ elongation} = \frac{12}{50} \times 100 = 24\% \text{ elongation}
\]

**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: \( 79 - 50 = 29 \text{ mm}^2 \)

\[
\% \text{ reduction of area} = \frac{29}{79} \times 100 = 37\% \text{ reduction of area}
\]
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 the HAZ of a weld 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 3000 kg. The diameter of the impression is measured with a special microscope and the reading is converted by consulting a table. Brinell readings are listed as BHN (Brinell Hardness Number). Soft iron is about 100 BHN and file-hard steel about 600 BHN.

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 3.16 (a) – Hardness testing by the ‘Rockwell B’ method
Chapter 3 – Testing of welds

Fig 3.16 (b) – Rockwell hardness tester

Fig 3.17 – Testing by the ‘Rockwell C’ method
Vickers hardness test
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 are the ‘Izod test’, and the ‘Charpy test’, which 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 that 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 3.18.
Chapter 3 – Testing of welds

Fig 3.18 – Impact testing

Izod

Charpy

Test piece
Moving pointer
Graduated quadrant
Anvil, vice or support
Pendulum
Striking knife edge
Fatigue testing

A knowledge of the 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 (ten million) cycles is taken as the number of reversals that 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**

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 in the weld such as lack of fusion or inclusions.

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 3.20 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 3.21, and fractured by steady loading or by blows.

Acceptable standards may be obtained by reference to the relevant code.

Macro testing

Both fillet and butt welded structures are macro tested to show the weld, fusion zone and surrounding area. A small cross section is removed from a competed 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.

![Diagram showing test piece with surface dressed smoothly before polishing, polished surface etched with acid, and highlighted weld structure.]

Fig 3.22 – Macro testing
Chapter 4 – Identification of metals

Introduction

It is important that the fabricator or welder is able to accurately identify any metal with which he or she is dealing. In the case of new work, the problem of identification is simplified as the material to be welded has probably been obtained from a manufacturer for a particular purpose, and the necessary information relating to the welding procedure can usually be obtained from the manufacturer or supplier.

Repair or maintenance welding is a quite different matter. The metal may have come from any one of a number of sources, and hence it may be impossible to obtain accurate specifications, but the welder must still identify the metal before deciding on the welding procedure.

If the metal is incorrectly identified, a costly weld failure may occur. For example, if the welder mistakes high carbon steel for mild steel, and uses normal welding procedures, the weld is certain to fail. Again, if the welder mistakes zinc die cast for aluminium and welds with a procedure appropriate for aluminium, the metal will surely sag and collapse.

Sometimes it is quite easy to identify a metal, but in other cases real detective work is necessary. This can be time consuming, but proper identification must be made because of the major variations in welding techniques involved in repairing different metals.

In this chapter we will look at the following.

- Identification methods
- Density testing
- Identification of wrought iron
- Identification of mild steel (low carbon steel)
- Identification of medium and high carbon steels
- Identification of alloy steels
- Identification of grey cast iron
- Identification of white cast iron
- Identification of malleable iron
- Procedure for metal identification.
Identification methods

The following methods may be used by a welder to help identify an unknown metal, that may require repair.

- The purpose the part serves, and its outward appearance
- The appearance and colour of the fracture
- Chipping and filing test (hardness test)
- Melting with the oxy-acetylene flame
- Grinding (spark testing)
- Density testing
- A magnetic test
- Chemical tests
- Comparison tests.

The purpose the part serves

Experience and knowledge are essential in this method of identification, but this simple and reliable indicator is often missed by the casual observer. To the operator with a good mechanical background, this test can provide much valuable information. The welder will know, for instance, that certain machine parts are always made from cast iron and others are usually steel forgings.

Outward appearance

All metals used in modern construction and fabrication are either cast, rolled, extruded, or forged. Some metals can be treated by all of these processes, whilst some can be treated by only one or two of the processes. This helps to narrow the field somewhat.

Metals such as iron, steel, copper, brass, bronze, and aluminium are often produced by ‘sand casting’. This means that they were poured into a sand mould when molten, then allowed to cool. This gives them a rough surface appearance, and some of the moulding sand may be embedded in the surface of the casting. Die castings have smooth surfaces with high definition, due to the metal moulds in which they are cast. Metals with low melting points are used for these castings, and castings made by this process are usually easily identified as aluminium or zinc alloys.

Wrought iron, mild steel, copper, brass, bronze and aluminium are procurable in sheets. The surfaces of wrought iron and steel plates have an oxide or scale finish, unless they are further treated by drawing, planishing, or polishing. Sheets of aluminium copper and brass are smooth and shiny after rolling.

Aluminium and copper alloys are the metals most suited to the extrusion process, in which ‘plastic’ metal is forced by pressure through a die. Extruded finish is smooth, and frequently very fine lines running along the extrusion may be visible.

Wrought iron, steel, copper, and some non-ferrous alloys are the most commonly forged metals. The process consists of heating the metals and then squeezing or hammering them to the desired shape. All forged work generally has oxidised surfaces. Drop forgings can be further identified by evidence of grinding to remove the ‘fin’ from where the dies come together during forging.
Appearance and colour of the fracture

It should be kept in mind that when looking at a metal, it is not usually the metal that we see but a layer of oxide on the surface of the metal. To visually examine the metal, we usually break the metal and examine the fracture. This provides a more accurate indication of the colour, as well as information about the grain structure of the metal.

The appearance of the surface where the metal is fractured shows the grain structure of the material. If the grains are large, the metal is generally brittle and weak. If the grains are small, the metal generally displays good mechanical properties. The fracture also shows the colour of the metal, which is a good means of identifying one metal from another. The test also helps to identify the type of metal by the ease with which it may be fractured.

The two main divisions of metals include the irons and steels (ferrous metals), which are indicated by their typical grey white colour, and the non-ferrous metals which come in two general colour classifications of yellow and white. Copper can be easily identified by its distinctive colour; the same applies to brasses and bronzes. Aluminium, white metal, die cast, zinc and the like are all of somewhat the same silver colour, although they may vary in shade.

<table>
<thead>
<tr>
<th>Fracture</th>
<th>Grey cast iron</th>
<th>Malleable iron</th>
<th>Low carbon and cast steel</th>
<th>High carbon steel</th>
<th>Alloy steel</th>
<th>Copper</th>
<th>Aluminium and alloys</th>
<th>Brass and bronze</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dark grey</td>
<td>dark grey</td>
<td>bright grey</td>
<td>very light grey</td>
<td>medium grey</td>
<td>red colour</td>
<td>white</td>
<td>red to yellow</td>
</tr>
<tr>
<td>Unfinished surface</td>
<td>evidence of sand mould</td>
<td>evidence of sand mould</td>
<td>dark grey forging marks may be seen</td>
<td>dark grey casting or forging lines may be seen</td>
<td>dark grey relatively rough</td>
<td>various degrees of reddish brown to green, due to oxides smooth</td>
<td>very light grey evidence of moulds or rolls</td>
<td>various shades of green brown or yellow</td>
</tr>
<tr>
<td>Newly machined surface</td>
<td>fairly smooth light grey</td>
<td>smooth surface light grey</td>
<td>very smooth bright grey</td>
<td>very smooth bright grey</td>
<td>very smooth bright grey</td>
<td>bright copper which dulls with time</td>
<td>smooth very white</td>
<td>red to whitish yellow very smooth</td>
</tr>
</tbody>
</table>
Chapter 4 – Identification of metals

Chipping test

The nature of the chip produced with a cold chisel varies considerably between different metals. For example, cast iron when being chip-tested, breaks off in small particles, but with mild steel the chip tends to curl and cling to the original piece. This test essentially discloses information about the ductility of the metal, also the ease with which the chisel cuts the metal is an indication of hardness.

<table>
<thead>
<tr>
<th>Appearance of chip</th>
<th>Grey cast iron</th>
<th>Malleable iron</th>
<th>Low carbon and cast steel</th>
<th>High carbon steel</th>
<th>Copper</th>
<th>Aluminium and alloys</th>
<th>Brass and bronze</th>
</tr>
</thead>
<tbody>
<tr>
<td>small partially broken chips</td>
<td>chips do not break short as in cast iron but will peel, similar to low carbon steel</td>
<td>smooth edges where cut</td>
<td>fine grain fractures edges are lighter in colour than low carbon steel</td>
<td>smooth chips</td>
<td>smooth chips</td>
<td>smooth chips</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ease of chipping</th>
<th>Grey cast iron</th>
<th>Malleable iron</th>
<th>Low carbon and cast steel</th>
<th>High carbon steel</th>
<th>Copper</th>
<th>Aluminium and alloys</th>
<th>Brass and bronze</th>
</tr>
</thead>
<tbody>
<tr>
<td>easy to chip</td>
<td>chips break off from base metal</td>
<td>easier cut or chipped</td>
<td>usually hard but can be chipped</td>
<td>very easily cut</td>
<td>very easily cut</td>
<td>easily cut</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size of chip</th>
<th>Grey cast iron</th>
<th>Malleable iron</th>
<th>Low carbon and cast steel</th>
<th>High carbon steel</th>
<th>Copper</th>
<th>Aluminium and alloys</th>
<th>Brass and bronze</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 mm</td>
<td>6–10 mm</td>
<td>can be continuous if desired</td>
<td>can be continuous if desired</td>
<td>can be continuous if desired</td>
<td>can be continuous if desired</td>
<td>can be continuous if desired</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 – Chipping test

Filing test

Filing gives a good indication of the hardness of a metal. The test is particularly useful when a comparison is made with a material of known composition.

<table>
<thead>
<tr>
<th>File reaction</th>
<th>Brinell hardness</th>
<th>Type of steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>File bites easily into metal</td>
<td>100</td>
<td>mild steel</td>
</tr>
<tr>
<td>File bites into metal with pressure</td>
<td>200</td>
<td>medium carbon steel</td>
</tr>
<tr>
<td>File does not bite into metal except with extreme pressure</td>
<td>300</td>
<td>high alloy steel</td>
</tr>
<tr>
<td>Metal can only be filed with difficulty</td>
<td>400</td>
<td>tool steel</td>
</tr>
<tr>
<td>File will mark metal, but metal is nearly as hard as the file and filing is impractical</td>
<td>500</td>
<td>hardened tool steel</td>
</tr>
</tbody>
</table>

Table 4.3 – Filing test
Melting with the oxy-acetylene flame

Melting a piece of metal with an oxy-acetylene flame will often reveal a great deal about it. The speed with which the metal melts, the appearance of the molten puddle and any slag, and the action of the puddle under the flame all combine to furnish clues as to its composition. Great care must be taken in applying this test, to ensure that further cracking does not develop due to expansion and contraction.

Where practicable, break off a small portion of the metal to use for the melting test, so as to avoid the possibility of cracking or undesirable changes in the metallurgical structure of the metal due to the heating and cooling cycle.

To carry out this test, the torch is adjusted and manipulated to form a neutral flame.

<table>
<thead>
<tr>
<th></th>
<th>Grey cast iron</th>
<th>Malleable Iron</th>
<th>Low carbon and cast steel</th>
<th>High carbon steel</th>
<th>Copper</th>
<th>Aluminium and alloys</th>
<th>Brass and bronze</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of melting (cold start)</td>
<td>moderate</td>
<td>moderate</td>
<td>fast</td>
<td>fast</td>
<td>slow</td>
<td>faster than steel</td>
<td>moderate to fast</td>
</tr>
<tr>
<td>Colour change while heating</td>
<td>becomes dull red before melting</td>
<td>becomes dull red before melting</td>
<td>becomes bright red before melting</td>
<td>becomes bright red before melting</td>
<td>will turn black, then red</td>
<td>no apparent change in colour</td>
<td>becomes noticeably red before melting</td>
</tr>
<tr>
<td>Action of the slag</td>
<td>quiet, tough, but can be broken up</td>
<td>quiet, tough, but can be broken up</td>
<td>quiet</td>
<td>quiet</td>
<td>quiet</td>
<td>quiet</td>
<td>appears as fumes</td>
</tr>
<tr>
<td>Appearance of the molten pool</td>
<td>fluid with bright spots</td>
<td>fluid straw white</td>
<td>liquid straw colour</td>
<td>lighter than low carbon steel</td>
<td>mirror-like surface under flame</td>
<td>same colour as unheated metal</td>
<td>liquid fumes easily</td>
</tr>
<tr>
<td>Action of the pool under the torch flame</td>
<td>quiet no sparks</td>
<td>boils, leaves blow holes metal sparks</td>
<td>molten metal sparks</td>
<td>sparks more freely than low carbon</td>
<td>tends to bubble solidifies slowly</td>
<td>quiet</td>
<td>quiet</td>
</tr>
<tr>
<td>Appearance of the slag</td>
<td>thick film develops</td>
<td>medium film develops</td>
<td>bright, fizzy</td>
<td>bright, fizzy</td>
<td>very little slag</td>
<td>stiff black scum</td>
<td>fumes with brass, not always with bronze</td>
</tr>
</tbody>
</table>

Table 4.4 – Oxy-acetylene flame test
Grinding (spark testing)

Spark tests should be carried out on a high speed grinder, preferably with a 300 mm grinding wheel, and where possible, it should be arranged so that the sparks are given off horizontally. For most accurate results, the sparks should be examined against a dark background. Be sure to wear protective goggles.

The colour, shape, average length and activity of the sparks are details that are all characteristic of the material tested. See Fig 4.1 for details of identification of metals by spark testing. By grinding known and unknown metal together, you can compare the sparks to identify the metal.

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrought iron</td>
<td>Long yellow streaks broadening to a leaf some distance from the grinding wheel.</td>
</tr>
<tr>
<td>Mild steel</td>
<td>The leaf is smaller and gives rise to a number of sparks. Some streaks are shorter.</td>
</tr>
<tr>
<td>Medium carbon steel</td>
<td>Very small leaf, larger sparks nearer the grinding wheel.</td>
</tr>
<tr>
<td>High carbon steel</td>
<td>Streaks less bright. Profusion of sparks starting very close to the grinding wheel. Complete absence of leaf.</td>
</tr>
<tr>
<td>Manganese steel</td>
<td>The streaks fork before forming sparks.</td>
</tr>
<tr>
<td>High speed steel</td>
<td>Faint red streaks terminating in a fork.</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Bright yellow streaks terminating in pointed ends.</td>
</tr>
<tr>
<td>Cast iron</td>
<td>Faint red streaks terminating in complex bushy sparks yellow in colour.</td>
</tr>
</tbody>
</table>

Fig 4.1 – Spark testing chart
Density testing
Metals may also be differentiated by means of the weight or density of the specimen. For example, zinc die castings and aluminium die castings often look alike. However, zinc is much heavier than aluminium; thus weight will quickly distinguish between the two metals.

Magnetic test
The use of a common magnet is an elementary method of identifying metals. For convenience, metals may be considered as magnetic, slightly magnetic, or non-magnetic.

Magnetic metals
Nickel steel, carbon steel, cast iron, malleable iron, straight chromium stainless steel, low alloy steels.

Slightly magnetic
Monel, work-hardened manganese steel, work-hardened austenitic stainless steel, and stainless steel with large amounts of ferrite (iron).

Non-magnetic
Austenitic manganese steel, austenitic stainless steel, and non-ferrous metals and alloys such as bronze, nickel-silver, brass, aluminium bronze, aluminium and its alloys, zinc, lead, tin and magnesium alloys.

Chemical tests
Many welders think that chemical tests are too difficult to carry out and therefore do not use them. Actually, many chemical tests are simple and very accurate, requiring only small bottles of test chemicals.

The following tests can be readily carried out in the ordinary workshop.

- To tell Monel from Inconel – one drop of nitric acid applied to the metal’s surface will turn blue-green in one minute on Monel, but will show no reaction on Inconel.
- To tell stainless steel from other steels – mix a solution of 94% wood alcohol and 6% nitric acid. Apply a drop, and in one minute unalloyed steels will discolour. Stainless steels will show no discolouration. A 10% nitric acid solution will etch (eat into or corrode) carbon and mild steels almost immediately, but will not etch stainless steel.
- To tell magnesium from aluminium – a zinc chloride and water solution (such as most acid type soldering fluxes) or muriatic acid and water will immediately blacken magnesium, but show no reaction in contact with aluminium. A drop of silver nitrate will turn magnesium dark but will not turn aluminium dark.
- Test for silver – sulphuric acid (or egg yolk) will turn high silver bearing materials green.
- To distinguish between nickel-chromium stainless steel, and straight low chromium stainless steel – a few drops of 45% phosphoric acid will bubble on low chromium stainless steel.
Test for molybdenum in steel – one drop of concentrated hydrochloric acid is left on the polished surface for three to five minutes, then absorbed on filter paper. One drop of 10% stannous chloride is put on the paper. A few drops of 10% potassium thiocyanate solution are placed on a second paper, and the two papers held together. If molybdenum is present, a pink or light red appears in the case of 0.2–0.5% molybdenum, and brownish red occurs with higher molybdenum content.

Remember to follow safety precautions when handling any chemicals.

Comparison tests
These consist of using known and clearly identified samples of various metals and comparing their behaviour (under the various foregoing tests) with the behaviour of the unknown metal. The sample with the properties that most closely resemble those of the unknown metal can then be used as a guide to identification.
Identification of wrought iron

Wrought iron consists essentially of a mechanical mixture of high purity iron and a slag of iron oxides and silicates. The slag in wrought iron is uniformly distributed throughout the pure iron in the form of very small particles, which are stretched out by rolling into threads or fibres. Wrought iron has good corrosion resistance, high ductility and resistance to fatigue failure, with a tensile strength of 240–355 MPa.

### Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.06%</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.45%</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.10%</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.06%</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.01%</td>
</tr>
<tr>
<td>Slag by weight</td>
<td>1.9–2%</td>
</tr>
</tbody>
</table>

### Uses

Wrought iron has been largely superseded by mild steel. It may still be found in locomotive fire boxes, pipes, and old fabrications in ships and boilers.

### Appearance

Outward appearance is similar to that of mild steel. It may be in the form of plate, bar, forgings, pipe, etc. Quite frequently, minor laps or folds can be seen on the surface.

Wrought iron has a fibrous structure, and if nicked and bent it will not generally break off short, as does mild steel, but will only partially break. The fibrous nature of the metal can be clearly seen. The colour of the fracture is a bright grey.

### Chipping and filing

Wrought iron is soft and ductile, and when cut with a chisel the metal tends to peel. It can be filed easily.

### Melting test

(Melting point 1500 °C)

Wrought iron becomes bright red before melting. It melts quietly, with little tendency to sparking. The molten puddle is liquid straw colour, and covered by a slag that is oily or greasy in appearance.

### Grinding

(See Fig 4.1)

A large volume of straw coloured sparks forms near the grinding wheel, broadening to a leaf at the end of the stream. Average stream length is 1.6 m.

**Weight:** 7608 kg/m³

**Magnetic:** Yes
Identification of mild steel (low carbon steel)

Low carbon steel is the metal in most common use today. The carbon content ranges from 0.05 to 0.3%. It has many desirable properties that allow many commercial applications. It can be found in the cast, rolled or forged condition.

Mild steel has a tensile strength of 400–550 MPa. The variations depend on the amount of carbon it contains, and to what degree it may have been cold worked. Mild steel castings generally have a lower carbon content than plates, and consequently they have lower mechanical properties than plates or forgings.

**Composition**

<table>
<thead>
<tr>
<th>Element</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>98.5–99.5%</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.1–0.3%</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.05–0.3%</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.05% – maximum</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.3–0.6%</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.05% – maximum</td>
</tr>
</tbody>
</table>

**Uses**

Low carbon steel can be found in most engineering construction including bridges, machinery, locomotives, ships, and buildings.

**Appearance**

The appearance of the steel depends upon the preparation and not upon the composition. It may be found in:

- cast form – which has a relatively rough, dark grey surface except where machined
- rolled form – in bar, sheet, plate or section
- forgings – usually recognisable by hammer marks or evidence of the telltale fin, usually seen on drop forgings.

**Appearance of fracture**

The fracture appears bright and crystalline. When nicked and bent, the piece will usually break.

**Chipping and filing**

Easily cut or chipped; the chips tend to be continuous but are more brittle than wrought iron. Files readily.

**Melting test**

(Melting point 1460 °C)

Melts quite rapidly and solidifies quickly when the flame is removed. The liquid metal colour varies from a straw to a brilliant white, with a tendency to spark more than wrought iron.
Grinding
(See Fig 4.1)
A moderately large volume of yellow-white sparks is given off in long streaks. The spark stream has a tendency to break into white forked spurs.

**Weight:** 7850 kg/m³

**Magnetic:** Yes
Identification of medium and high carbon steels

Steels in the medium carbon group contain 0.3% to 0.5% carbon. Steels in the high carbon group range from 0.5% to 1.7%. The identification of steels in the former group presents a problem, because at one end of the scale they are similar to mild steel, and at the other end they are similar to the high carbon steels.

The best tests in cases of medium carbon steels are comparison tests with known samples. Samples of a number of various types of carbon steels are easily obtainable, and comparison with these provides a reliable means of identification.

High carbon steels

Uses

High carbon steels may be used to make tools, razors, saws, knives, dies etc. Heat treatment of the implements made from high carbon steel is usually required.

Outward appearance

The unfinished surface is dark grey. Implements made from high carbon steel usually display a precision surface finish with true and sharp edges.

Appearance of fracture

High carbon steels usually display a very fine grain structure, and are whiter in colour than mild steel.

Chipping and filing

High carbon steels are harder and less ductile than steels of lower carbon content. In the hardened condition, the metal is too hard to be chipped with a chisel and cannot be filed.

Melting test

The molten metal is brighter than in the case of low carbon steel, and the melting surface has a cellular appearance. Under the oxy-acetylene flame, the carbon is released in the form of carbon monoxide gas, and the metal will boil and bubble.

Grinding

(See Fig 4.1)

The metal gives off a moderately large volume of brilliant white sparks with numerous spurs close to the grinding wheel.
Identification of alloy steels

Appearance
Alloy steels appear in various forms such as drop forgings, castings and plates, or may have machined surfaces. They have greater strength and durability than most other steels, and a given strength is secured in a part with less weight of material than when other steels are used.

Nickel, chromium, tungsten, manganese, vanadium, molybdenum, cobalt and silicon are the most common elements used in the making of alloy steels.

Appearance of fracture
Generally the alloy steels are close-grained. At times the fracture might be said to have a velvety appearance.

Chipping and filing
Alloy steels vary so much that it is not possible to give any reliable guide to identification by this method.

Melting test
The action of the metal, when melted with the torch, will depend upon the nature of the alloy. Steels containing a considerable amount of chromium produce a greenish coloured slag when cold.

Grinding sparks
The various alloy steels produce sparks characteristic (both in shape and colour) of their composition. Some of the more common alloys used in steel, and their effects on the spark stream, are as follows.

Manganese
Steels containing manganese in small amounts produce a spark similar to a carbon steel spark. A moderate increase in manganese increases the volume of the spark-stream and the intensity of the bursts.

A steel containing 11-14% manganese will give the characteristic burst of sparkles at right angles to the spark stream.

Nickel
Is best recognised when the carbon is low, as the spark bursts are not particularly prominent. The nickel spark is short and sharply defined, with a dash of brilliant light before the fork.
Chromium

Steels containing 1–2% chromium have no outstanding features in the spark test. Chromium in large amounts can shorten the spark-stream by one-half, compared to the same steel without chromium, and yet not dim its brightness. Other elements can shorten the spark-stream to a similar extent, but also make it duller.

An 18% chromium 8% nickel stainless steel produces a spark similar to wrought iron, but only half as long. A steel containing 14% chromium, and no nickel, produces an abbreviated version of the low carbon steel spark.

A 15% chromium and 2% carbon steel (chromium die steel) produces a spark similar to that of carbon steel, but one-third as long.

Molybdenum

Steels containing molybdenum produce a characteristic spark with a detached arrowhead similar to wrought iron. Molybdenum alloyed steels usually contain nickel or chromium, or both.

Tungsten

This element is the simplest to recognise. It imparts a dull red colour to the spark-stream near the wheel, and decreases the size of or completely eliminates the carbon burst. A tungsten steel containing 10% tungsten has short, curved orange spearpoints at the end of the carrier lines. Lower tungsten content causes small white bursts to appear at the end of the spearpoints.

Carrier lines may be anything from a dull red to orange in colour, depending on the other elements present, providing that the tungsten content is not too high. Although some other metals also give off a red spark, there is enough difference in their characteristics to distinguish them from the tungsten spark.
Identification of grey cast iron

If molten iron is permitted to cool quite slowly, the chemical compound of iron and carbon (iron-carbide) has time to break up to a certain extent, and much of the carbon separates out in tiny flakes of graphite scattered throughout the metal. This ‘free’ or graphitic carbon, as it is called to distinguish it from combined carbon, gives the grey fracture characteristic of ordinary grey cast iron. This ‘free’ carbon helps explain the low ductility and tensile strength (125–205 MPa) of cast iron.

Uses

Grey cast iron has many uses, from cooking stoves to automotive cylinder blocks and from fire hydrants to machine bases.

Appearance

Castings present a characteristic appearance. The un-machined surface is a very dull grey in colour, and may be somewhat roughened by the sand mould used in casting the part. Cast iron castings are rarely machined all over. The un-machined castings may be rough ground in parts, to remove rough sections or edges.

Appearance of fracture

The metal breaks off short with no distortion. The fractured surface is dark grey in colour.

Chipping

Chips are brittle and break off in small pieces.

Melting test

The puddle of molten metal is very quiet and very fluid, and appears to be contained in a heavy sack of oxide. The surface of the molten pool can be easily depressed by the pressure of the gases in the torch flame, but when the torch flame is raised the depression disappears immediately. The molten pool takes time to solidify, and does not spark.

When applying the melting test, care must be taken to avoid heating the casting in places where the resulting expansion and contraction may cause fractures.

Grinding

(See Fig 4.1)

A small volume of dull red sparks form in a straight line close to the wheel. These break up into many fine, repeated spurs, which change to a straw colour.

Magnetic: Yes
Identification of white cast iron

The carbon in white cast iron is present in the form of iron carbide. White cast iron is produced either by cooling the molten iron so rapidly that the carbon does not have time to separate from the iron carbon compound, or by adjusting the composition and cooling less rapidly. Examination of such castings will show them to be very hard and brittle, often impossible to machine except by grinding.

Uses

Completely white cast irons have comparatively few engineering applications because of their brittleness. White iron surfaces on grey iron cores, produced by composition adjustment or by chilling the surface in metal ‘chills’, are a useful type of casting. Among the common chilled iron castings are plough-shares, chilled rolls, balls for ball mills, stamp shoes, dies and wear plates of various types.

Appearance

This is similar to that of grey cast iron, but is lighter in colour. There is evidence of sand moulding.

Fracture

White cast iron has a fine, bright, silvery white appearance when fractured.

Chipping test

White cast iron is too hard to chip or file.

Melting test

The metal melts in a somewhat similar manner to grey cast iron, but is more sluggish when molten.

Grinding

(See Fig 4.1)

A small volume of dull red sparks is given off, with fewer straw coloured spurs than in the case of grey cast iron.
Identification of malleable iron

Malleable cast iron is stronger and tougher than grey cast iron, and can be bent to a certain extent without breaking. It is often used therefore in applications for which grey cast iron would be too weak and brittle.

Two types of malleable cast iron are made:

- black heart malleable cast iron
- white heart malleable iron.

Uses

It is used extensively in the construction of armoured fighting vehicles, mincing machines, bicycle brackets, agricultural machinery, lawn mowers and screwed pipe fittings.

Appearance

The surface is rather like that of grey cast iron, but is smoother, free from sand, and lighter in colour. Pipe fittings are usually galvanised.

Appearance of fracture

In black heart malleable iron, the fracture shows two zones; an outer thin layer of bright steel-like metal and an inner zone or core, much darker in colour.

White heart malleable iron has a white crystalline fracture. Both types vary considerably in quality, but the metal should bend and distort prior to fracture.

Chipping test

The chips will curl off in a similar manner to a mild steel chip. However, they will break more readily than the mild steel chips.

Melting test

In the case of black heart malleable iron, the molten metal tends to boil under the flame, and blow holes will appear in the melted section when the flame is withdrawn. In addition, the melted section will be hard and brittle when cooled. The tested section will have been changed to the white iron state by the melting and cooling.

White heart malleable iron, when of good quality and in thin sections, will melt in a similar manner to mild steel. In heavier sections it will resemble black heart malleable iron.

Grinding test

This varies with the quality of the metal. In the case of black heart malleable iron, the surface layer gives off sparks very similar to those of mild steel or wrought iron, while the dark inner core gives sparks which resemble those from grey cast iron, but are in larger volume. White heart, when of good quality, gives sparks very similar to those from wrought iron.
Procedure for metal identification

Identification should follow a logical, set sequence. The procedure is best carried out with the aim of excluding groups of metals from consideration. For example, a simple magnetism test will exclude all but the magnetic metals.

Simple tests that do not damage the material should be conducted wherever possible, for example a chipping or filing test may identify cast iron as easily as would an oxy-flame melting test. However, there is far less risk of damaging the material with a file or chisel than there is with an oxy-flame.

Table 4.5 on the following page sets out the recommended sequence for identification of common metals.
Table 4.5 – Sequence for identification of common metals
Introduction

The ease with which a metal can be fabricated is dependent upon the ease with which it can be cut, formed and welded.

There are many materials available to the fabricator. These range from the ‘everyday’ to the ‘exotic’.

It is by understanding the properties of these metals, and the processes applied to them, that the fabricator is able to produce quality, cost effective products.

In this chapter we will look at the following.

- The metals we use
- General properties of metals
  - physical properties
  - mechanical properties
- Processing of metals
- The importance of grain structure
- Deformation of metals.
The metals we use

Not all the metals in existence are suitable for engineering applications. Factors such as poor mechanical properties or high cost may preclude their use. The suitability of a metal for use for a particular application depends on its:

- physical and mechanical properties that are required
- ease of fabrication
- weldability
- cost.

Metals are commonly divided into two groups.

- Ferrous metals – those where the major component is iron.
- Non-ferrous metals – these are metals which contain no iron at all, or in which iron is only a minor component of the alloy.

They can then be further classified into sub-groups.

The **ferrous metals** that are commonly encountered by the fabricator or welder are:

- carbon steel
- low alloy steels
- austenitic stainless steel
- austenitic manganese steel
- nickel steels.

The commonly encountered **non-ferrous** metals are:

- aluminium and its alloys
- copper and its alloys
- nickel alloys
- titanium alloys.

Metals in the non-ferrous group are generally selected for use where specific properties such as corrosion resistance or light weight are desired. Apart from aluminium and its alloys, the non-ferrous metals are rarely used for general fabrication.

By far the most commonly fabricated metal is low carbon steel. This is because low carbon steel:

- has good mechanical properties
- is easily formed
- is ideally weldable
- is cost effective.
**General properties of metals**

As a group, metals generally exhibit the following characteristics.

- All metals except mercury are solid at normal temperatures.
- Metals are generally hard when compared to other substances.
- Metals have high relative densities (i.e., they are heavy).
- Metals have low specific heats when compared to non-metals, (i.e., comparatively small increases in heat are required to increase temperatures).
- They reflect nearly all wavelengths of light, and are therefore nearly all silvery-white in colour (copper is a notable exception).
- Metals are comparatively difficult to penetrate with x-rays.
- Most metals are magnetic to some degree. However, in practical terms, magnetism is noticeable only in iron, nickel, and cobalt.
- Metals can be deformed.
- Metals have relatively high thermal and electrical conductivity.
- Metals in the solid state exist as crystals (grains).

The ‘properties’ of an object or a material are those characteristics that distinguish it from others. Properties may be divided into two groups; ‘physical’ or ‘mechanical’ properties.
Physical properties

Physical properties are the properties which can be determined without mechanical testing. These are:

- colour
- electrical conductivity
- thermal conductivity
- mass
- corrosion resistance
- magnetism
- thermal expansion
- hardenability.

Colour

As mentioned, most metals apart from copper and its alloys appear silvery-white in colour. It should be noted however that metals form oxides on the surface, which may vary in colour. One should keep in mind that in most cases when looking at a metal it is not the metal that we see, but an oxide film on the surface.

Mass

Mass is the amount of matter contained in an object. Weight is the effect that gravity exerts upon an object. Gravity exerts a force of 1 kg upon 1 kg of mass and it is generally acceptable in most cases to use the term weight instead of mass.

Density is the mass per unit of volume (e.g., 1 m$^3$ of steel has a mass of 7850 kg, i.e., its density is 7850 kg/m$^3$). Aluminium has a density of 2700 kg/m$^3$. Therefore steel would weigh approximately three times as much as an equal volume of aluminium.

Electrical conductivity

Is the rate at which a metal conducts electricity. As a general rule, high rates of thermal and electrical conductivity go hand in hand. Although silver has the highest electrical conductivity, copper and aluminium have the highest electrical conductivity of the metals in common use.

Thermal conductivity

Is the rate at which a substance will conduct heat. Metals possess good thermal conductivity. Copper has the highest thermal conductivity of the metals in common use.

Corrosion resistance

Metals can be corroded away due to chemical reactions with other elements and/or substances (e.g., iron forms rust in a reaction with oxygen). Some metals form oxides on the surface which are impervious to further oxidation. This oxide film can then prevent further corrosion, as in the case of aluminium and stainless steel.
Magnetism
Some metals exhibit magnetic attraction. This is most evident in ferrous metals, however other metals such as nickel and cobalt exhibit a slight magnetic attraction.

Thermal expansion
Metals will expand when heated and contract when cooled. Further to this, a particular metal will expand a given amount for each degree of temperature it rises, and contract the same amount for each degree of temperature it falls (coefficient of linear expansion).

Steel expands 0.000012 of its length for each degree Celsius its temperature is raised.

Example
What increase in length would occur if a steel beam 6200 mm in length was heated 200 °C?

\[
\text{Increase} = \text{original length} \times \text{coefficient of linear expansion} \times \text{rise in temp}
\]
\[
= 6200 \text{ mm} \times 0.000012 \times 200
\]
\[
= 14.88 \text{ mm}
\]

Hardenability
The ability of a metal to be hardened by heat treatment. This is important in the manufacture of tools, springs, and other objects that must be shaped while in a relatively soft condition, and then hardened to make them suitable for use.

Grain structure
All metals in the solid state are made up of grains. Each grain is crystal of the metal alloy. The grains are held together by a powerful attraction force. It is the grain structure that determines the properties of a metal.

In this regard there are three important considerations:
- the composition of the grain
- the size and shape of the grain
- the strength of the bond between the grains.
Mechanical properties

Mechanical properties are those properties that are determined with the aid of mechanical testing (i.e., the application of mechanical force).

Mechanical properties basically determine the uses to which a metal can be put, when strength and mechanical considerations are important. Some common mechanical properties are listed below.

- **Tensile strength (tenacity)** – The resistance that a metal has to a force acting directly to pull it apart. As hardness increases, so does tensile strength.

- **Ductility** – The property that allows a metal to be permanently deformed before failure. The classic definition is the ‘ability of a metal to be drawn’. Ductility is of particular importance in welding, as it enables the weldment to yield due to shrinkage when the weld zone is cooling, thus preventing cracking. Brittleness is a term used to describe a lack of ductility.

- **Elasticity** – Most metals do not permanently deform immediately when force is applied to them. As the load is applied to a test sample in a tensile testing machine for example, the metal will be seen to stretch for some time. At first it is an elastic stretch, whereupon the removal of the load the metal would return to its original length. If on the other hand the loading was increased, the metal would go beyond its elastic limit and a permanent deformation would result. So we could say that elasticity is the property that will enable a metal to return to its original shape upon the removal of distorting forces.

- **Malleability** – The property that enables a metal to be deformed by forging (i.e., forged or hammered into thinner sheets or other shapes).

- **Hardness** – Usually defined as ‘the resistance that a metal has to forcible penetration by another object’. Another definition is ‘the resistance that a metal has to abrasion’.

- **Toughness** – The resistance that a metal has to a suddenly applied load (i.e., impact resistance). Toughness is a combination of the properties of hardness and ductility. Hardness will enable the metal to resist deformation, while ductility will enable the metal to resist fracture.

Table 5.1 on the following pages lists the properties of common metals.
<table>
<thead>
<tr>
<th>Metal</th>
<th>Chemical Symbol</th>
<th>Density kg/m$^3$</th>
<th>Melting point $^\circ$C</th>
<th>Tensile strength (MPa) (soft)</th>
<th>Elongation %</th>
<th>Characteristics and use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>Al</td>
<td>2700</td>
<td>660</td>
<td>59</td>
<td>60</td>
<td>The most widely used of the non-ferrous metals.</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Be</td>
<td>1800</td>
<td>1285</td>
<td>310</td>
<td>2.3</td>
<td>A light metal, the use of which is limited by its scarcity. Commonly alloyed with copper.</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Cd</td>
<td>8600</td>
<td>321</td>
<td>80</td>
<td>50</td>
<td>Used for plating steel, and to strengthen copper.</td>
</tr>
<tr>
<td>Chromium</td>
<td>Cr</td>
<td>7100</td>
<td>1890</td>
<td>220</td>
<td>0</td>
<td>A metal that resists corrosion, and is therefore used for plating and in stainless steels.</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Co</td>
<td>8900</td>
<td>1495</td>
<td>250</td>
<td>6</td>
<td>Used mainly in permanent magnets and in high speed steels.</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>8900</td>
<td>1093</td>
<td>220</td>
<td>60</td>
<td>Used mainly where very high electrical conductivity is required; also in brass and bronzes.</td>
</tr>
<tr>
<td>Gold</td>
<td>Au</td>
<td>19 300</td>
<td>1063</td>
<td>120</td>
<td>30</td>
<td>Of little use as an engineering metal, because of softness and scarcity. Used mainly in jewellery, electronics and as a system of exchange.</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>7930</td>
<td>1535</td>
<td>500</td>
<td>10</td>
<td>Quite soft when pure, but rarely used in engineering in the unalloyed form.</td>
</tr>
<tr>
<td>Lead</td>
<td>Pb</td>
<td>11 300</td>
<td>327</td>
<td>18</td>
<td>64</td>
<td>Very resistant to corrosion. Used in chemical engineering.</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>1700</td>
<td>651</td>
<td>180</td>
<td>5</td>
<td>Used in conjunction with aluminium in the lightest of the engineering alloys.</td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn</td>
<td>7200</td>
<td>1260</td>
<td>500</td>
<td>20</td>
<td>Used mainly as a de-oxidant in steel.</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Mo</td>
<td>10 200</td>
<td>2620</td>
<td>420</td>
<td>30</td>
<td>A heavy metal, used mainly in alloy steels. One of the main constituents of modern high-speed steels. Imparts creep resistance to steels.</td>
</tr>
</tbody>
</table>

Table 5.1 – Properties and uses of common metals
### Table 5.1 (cont) – Properties and uses of common metals

<table>
<thead>
<tr>
<th>Metal</th>
<th>Chemical Symbol</th>
<th>Density kg/m³</th>
<th>Melting point (°C)</th>
<th>Tensile strength (MPa) (soft)</th>
<th>Elongation %</th>
<th>Characteristics and use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>Ni</td>
<td>8900</td>
<td>1458</td>
<td>310</td>
<td>28</td>
<td>A very adaptable metal used in both ferrous and non-ferrous alloys. The metallurgist’s main ‘grain-refiner’.</td>
</tr>
<tr>
<td>Niobium</td>
<td>Nb</td>
<td>8600</td>
<td>1950</td>
<td>270</td>
<td>49</td>
<td>Also known as ‘columbium’ in the USA. Used mainly in alloy steels.</td>
</tr>
<tr>
<td>Silver</td>
<td>Ag</td>
<td>10 500</td>
<td>960</td>
<td>140</td>
<td>50</td>
<td>Has the highest electrical conductivity, but is used mainly in jewellery and, in a few countries, for coinage.</td>
</tr>
<tr>
<td>Tin</td>
<td>Sn</td>
<td>7300</td>
<td>232</td>
<td>11</td>
<td>60</td>
<td>Widely used but increasingly expensive. ‘Tin cans’ carry only a very thin coating on mild steel.</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti</td>
<td>4500</td>
<td>1725</td>
<td>230</td>
<td>55</td>
<td>A light but strong metal that is becoming increasingly important as its price falls, due to the development of its technology.</td>
</tr>
<tr>
<td>Tungsten</td>
<td>W</td>
<td>19 300</td>
<td>3410</td>
<td>420</td>
<td>16</td>
<td>Used in electric lamp filaments, because of its high melting point. Is also a major constituent of most high speed steels.</td>
</tr>
<tr>
<td>Vanadium</td>
<td>V</td>
<td>5700</td>
<td>1710</td>
<td>200</td>
<td>38</td>
<td>Used in some alloy steels as a grain refiner.</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>7100</td>
<td>420</td>
<td>110</td>
<td>25</td>
<td>Used widely for galvanising mild and low-carbon steels. Also as a basis for some die-casting alloys. Brasses are copper-zinc alloys.</td>
</tr>
<tr>
<td>Zirconium</td>
<td>Zr</td>
<td>6400</td>
<td>1800</td>
<td>220</td>
<td>25</td>
<td>Used as a grain-refiner in steels.</td>
</tr>
</tbody>
</table>
Processing of metals

A metal’s properties such as ductility, malleability, or the ability to change from a solid to a liquid when heated, enable various processes to be successfully applied as a means of changing the shape, and importantly, the mechanical properties of metals.

The commonly used processes are listed below.

- **Extrusion** – Forcing (pushing) metal through a die.
- **Drawing** – Pulling ductile metal through a die, thereby reducing its cross sectional area.
- **Welding** – A union between pieces of metal, where the faces are rendered plastic or liquid by heat or pressure or both. Filler metal may be added.
- **Moulding** – The forming of metal shapes by pouring liquid metal into prepared moulds, and allowing it to solidify. The metal is liquified by heat.
- **Forging** – Hot steel in a plastic state is worked by hammers, presses or other forging machinery into required shapes. Heating must be carried out uniformly, and within the correct forging temperature range. Forging may be carried out by hand or by mechanical means.
- **Hot rolling** – This process is necessary to form steel into strips, bars, angles, beams and other sections. Plain or grooved rolls are used to roll the material into the finished shapes with which we are familiar. The hot rolling process, carried out while the steel is in the heated state, causes a refining of the grain structure of the material. The grain size is decreased, and the mechanical properties improved.
- **Cold working** – The hot working processes cannot be carried out to exact dimensions, on account of contraction due to subsequent cooling. Scale is produced during hot rolling processes, which leaves rough surfaces. Cold working is used to produce smooth, bright surfaces and accurate dimensions. The processes used are cold rolling, cold drawing, stamping and pressing. Cold rolling gives greater tensile strength and hardness, but with some decrease in ductility.
- **Heat treatment** – The process of applying a controlled heating/cooling cycle to a metal, to bring about a desired change in mechanical properties.
The importance of grain structure

As mentioned previously, metals are made up of grains when solid at ambient temperatures. It is this grain structure that determines the properties of the metal. The exception to this is mercury, which is liquid at ambient temperatures.

The properties of a metal are determined by the:
- composition and structure of the grains
- size and shape of the grains
- strength of the bond between the grains.

Composition and structure

A metal will adopt the characteristics of the grains of which it is composed. If the metal is composed of grains that are soft and weak, the metal itself will tend to be soft and weak. This is the case with pure iron.

If the material is composed of grains that are hard and strong, the material itself will tend to be hard and strong. This is the case with high carbon steel, where the grains have been changed by alloying.

In the case of a metal where there is more than one grain type, the properties of the metal will vary, tending to lean towards the characteristics of the grain type that makes up the greater part of the metal.

The composition of the grain may be changed by alloying. This is done by adding various elements during the manufacturing process.

Size and shape

Metals with fine, regular shaped grains generally possess superior mechanical properties compared to those where the grain is large and/or irregular in shape. Grain size is commonly controlled by adding grain refining elements (such as nickel) during manufacture, or by subsequent heat treatment.

Bond strength

The grains of the metal are held together by a force that attracts them to one another. The strength of this bond significantly affects the mechanical properties of the metal. When a metal is fractured or torn apart, it is usually because the load applied exceeds the strength of the bond and the grains part company. Impurities in the metal commonly do not dissolve into the grains and are expelled to the grain boundaries, causing grain boundary weakness. This causes a progressive loss of tensile strength and toughness, as the amount of impurities increases.

The grain structure of metals can be changed by:
- alloying
- heat treatment
- cold working
- hot working.
Alloying
Few metals are used for engineering purposes in their pure form; most are alloyed with other elements to make materials with enhanced properties.

Alloys are not compounds, (chemical combinations) but are physical mixtures or solutions. When metals are alloyed, elements that are soluble become part of the crystal structure (grain). Elements that are insoluble (eg silicon or sulphur) generally accumulate at the grain boundaries.

An alloy system includes all alloys made from the same basic elements in every possible combination, for example:
- plain carbon steels include all proportions of useable carbon in iron
- brass includes all copper zinc alloys
- bronzes, which were once defined as copper/tin alloys, are now defined as any alloy of copper except those of zinc.

Heat treatment
Heat treatment is the process of applying a controlled heating/cooling cycle to a metal, in order to bring about a desired change in the mechanical properties of the material. Some metals are hardenable (ie they have the ability to harden by heat treatment). Heat treatment of hardenable materials can bring about significant changes in the mechanical properties of the metal by changing the internal structure of the grain. Metals that are non-hardenable respond less to heat treatment. The main effect of heat treatment on non-hardenable metals is to change the size and shape of the grains, but not the internal structure.

Cold working
Grain or crystal deformation can have a marked effect on the mechanical properties of a metal. For instance when a metal is being rolled in its cold state, the crystals in the metal will become greatly elongated in the direction of rolling. See Fig 5.1.

The crystalline structure has now become fibrous, and strain hardening of the metal has occurred. This sometimes undesirable structure can be modified by heat treatment.
Cold working need not necessarily imply that the metal is cold. The usual definition of cold working is ‘the mechanical deformation of the metal, when its temperature is below its recrystallisation temperature’.

A summary of the effects of cold working upon the physical and mechanical properties is as follows.

- The grain structure is deformed.
- Hardness is increased.
- There is a build up of residual stresses.
- Tensile strength is increased.
- Impact resistance is decreased.
- Fatigue resistance is decreased.
- Ductility is decreased.

Some metals and alloys cannot be cold worked because they tend to be brittle when cold. This characteristic is called cold shortness.

**Hot working**

Hot working is the term used to define the mechanical deformation of a metal whose temperature is above its recrystallisation temperature.

Most metals deform more easily if they are first heated above their recrystallisation temperature. This is why so much shaping of metals is carried out when the metal is hot. Hot working a metal refines the grain structure, and does not produce the hardness and loss of ductility that is associated with cold working.

The effects of hot working can be compared with the effects of cold working as follows.

- There is no build up of residual stress.
- The grain structure is refined.
- The mechanical properties may be improved.
- Work hardening does not occur.

Some metals and alloys cannot be hot worked because they are brittle when hot. This characteristic is called hot shortness.
Deformation of metals

A bar of metal is composed of millions of separate grains. Each grain is built of atoms arranged in a geometrical pattern. Most atoms are contained within each grain, but some atoms become trapped between grains at the grain boundaries during solidification.

If stress is applied to such a granular arrangement, the stress acts in different ways, depending on the orientation of the planes of atoms in each grain. What usually happens is that one plane of atoms tends to slide over another. If the stress applied is below the yield strength of the metal, the atoms are temporarily moved slightly away from each other. Removal of the stress allows the atoms to move back to their original positions. This is referred to as elastic movement.

Once the force exceeds the elastic limit of the material, the atoms slide over each other so that a permanent re-alignment occurs. This permanent re-alignment is known as plastic deformation.
Chapter 6 – Welding procedures

Introduction

The objective in establishing welding procedures is to develop the best and most economical means of producing welds to a set standard.

Once a suitable procedure has been established and proved suitable for use, 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.

- The necessity for welding procedures
- Obtaining the welding procedure specification
- Application of code book
- Carbon equivalent
- Calculation of pre-heat
- Qualification range.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welder certification</td>
<td>Shows the ability of a welder to pass an examination in welding competency, to a minimum acceptance standard (e.g., AS 1796). It does not indicate current competency nor ability to complete specific weldments to code requirements. Welder certification is portable.</td>
</tr>
<tr>
<td>Welder qualification</td>
<td>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.</td>
</tr>
<tr>
<td>Welding procedure</td>
<td>A specific, pre-planned course of action followed to complete a particular weldment. Procedures may be informal (passed to welders verbally) or formal – written instructions to be followed.</td>
</tr>
<tr>
<td>Welding procedure qualification (WPQ)</td>
<td>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.</td>
</tr>
<tr>
<td>Welding procedure test</td>
<td>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.</td>
</tr>
</tbody>
</table>

Qualified welding procedure – also known as a:

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding procedure specification (WPS)</td>
<td>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.</td>
</tr>
<tr>
<td>Procedure qualification record (PQR)</td>
<td>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.</td>
</tr>
<tr>
<td>Production weld test (PT)</td>
<td>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.</td>
</tr>
</tbody>
</table>
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
- 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 is therefore responsible for writing, qualifying and recording their own welding procedures. Alternatively, procedures qualified by the client may be used.

The welding procedure specification (WPS) 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 WPS

There are three ways of obtaining a WPS, through:

- the use of an existing procedure
- the use of a ‘pre-qualified’ procedure
- a 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 all of the following comply with the requirements of the relative clauses of the code:

- parent metal
- weld preparation
- welding consumables
- workmanship standards.

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 depend upon the application code, welding process and other variables. There are however some considerations that 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 450 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. Frequent amendments to code books are published, and 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 HAZ due to welding, and this must be taken into account when formulating welding procedures. For example:

- low carbon steel (< 0.3%) – generally weldable with any grade of consumable without pre-heat, except for heavy thickness
- medium carbon steel (0.3%–0.5% C) – usually requires hydrogen-controlled consumable and increases in pre-heat as carbon content hardness and thickness increases
- high carbon steel (0.5%–1.7% C) – 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.

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 % 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**

\[ CE (Carbon equivalent) = C\% + Mn\% \]

for carbon manganese steels

**Method 2**

\[ CE = C\% + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{Ni + Cu}{15} \]

(for other low alloy steels)

\[
= 0.12 + \frac{0.12}{6} + \frac{(2.5 + 1.0)}{5} + \frac{0.015 + 0}{15}
\]

\[
= 0.12 + 0.02 + 0.7 + 0.01
\]

\[ CE = 0.85 \]

**Example**

Calculate the equivalent for a low alloy steel having the following composition.

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.12%</td>
</tr>
<tr>
<td>Mn</td>
<td>0.12%</td>
</tr>
<tr>
<td>Cr</td>
<td>2.5%</td>
</tr>
<tr>
<td>Mo</td>
<td>1.0%</td>
</tr>
<tr>
<td>Cu</td>
<td>0.015%</td>
</tr>
</tbody>
</table>

\[ CE = \frac{0.12 + 0.12 + (2.5 + 1.0 + 0) + 0.015 + 0}{6} + \frac{6}{5} + \frac{15}{15} \]

\[
= 0.12 + 0.02 + 0.7 + 0.01
\]

\[ CE = 0.85 \]

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 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:

- AS/NZS 1554.1 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 6.1).
This table has been removed. 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 1548:1995.

Table 6.1 – Relationship between carbon equivalent and group number
Table 6.2 – Relationship between carbon equivalent and group number

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. 6.1.
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 on Table 6.2 and the closest curve selected.
The heat input is then calculated using the following formula.

\[
\text{Heat input} = \frac{\text{Amps} \times \text{Volts} \times 60}{\text{Travel speed in mm/min} \times 1000}
\]

Heat input is expressed in kJ/mm.

The heat input and joint weldability index are then combined to give the minimum pre-heat temperature. For this purpose, either Fig 6.2 or Fig 6.3 is used; depending whether or not hydrogen-controlled welding consumables are used.

This graph has been redrawn. It was reproduced from Figure 5.3.4 (B) on page 54 of AS/NZS 1554.1:2004.

Fig 6.2 – Pre-heating determination for hydrogen-controlled manual metal-arc electrodes and semi-automatic and automatic welding processes
Example
A butt 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: \[
\frac{\text{Amps} \times \text{Volts} \times 60}{\text{Travel speed mm/min} \times 1000}
\]
   therefore: \[
   \frac{120 \times 25 \times 60}{180 \times 1000}
   \]
   \[
   1.0 \text{ kJ/mm}
   \]
5. Minimum pre-heat = 50\(^{\circ}\) 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. 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 give the weld metal composition and properties required of the finished weld. The welding situation must be taken into account, and the consumable chosen must provide cost effective welding. Important considerations are tensile strength, weld metal toughness and alloy content.
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 mm–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 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 that the company has qualified) become part of the procedure qualification record (PQR).

A welding procedure will contain information such as the:
- 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.
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.

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

A WPQ is normally written up by a qualified welding supervisor or welding engineer. It is usually written on a proforma that will address all the relevant information required. The format of such a proforma should ensure that all information is clearly stated and easily understood by the welder. Information that 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 Fig 6.5.
### Fig 6.5 – Example of a welding procedure qualification (WPQ)

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Notes

Approvals

CLIENT / / CONTRACTOR / /
### Appendix

**Metals and fabrication competency mapping**

**Arc Welding 2**

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<th>Competency title</th>
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Arc Welding 2

This resource is specifically designed to provide basic underpinning knowledge related to a number of competency units used in the Engineering Tradesperson Fabrication (Heavy) pathway across TAFE WA from January 2007. This pathway was specifically designed to meet the needs of the heavy metal fabrication industry after industry consultation 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 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 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.
DESCRIPTION
This resource supports learners to develop intermediate-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
- Weld defects
- Testing of welds
- Identification of metals
- Metals and their properties
- Welding procedures

The book is divided into separate chapters, each containing workshop-based activities that will provide opportunities for practice before assessment.

A comprehensive mapping guide is included, to show where the content in this resource aligns with the relevant competencies.

EDITION
2007

CATEGORY
Metals & Engineering

TRAINING PACKAGE
• MEM05