

# INTRODUCTION TO METALLURGY

Weldability of Metals



Government of Western Australia Department of Training and Workforce Development

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# ENG549

# Introduction to Metallurgy

Learning resource

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1 Prospect Place West Perth WA 6005 Tel: (08) 6212 9700 Fax: (08) 9227 8393 Email: sales@dtwd.wa.gov.au Website: www.vetinfonet.dtwd.wa.gov.au





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# Chapter 1 – Carbon steels

## What is steel?

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

#### Iron

Iron has mechanical properties similar to those of copper. The tensile strength of iron is 139 MPa. Iron is too weak and too soft for most engineering and structural applications.

#### Carbon

Carbon has the greatest effect of any element when alloyed with iron. Increasing the carbon content of low carbon steel will:

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

Even small amounts of carbon will bring about significant improvements in the mechanical properties of steel. Once the carbon content of steel exceeds 0.3%, the steel becomes 'hardenable', ie it has the ability to be hardened by heat treatment.

Heat treatment is an important process, and can be used to bring about significant changes in the mechanical properties of steels. For example, a high carbon steel in the soft state may be cut with a hacksaw, but following heat treatment it may be so hard that the only practical method of cutting is by grinding.

## **Elements in steel**

The composition of plain carbon steel is as follows.

IIOII (Fe)	
Carbon (C)	0.05%–1.7%
Phosphorous (Ph)	0.05% max
Silicon (Si)	0.35% max
Sulphur (S)	0.06% max
Manganese (Mn)	0.8% max

Apart from carbon, which is used to control the mechanical properties of steel, the other elements present are either impurities or are added for such functions as de-oxidation or grain refinement. Complete removal of phosphorous and sulphur during the manufacture of steel is expensive and unnecessary, provided the level of each is below the listed above maximum percentages. The effect of these elements on plain carbon steel is as follows.

#### • Phosphorous

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

#### Silicon

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

#### • Sulphur

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

#### Manganese

Although carbon/manganese steels (1.0%–1.8% Mn) make use of manganese to improve hardness and tensile strength, in plain carbon steels manganese is used:

- as a grain refiner
- o as a de-oxidiser
- to counteract the effect of sulphur in promoting hot shortness.

Plain carbon steels contain manganese in the range of 0.3% to 0.8%.

Steels may be divided into two main groups.

- **Plain carbon steels** Where the element used to improve mechanical properties is carbon.
- **Alloy steels** Where elements other than carbon are used to improve mechanical properties.

# Metals & Fabrication



## Plain carbon steels

Plain carbon steels are divided into three groups, which are:

- low carbon steel
- medium carbon steel
- high carbon steel.

#### Low carbon steel

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

#### Medium carbon steel

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

#### High carbon steel

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



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

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

Low carbon steels are ideally weldable, however in the hardenable medium and high carbon steels, increasing carbon content leads to a progressive loss of weldability. Careful consideration must be given to welding procedures when these steels are used.



Carbon class	Carbon range %	Typical uses
low (dead mild)	0.05–0.15	chain, nails, rivets, wire, pressing steels
(mild)	0.15–0.30	structural sections and plates
medium	0.30–0.50	axles, gears, drop forgings, con-rods, shafts
high	0.50-0.60	crankshafts, scraper blades
	0.60–0.75	car springs, anvils, bandsaws
	0.75–0.90	chisels, punches
	0.90–1.00	knives, shear blades, springs
	1.00–1.10	milling cutters, dies, taps
	1.10–1.20	lathe and woodworking tools
	1.20–1.30	files, reamers
	1.30–1.40	dies for wire drawing
	1.40–1.50	metal cutting saws
cast irons	above 1.70	n/a

Typical uses for carbon steels are shown in Table 1.1.

#### Table 1.1 – Uses of carbon steels

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### Classification and availability of plain carbon steels

Plain carbon steels are manufactured in Australia as:

- plate and slab (to Australian Standard® 3678)
- structural steel sections (to Australian Standard® 3679)
- coil, strip and sheet (to Australian Standard® 1594).

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

#### Classification

Steels covered under AS/NZS 3678 and AS/NZS 3679 are specified by:

- standard number
- nominal minimum yield stress
- a 'WR' prefix where appropriate for weather resistant (weathering) steels

eg AS/NZS 3678 – 250

AS/NZS 3679 - WR 350/1.

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

eg WR 350/1 L0 – indicates that an impact test has been conducted at 0 °C.

350 L15 – indicates that a low temperature impact test has been conducted at -15 °C.

Grade	C% max	CE max	Yield min	UTS min MPa	Min % elongation
200	0.15	0.25	200	300	24
250 and 250 L15	0.22	0.44	250	410	22
300 and 300 L15	0.22	0.44	300	430	21
350 and 350 L15	0.22	0.48	350	450	20
400 and 400 L15	0.22	0.48	400	480	18
450 and 450 L15	0.22	0.48	450	500	16
WR350/1 and WR350/1 L0	0.14	not specified	350	450	20

The grades of steel plates available under AS/NZS 3678/3679 are given in Table 1.2.

Table 1.2 – Steel grades to AS/NZS 3678 and AS/NZS 3679



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

#### Weldability of plain carbon steels

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

- the quality of the finished weld
- the ease of making the weld
- cost.

Low carbon steel is considered to be ideally weldable as it is easy and cheap to weld. Because the material is not hardenable, a sound weld usually results.

As the carbon content increases, hardenability increases. Consequently weldability decreases in medium and high carbon steels. This is the result of the formation of martensite, a brittle constituent in the grain structure, which forms when steel containing more than 0.3% carbon is cooled rapidly from elevated temperatures.

#### Welding low carbon steels

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

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

#### Summary

- Low carbon steels are relatively ductile and are easily welded.
- Pre-heating is normally unnecessary except to reduce shrinkage stresses in thick sections.
- Rapid quenching, eg water quenching, should be avoided as a loss of ductility results.

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### Welding medium carbon steels

#### The formation of martensite

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

#### The effect of dilution

'Dilution' is the extent to which deposited weld metal is diluted by molten parent metal during welding. Weld metal is composed of a mixture of the filler material used, and the parent metal melted by fusion. Carbon pick-up in the weld metal from the fused base metal can result in reduced ductility of the weld metal, which in turn will increase the possibility of cracking.

The amount of dilution is obviously influenced by the degree of penetration. Therefore, care should be taken to avoid excessive fusion into the parent metal. This can be achieved by restricting the welding amperage to that which is necessary to provide good fusion. Dilution is not a problem where the carbon content is reasonably low, and on medium carbon steels this is usually within safe limits, but in high carbon steels dilution needs careful control.

#### Summary

- Medium carbon steels present the possibility of cracking in the heat-affected zone, due to martensite formation.
- Pre-heating may be required, depending on the cooling rate of the weldment, and the heat input from welding. The higher the carbon content, the higher the pre-heat temperature.
- The use of hydrogen-controlled consumables, and/or processes, is highly advisable.
- Consideration should be given to the amount of penetration and fusion into the parent metal, with the aim of minimising dilution.
- Rapid cooling of the weld zone is to be avoided.



#### Welding high carbon steels

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

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

#### Summary

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



# Chapter 2 – Cast iron

## What is cast iron?

Cast iron is an alloy of iron, carbon, and silicon. In some types of cast iron, other elements are added. Cast irons have a lower melting point than steel due to the higher carbon content. Cast irons are very fluid when molten, which makes them easier to cast.

As with other metal groups such as 'aluminium' or 'stainless steel', a range of alloys tend to be 'lumped together' under a common heading, despite the fact that the properties of the various metals may vary considerably.

The composition of cast irons is as follows.

Carbon	2.0%-4.5%
Silicon	0.9%-4.0%
Iron	remainder





### Types of cast iron

There are several types of cast iron. What differentiates them is the:

- carbon content
- silicon content
- addition of other alloys
- heat treatment.

#### Grey cast iron

Grey cast iron contains 1.0% to 3.0% silicon and typically around 2.5% carbon. The microstructure is composed of ferrite, pearlite, and flakes of free graphite (pure carbon). The higher the amount of free graphite the softer and more machinable the alloy. Silicon is used to promote this free graphite formation. Slow cooling of the solidifying and cooling metal is necessary if grey cast iron is to be produced. Grey cast iron is used extensively in industry. It is easily cast, machinable, and readily weldable; provided sound welding practices are followed.



Fig 2.1 – Grey cast iron

#### White cast iron

White cast iron has a lower silicon content than grey cast iron, and is produced by rapid cooling of the casting. There is no free graphite in white cast iron and the resulting pearlite and cementite structure is extremely hard and brittle. White cast iron can be recognised by its hardness and the silvery-white appearance of the fracture. It can only be machined by grinding, and is in a practical sense not weldable.

#### Malleable cast iron

Malleable cast iron is basically a white cast iron that has been heat treated for long periods through an annealing process. This converts the graphite into a cluster of irregularly shaped rosettes. Because the carbon has been treated in this way, malleable cast irons are stronger and tougher than the grey variety and will often bend before fracturing.

Malleable cast irons seldom fracture in service because of their improved properties, but if they do, they can be repaired by a braze welding technique. Fusion welding is not recommended, as the temperatures required to melt the material will destroy its heat treatment properties and convert it back into a hard, brittle white cast iron.







Fig 2.2 – Malleable cast iron

#### Spheroidal graphite (SG) cast iron

Spheroidal graphite, sometimes called nodular cast iron, contains graphite in the form of tiny spheroids or nodules. These shapes are formed by adding small amounts of nickel and magnesium to the liquid metal during production. The spherical (round) shape of the graphite makes these cast irons the strongest and toughest of all the types mentioned in this section.



Fig 2.3 – Spheroidal graphite (SG) cast iron

#### **Chilled iron**

Similar to grey cast iron in composition but with a lower silicon content, chilled iron is made by casting against a chilled iron surface. The surface of the material (up to 12 mm thick) is extremely hard due to rapid cooling, while the body of the casting has a softer, more ductile grey iron structure. A typical use is wheels for rail cars.

#### **Special cast irons**

There are a number of special purpose cast irons commercially available to suit specific industrial uses. Irons for special uses such as Ni-hard contain elements such as chromium, nickel, vanadium and so on, to improve such properties as:

- tensile strength
- resistance to oxidation (scaling)
- corrosion resistance
- wear resistance.

These special cast iron materials are produced at much greater cost and their composition generally makes them difficult to weld.



#### **Properties of cast irons**

While it must be said that the properties of cast irons vary from type to type, they have the same following general properties when compared to steel. These are:

- low tensile strength
- low melting point
- low ductility
- low weldability
- readily heat treatable
- good compressive strength
- retention of stiffness at high temperatures.

Material	% carbon	Tensile strength (MPa)	Ductility % Elongation %	Hardness (BHN)	Melting point °C
low carbon steel	0.15 – 0.25	300 – 450	26%	120	1460
medium carbon steel	0.4 – 0.5	600 - 800	22%	200	1380
grey cast iron	3.0 - 4.0	152 – 186	nil	180	1260
malleable cast iron	2.5 – 3.5	340 – 430	18%	110	1260
S.G. iron	2.5 – 3.5	460 - 600	20%	180	1260
white cast iron	2.0 - 4.0	500 - 600	nil	420	1260

 Table 2.1 – Properties of steels and cast irons

In the molten state, cast iron is extremely fluid. This makes it ideal for casting, as it flows easily into small cavities within the mould. The lack of ductility exhibited by cast irons makes it unsuitable for forming by other methods.



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#### Industrial uses of cast irons

Туре	Use
Grey cast iron	ingot moulds
	automotive cylinders and piston rings
	flywheels
	water pumps
	machine cases
White cast iron	wear plates
	dies
	manufacture of malleable cast iron
S.G. cast iron	cast crankshafts
	agricultural and marine castings
	heavy machinery frames
	hand tools
Malleable cast iron	hubs
	brake drums
	wheel hubs
	pipe fittings and plumbing supplies

Table 2.2 – Industrial uses of cast irons

#### MMAW of cast iron

The weldability of cast iron varies from type to type. However with the exception of white cast iron, most are weldable using the MMAW process.

The two main factors that reduce the weldability of cast iron are:

- low ductility
- the effects of the heating/cooling cycle of welding.

#### Low ductility

There are two main approaches to overcoming this problem, by:

- deposition of ductile weld metal which will yield during shrinkage
- pre-heat followed by slow cooling to ensure even expansion and contraction of the part, thereby minimising shrinkage stresses.



#### The heating/cooling cycle

With the high percentage of carbon present in cast irons, the material is extremely hardenable. Further to this, when cast irons are produced the cooling cycle is a major factor in the resultant properties of the material. It is essential that the heating/cooling cycle of welding is carefully controlled, if cracking is to be avoided when welding.

The critical temperature of cast irons is around 790 °C. At this point, phase changes leading to cracking may occur. For this reason, pre-heating should be limited to 760 °C maximum and the heat from welding limited to as narrow a zone as possible.

Slow and even cooling of the material after welding is essential. Unless welded using the 'cold' method, once welding has been completed, the casting is commonly reheated to ensure an even temperature throughout. This is followed by controlled cooling in a furnace, lime box or by some other means.

### Welding recommendations

#### **Control of dilution**

Use just enough current to get good fusion without voids or slag inclusions. Every attempt should be made to minimise the amount of cast iron melted into the weld. When covered electrodes with a steel core are used, the deposited metal becomes high-carbon steel, due to a mixture of the high-carbon cast iron. If this deposit cools quickly, it becomes extremely hard and brittle and may crack. Moreover, it is not machinable.

The use of nickel based electrodes usually solves this problem. As contrasted with iron based electrodes, non-ferrous alloys do not harden appreciably when deposited on cast iron base metal. The weld deposits are therefore machinable. However, the hardening of the cast iron in the HAZ adjacent to the line of fusion (due to the quenching action of the mass of cold metal in back of it) remains much the same as in the case of welding with a steel electrode.

#### Controlling bead shrinkage

The shrinkage or contraction of steel as it solidifies from the molten state is greater than that of cast iron. Therefore, when the deposit from a steel electrode is deposited on cast iron, the weld shrinks more than the cast iron on which it is deposited. This differential shrinkage causes a residual strain in both the weld metal and the cast iron.

A bead of weld metal deposited on cast iron will be in tension if allowed to cool without further treatment. At the same time, the cast iron on which the weld metal has been deposited will be stressed, due to the pulling action of the weld metal on the cast iron. Since the cast iron is weaker, failure may occur as a break in the cast iron just outside of the line of fusion. If the weld is thin in cross section, failure such as cracks in the bead may occur. Since the strain is cumulative, it increases with a straight length of weld. To reduce the strain, deposit the weld metal in short lengths and allow each to cool (Fig 2.4).

By depositing small welds in various parts of the work, one weld is allowed to cool and contract while the operator is depositing metal in another location. An alternative is to peen the deposited weld metal lightly before it has a chance to cool. This causes the weld metal to stretch. In many cases, it is best to use a combination of short welds and peening. Use small-ball (12 mm-20 mm) peening hammers.





Fig 2.4 – Controlling bead shrinkage

#### Preparation for welding

Because cast iron is not fabricated, virtually all welding of cast iron is for the purpose of repairing broken or cracked castings. The simplest method of locating and determining the extent of cracks is to use dye penetrant procedures.

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 www.wpc.westone.wa.gov.au.

#### Cleaning the joint area

Make certain the casting is clean. Remove surface oil, rust, water and other foreign material. If possible, grind off the 'skin' of the casting which may contain sand or other impurities from the mould. To prevent porosity, especially when using the nickel base type of electrode, remove all water and oil that may have penetrated deeply into the pores of the casting. This can best be done by heating to around 260 °C and holding for about an hour. The first pass on a contaminated casting may have porosity resulting from embedded contaminants, but subsequent passes usually will be satisfactory due to the heating by the first bead.

#### Preparing the joint

Prepare the joint with a 90° vee so that a weld with a cross section at least equal to the material cross section can be made without deep penetration and a mixture of the base metal into the weld deposit. Sometimes when repairing a crack, the heat of the arc will create stresses that cause the crack to propagate. To avoid this, drill a small hole at each end of the crack. Grind, chip or machine the crack to create the V-groove. Arc-gouging can be used on castings that have been pre-heated for welding. Be sure the groove extends to the bottom of the crack. On sections more than 5 mm thick, bevel the edges so that the root of the joint is 3 mm to 4 mm wide. If the crack extends through the section, leave about a 3 mm gap and 1.5 mm root face, as illustrated in Fig 2.5.



Fig 2.5 – Recommended preparation for repairing cracks extending through thick cast iron parts

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#### Welding procedure

There are two ways of arc-welding cast iron:

- hot
- cold.

#### Welding cast iron 'hot'

For best results when welding cast iron, pre-heat is necessary. Pre-heat between 260–650 °C will provide:

- a sound deposit with good mechanical properties
- less chance of shrinkage cracking
- a machinable deposit.

Basically, welding procedures for cast iron are designed to reduce penetration and prevent the formation of undesirable grain structures during welding and subsequent cooling.

Associated with welding cast iron are the contraction stresses, which must be accommodated in the parent metal upon cooling. This presents a problem, due to the hardening effect and loss of ductility associated with rapid cooling.

If a casting is pre-heated to a suitable temperature prior to welding, the hardening effect will be reduced, stresses will be more easily absorbed and the tendency toward cracking will be reduced, provided cooling is slow and uniform.

#### Pre-heat

Pre-heat should be applied evenly, to ensure uniform expansion and contraction of the casting. The higher the pre-heat temperature, the slower the cooling rate. However 760 °C is the recommended maximum, and pre-heat temperatures should never be allowed to reach 790 °C.

Pre-heat temperature should be maintained throughout the welding operation.

#### Preparation

Firstly the crack should be located. Dye check is recommended, as it will show extremities of the crack that are not readily visible.

To prevent the crack spreading with the application of heat, it is recommended that a small hole be drilled at each end of the crack, along the line of the crack approximately 5 mm past the visible indication.

Prepare a vee joint so that a weld with a cross-section at least equal to the thickness of the casting can be made without deep penetration.

Preparation can be by grinding, machining, chipping or arc-gouging on pre-heated castings. Be sure that the groove extends to the bottom of the crack, so that complete penetration may be obtained.

#### Cleaning

The metal should be cleaned thoroughly. The 'skin' of the casting should be ground off, and the pre-heat will remove moisture or oil – a cause of porosity.







#### Welding

Usually done with steel electrodes, which give a good result for less cost. However if maximum machinability is required, nickel electrodes should be used.

Runs should be kept short, to further reduce the tendency toward cracking, and low amperages should be used. Do not weave, use stringer beads.

#### Cooling

The casting should be cooled as slowly as possible in the furnace, lime or a thermal blanket. If the casting has cooled during welding, it must be re-heated prior to cooling.

#### Welding cast iron 'cold'

In certain cases it may not be practical to pre-heat a casting that is in need of repair. An alternative is to weld the casting 'cold'. The procedure is to locate and prepare the crack as for welding 'hot'. It is important that the metal is clean. Oil etc can be burnt out of the casting with the gas welding or cutting torch, in which case the metal is allowed to cool completely before welding.

#### Technique

Amperage should be kept as low as practicable and weld beads should not exceed 40 mm in length. The object is to keep the casting as cool as possible. To prevent excessive heat build-up, further runs should not be deposited until the casting is 'hand cool'. A back-step method is used to fill craters and in a relatively large vee, a random sequence may be used to spread the heat.

Peening of the weld metal is recommended to help relieve shrinkage stresses. Dilution of weld metal should be kept to a minimum and cooling should be slow. A steel electrode may be used, but a nickel electrode is much preferred as it is not only more ductile and better able to absorb contraction stresses, but also gives it a machinable deposit.

The steel electrodes would pick up carbon from the casting, and due to rapid cooling would produce a hard, non-machinable deposit.

#### Electrodes for welding cast iron

Electrodes for welding cast iron may have either a steel base or be non-ferrous. Ferrous base electrodes are usually used where pre-heat is employed, or a machinable deposit is not required. If the cold technique is employed or machinability is important, non-ferrous electrodes are chosen. It should be kept in mind however, that even when non-ferrous electrodes are used the HAZ adjacent to the weld will be hard and non-machinable if welded with the cold technique. The electrode types include:

- core wire of monel
- core wire 55% Ni/45% FE give machinable deposits without pre-heat
- core wire pure nickel
- core wire low carbon steel for repairs to thick sections. To produce machinable welds, pre-heat to 550 °C is necessary
- core wire of silicon-bronze or tin-bronze repair of thin sections where colour match is not important. No pre-heat required.



#### Other techniques

- Buttering Where the sides of a large vee are lined with nickel electrodes and the groove filled with an E6918 (refer AS/NZS 4857:2006 'B' classification) to produce a machinable deposit.
- Studding The casting is prepared, and short studs are screwed into the vee and reinforcement areas. The studs are welded around and the vee is filled.

#### Buttering

Where larger Vs are to be welded, it is sometimes beneficial to line the sides with nickel based electrodes, and then fill in the remaining void with mild steel E4918 (refer AS/NZS 4855:2007 'B' classification) electrodes. This process is called 'buttering'. Shrinkage is lessened since the layers of deposited metal on each side of the groove can cool without restraint, and a smaller volume of deposit subject to restraint is required for filling the final groove. This same technique can be applied to the filling of voids or blow holes in castings to produce machinable deposits.



Fig 2.6 – Buttering

#### Studding

As explained previously, the chilling action on the cast iron, along with the high carbon content, increases and brittleness, thereby weakening the strength of the cast iron just outside of the line of fusion. Welds in cast iron, if of sufficient thickness, may be strengthened mechanically by a process called studding. Studs of steel approximately 6 mm to 10 mm in diameter should be used. The crack in the casting should be V-cut, drilled and tapped so that the studs may be screwed into the V or the area of reinforcement. The studs should project about 4 mm to 8 mm above the surface. In such cases the strength of the weld may safely and conservatively be taken as the strength of the studs. It is considered good practice to first weld one or two beads about each stud, making sure that fusion is obtained both with the stud and cast-iron base metal. Straight lines of weld metal should be avoided if possible.

Welds should be deposited intermittently, and each bead should be peened before cooling.









# Chapter 3 – Low alloy steels

Steel is an alloy of iron and carbon. There are however many types or groups of steels, and many grades within each group.

Steels can be classified into two main groups.

#### Alloy steels

Alloy steels are steels where the properties of the steel are controlled with elements other than carbon.

Alloy steels are divided into two groups which are:

- low alloy steels where the total alloy content is less than 5%
- high alloy steels where the total alloy content is greater than 5%.

Examples of high alloy steels in common use are stainless steels and austenitic manganese steel.

#### Low alloy steels

The low alloy steel group is a particularly useful group of steels, as each has properties that make it suited to particular applications. The low alloy steel types in common use are:

- carbon manganese steels
- weather resistant steels
- quench and tempered steels
- creep resisting steels.

The properties of these low alloy steels are gained by the addition of alloying elements other than carbon. The major advantage of these steels is that we can bring about improvements in mechanical properties (such as hardness and tensile strength) without the accompanying lack of ductility that occurs when carbon is used to improve mechanical properties.

Further to this, we get a combination of the desirable properties that the addition of each of the alloying elements brings. For example – if we alloyed a steel with:

- chromium to improve hardness, tensile strength and corrosion resistance
- nickel to improve toughness and promote a fine grain structure
- molybdenum to impart creep resistance,

we would finish up with a strong, tough, corrosion resistant and creep resistant steel.



#### Alloying elements in steel

Some common alloying elements and their effects are as follows.

#### Manganese

Added to plain carbon steels to combine with sulphur to reduce hot shortness. Manganese slows down the transformation of austenite, thus increasing hardenability. It is used as a de-oxidiser. Above 11% manganese maintains an austenite grain structure at room temperature and confers the ability to work harden.

#### Chromium

Increases hardness and tensile strength without reducing ductility, and increases corrosion resistance at both high and low temperatures. Chromium steels retain their strength at high temperatures. Increases hardenability.

#### Nickel

Nickel is a grain refiner and an austenite former. It improves tensile strength without reducing ductility, ie improves toughness. Improves corrosion resistance.

#### Molybdenum

Will increase the hardenability of steels. Reduces temper brittleness of chromium steels and reduces the tendency toward creep (the slow stretching of a metal under stress at high temperatures). Also raises the critical temperature points in steel.

Increases the mechanical properties of heat treated steels and can induce secondary hardening in high speed steels. Produces a fine grain structure.

#### Tungsten

Enables steel to remain hard over a wide range of temperatures and is used in high speed steels. Produces a strong, hard alloy and has a considerable effect on grain structure.

#### Copper

Helps resist atmospheric corrosion and also increases strength.

#### Cobalt

Imparts the quality of red hardness.

#### • Sulphur

Improves machinability.







### General weldability of low alloy steels

As previously mentioned these steels are hardenable (most grades), and are subject to cracking as a result of cutting and welding, if correct procedures are not followed. The key to successful welding of these steels is:

- careful control of heat input
- selection of consumables
- suitable techniques and procedures.

#### Heat input

As previously mentioned, these steels are hardenable and rapid cooling may lead to the formation of martensite in the heat affected zone adjacent to the weld. This can be controlled by:

- pre-heat
- taking advantage of the heat of the welding process.

#### Post-heat

The higher the heat input – the slower the cooling rate. As a general rule, slow cooling rates are desirable when welding low alloy steels.

#### Selection of consumables

Most steels in these categories require the use of hydrogen-controlled welding consumables as a means of eliminating HAZ cracking. Electrodes are chosen which:

- deposit weld metal of similar composition to the base metal
- give the required tensile strength
- give the required impact properties
- minimise hydrogen in the weld zone.

For MMAW metal arc welding, electrodes conforming to AS/NZS 4856:2006 are normally chosen. These electrodes will provide good ductility of the weld metal and also help minimise dilution.

Dilution of the weld metal by the molten parent metal leads to pick-up of alloying elements, and reduced ductility of the weld metal.



### **Techniques and procedures**

The use of sound welding techniques and procedures can significantly improve the results obtained when welding steels in these groups. Amongst these are as follows.

- Determine pre-heat requirements prior to flame cutting.
- Ensure all flame cut surfaces are clean and smooth.
- Ensure alignment and fit-up to close tolerances.
- Meet all conditions of pre-heat prior to tacking.
- Make long convex tacks of sufficient throat thickness.
- No arc strikes outside the weld preparation.
- Use preparation and welding variables aimed at minimising dilution.
- Ensure removal of all moisture.
- Ensure consumables are moisture free.
- Feather tacks do not weld over broken tacks.
- Deposit convex weld beads to allow for contraction.
- Use a suitable welding sequence.
- Maintain strict control over interpass temperatures.
- Clean thoroughly between runs.
- Ensure a smooth, notch free cover pass.
- Apply post-weld heat treatment as required.

There are four main groups of low alloy steels commonly encountered by the welder. These are:

- carbon-manganese steels
- weather resistant (weathering) steels
- quench and tempered steels
- creep resisting steels.

#### **Carbon-manganese steels**

These steels contain carbon (usually 0.2%-0.26%) and manganese in the range of 1% to 1.8%. Manganese in these quantities increases hardenability and tensile strength. These steels are 'high strength structural' and 'high strength low alloy' steels.

These steels are classified under AS 1548 – Steel plates for boilers and pressure equipment. They are readily weldable with all common welding processes. They are also weldable with all manual metal arc electrodes classified under AS/NZS 4855, although pre-heat is commonly applied when hydrogen-controlled electrodes are not used.

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#### Weather resistant steels

Steel to AS/NZS 3678 (WR350/1 and WR350/1LO) is available and is a low alloy medium tensile steel of high yield strength, having superior corrosion resistance under atmospheric conditions. Weathering steel is especially suitable in the transportation field and for structural works where corrosion resistance and also a reduction in mass is important.

Corrosion resistance is approximately 4–6 times that of normal structural steels, and their tensile strength is approximately 50% greater than that of low carbon steel.

#### Chemical composition of weather resistant steels

Element	Range %	Typical %
Carbon	0.12 max	0.10
Phosphorus	0.12 max	0.09
Maganese	0.25-1.00	0.85
Silicon	0.20-0.70	0.45
Sulphur	0.050 max	0.025
Nickel	0.40 max	0.25
Chromium	0.40-1.00	0.70
Copper	0.15-0.45	0.25

#### **Mechanical properties**

•	Yield stress (min MPa)	345.
•	Tensile strength (min MPa)	483.
•	Elongation in 200 mm (min %)	18.

#### Welding of weather resistant steels

Weathering steel can be readily welded both to itself and to structural carbon steel. Welding is done in the normal manner. A good operator employing good practices for structural carbon steel using manual metal arc welding electrodes, or any of the semiautomatic and automatic processes, will get good results.

For manual metal arc welding, electrodes of the AS/NZS 4855 E43XX types are generally satisfactory. When higher strengths are essential, electrodes conforming to AS/NZS 4855 E49XX (reference should be made to AS/NZS 4855 Classification 'B') may be used. When joints are being made to structural carbon steel, an electrode should be chosen to match the strength level of the structural carbon steel.

Where corrosion resistance and appearance are important and multirun welds are necessary, an alloy electrode, containing 21% nickel is required. (Reference should be made to AS/NZS 4855 Classification 'B').



Pre-heat requirements may be summarised as follows.

Electrode	Thickness	Pre-heat or interpass temperature (min °C)
Other than low hydrogen	12.5 mm and less	10
	over 12.5 to 25 mm	100
Low hydrogen	12.5 mm and less	10
	over 12.5 to 25 mm	10

Table 3.1 – Pre-heat requirements for weather resistant steels







# **Quenched and tempered steels**

Quenched and tempered steels are high strength, low alloy steels supplied in the quenched and tempered condition. The chemical composition usually includes numerous alloying elements such as maganese, silicon, nickel, chromium, molybdenum, vanadium, copper, titanium and boron. The manufacture of these steels normally involves water quenching from 900–950 °C, and tempering at 550–650 °C for structural grades and 150–550 °C for wear resistant grades.

Available structural grades are:

- TIA produced by United States steel
- Bisalloy 80% produced by Bisalloy Steels Pty Ltd, Australia
- WEL-TEN 60 and WEL-TEN 80c produced by Nippon Steel, Japan.

Available wear resistant grades are:

- Bisalloy 320, 360 and 500
- WEL-TEN AR430 AR360C and AR500E.

The composition of USS TIA is:

С	Mn	Р	S	Si	Ni	Cr	Мо	V	Cu	В
0.10/	0.60/	0.035	0.040	0.15/	0.70/	0.40/	0.40/	0.03/	0.15/	0.002/
0.20	1.00	max	max	0.35	1.00	0.65	0.60	0.08	0.50	0.006

Table 3.2 – Composition of USS TIA

Quenched and tempered steels offer several advantages over structural carbon steels.

- High strength The tensile strength of quenched and tempered steels is about three times greater than that of structural carbon steel.
- Corrosion resistance The atmospheric corrosion resistance of quenched and tempered steels is about three times that of structural carbon steel.
- Toughness Quenched and tempered steels are tougher, and in particular display good low temperature notch toughness.
- Abrasion and impact resistance Some grades of quenched and tempered steel are heat treated to give high hardness with good abrasion and impact resistance.
- Economy For structural fabrication purposes, thinner sections of quenched and tempered steels can offer the same strength as much thicker structural carbon steel sections. Apart from design advantages of lighter weight, thinner sections make handling easier, and welding and cutting faster.

#### Applications

Quenched and tempered steels, because of their strength, toughness and lighter weight (reduced thickness), are being widely used for such fabrications as bridges, crane jibs, dump truck bodies, gas and liquid tanks, and even the structural members for large buildings.

When supplied in the higher hardness grades, quenched and tempered steels are widely used in quarries, mines and ore treatment plants on components such as excavator buckets, ore chutes and wear plates.





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## Weldability of quenched and tempered steels

These steels can be welded satisfactorily by the major welding processes when proper procedures are used. The most widely used processes are MMAW, GMAW, FCAW and SAW. The cooling rate of welds made with these processes is such that the mechanical properties of the weld are close to that of the quenched and tempered steel, thus re-heat treatment is unnecessary.

Other welding processes such as gas welding and electro-slag welding subject the steels to prolonged heating and slow cooling which affects the temper, and re-heat treatment is usually necessary if full mechanical strength is required. These processes, therefore, are generally avoided.

#### **Electrodes**

For applications where the weld must be as strong as the steel and maximum weld metal toughness is required, E76XX or E83XX electrodes conforming to AS/NZS 4857 Classification 'B' should be used. For applications where weld strength is not required to be as high, (eg attaching wear plates), then lower strength electrodes such as E43XX or E49XX (conforming to AS/NZS 4855 Classification 'B') are adequate, and in fact often desirable to reduce the risk of cracking in highly restrained joints.

It is also essential that low hydrogen electrodes are baked prior to use (in line with manufacturers' recommendations) to remove moisture from the flux coating.

#### **Pre-heating**

The main purpose of pre-heating is to reduce the cooling rate of the weld and adjacent base metal. Also by cooling the weld zone more slowly, shrinkage stresses are reduced. But, pre-heating of quenched and tempered steels can be overdone.

If the cooling rate is too slow the beneficial effects of the quenching and tempering, particularly notch toughness, are destroyed. The problem, therefore, is to control the cooling rate and control the welding heat input so the cooling rate is neither too fast nor too slow.





# Recommended minimum pre-heat temperatures for quench and tempered steels

Grada	Plate thickness (mm)				
Grade	<13	13–25	25–50	>50	
Minimum pre-heat temp (°C)					
High strength structural grades					
450 Mpa min. yield stress	10	25	75	100	
620 Mpa min. yield stress	50	100	125	150	
680 Mpa min. yield stress	50	100	125	150	
Abrasion resistant grades					
320 HB	50	100	125	150	
360 HB	50	100	125	150	
500 HB	100	150	150	_	
Maximum interpass temp (°C)					
All grades	100	175	200	220	

Table 3.3 – Minimum pre-heat temperatures for quench and tempered steels

#### Fabrication techniques for quench and tempered steels

- Flame cutting Pre-heat to 100–200 °C max is required where flame cutting is carried out in very cold conditions (below 10 °C) or in heavy plate thicknesses.
- Gouging Flame gouging of quench and tempered steels is not recommended, due to the high heat input. Arc-air gouging is the preferred method.
- Poor fit-up is to be avoided.
- Close control of heat input and interpass temperature must be exercised.
- Minimise joint restraint when welding.
- Stringer beads are preferred when welding. When weaving techniques are employed, the maximum width of the weave should be 2 x the electrode diameter.



### **Creep resisting steels**

Creep is the slow stretching of a metal at elevated temperatures. This will occur even though stresses are below the yield strength of the metal. The chrome/moly group of steels resists creep, and is commonly used in process applications such as refineries, steam generation and chemical plants. The high strength-to-weight ratio also makes it ideal for use in aircraft structures, and motorcycle, bicycle and race car frames.

This alloy group includes such alloy compositions as:

- carbon 0.5% molybdenum (ASTM Steel types Al 61, A204, Al 82 etc)
- 1.0–1.5% chromium 0.4–0.6% M.O. (ASTM Steel types A213, A335 etc)
- 2.0–2.5% chromium 0.9–1.1% molybdenum (ASTM Steel types AI 99, A200–A213)
- 4.5–5.5% chromium 0.45–0.65% molybdenum (ASTM Steel types A155, A199, A200, A213).

This list contains only alloy steels commonly found in industry and is in no way complete.

#### Weldability

As the alloy content of these steels increases, so does the hardenability and the tendency towards cracking. These steels should be welded using dry, hydrogen-controlled electrodes which deposit weld metal of similar composition to the parent metal. These electrodes are classified in AS/NZS 4856.

Pre-heating and interpass temperature control is also employed in addition to post-heat treatment (stress relieving), when welding creep resisting steels. Also the completed weld joint is usually subjected to stringent non-destructive testing, ie radiography, ultrasonic testing and dye checking. Non-destructive testing is generally carried out after post-weld heat-treatment.

On many occasions it may be necessary to weld creep resisting steels when there are no welding procedures available. To aid the welding operator to successfully weld these alloys, the following guidelines will be useful.

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#### Welding technique

Group 1: Carbon - 0.12%/0.5% molybdenum

Electrode: ISO 3580-B-E49XX IM3

A short arc with a slow travel speed should be adopted and only dry electrodes used. The following pre-heat and interpass temperatures should be employed: for plate thicknesses 25 mm to 50 mm: 100 °C, more than 50 mm: 150 °C. If stress relieving is required, it should be carried out at a temperature of 580–620 °C for a time in minutes equal to 2.5 times the plate thickness in mm, with a minimum time of one hour.

Group 2: 1.0–1.5% chromium, 0.4–0.6% molybdenum

Electrode: ISO 3580-B-E55XX CM

A short arc and slow travel speed should be adopted and only dry electrodes used. The following pre-heat and interpass temperatures should be employed: for plate thickness 12.5 mm to 25 mm: 100-150 °C. Above 25 mm: 1500-200 °C. Stress relieving is carried out at 680–700 °C for a time in minutes equal to 2.5 times the plate thickness in mm, with a minimum time of one hour. Rapid cooling of the welded workpiece should be avoided.

Group 3: 2.0-2.5% chromium, 0.9-1.1% molybdenum

Electrode: ISO 3580-B-(62XX-2CIM)

It is essential to use a short arc and only dry electrodes. A pre-heat and interpass temperature of 200 °C minimum is required. Stress relieving is carried out at 700–740 °C for a period of minutes equal to five times the plate thickness in mm with a minimum of two hours.

Group 4: 4.5-5.5% chromium, 0.45-0.65% molybdenum

It is essential that a short arc combined with slow travel speed is used, and that only correctly dried electrodes are used. A pre-heat and interpass temperature of 300 °C to 350 °C is employed, followed immediately by post-weld heat treatment. Stress relieving is at a temperature of 720–760 °C for a period in minutes equal to five times the plate thickness in mm with a minimum of two hours.

#### For Group 4



#### Activity

Using AS/NSZ 4856, determine the electrode type/classification for 'A' and 'B' classification in Group 4.






# Chapter 4 – Classification of alloy steels

Alloy steels are divided into two groups.

- Low alloy steels Where the total alloy content is less than 5%.
- **High alloy steels** Where the total alloy content is greater than 5%.

# Low alloy steels

The low alloy steel group is a particularly useful group of steels. Steels in this group possess excellent mechanical properties, and each has additional properties which make it suited to particular applications. The low alloy steel types in common use are:

- carbon-manganese steels
- weather resistant steels
- quenched and tempered steels
- chrome/molybdenum steels
- nickel steels.

## Carbon-manganese steels

These micro-alloyed steels containing from 0.5% to 1.8% manganese are manufactured to AS 1548, and are intended for use primarily in the fabrication of pressure vessels and boilers. These plates are silicon-aluminium killed (de-oxidised), and are supplied up to a maximum thickness of 150 mm. Plates may be supplied as rolled, or in the heat-treated condition, and are supplied with certificates of chemical analysis and mechanical testing.

The manufacturer produces the steel to more stringent quality requirements (ie the chemical composition is strictly controlled to much finer tolerances than is the case with mild steel). The manufacturer also carries out more stringent, non-destructive and destructive testing to ascertain the steel's physical and mechanical properties. It also clearly identifies the steel with identifying numbers legibly marked on the plate.

The steel is supplied to the purchaser with a set of test certificates showing such things as:

- the purchaser's order number
- the identification code of the material
- the process of manufacture
- the ladle analysis in respect to all elements
- the temperature at which tests are carried out to ascertain mechanical properties
- details of any heat treatment applied to the plate or test samples (if any).



Further to this, each plate shall be clearly identified with:

- the manufacturer's name or identification mark
- the grade designation
- the plate or identification number
- the direction of rolling.

# Classification of steels to AS 1548–1995

Steels to AS 1548 are classified as follows.

- **Type** steel is of two types:
  - 5 = silicon/aluminium killed, niobium treated 0
  - 7 = silicon/aluminium killed. 0
- UTS designates the minimum ultimate tensile strength in MPa:
  - Grades: 430, 460, 490. 0

## Heat treatment

- R = as rolled
- N = normalised (870-930 °C)
- A = as rolled (may be normalised)

#### Impact properties

Specifies notch toughness at a particular temperature.

H = high temperature (300  $^{\circ}$ C)

L0 = 0 °C

L20 = -20 °C

Example: AS 1548-5-490 NL20







The grades available under AS 1548 are given in Table 4.1.

This table has been removed. It was reproduced from Table 1 on page 8 of AS 1548-1995.

Table 4.1 – Available grades



# Weather resistant steels (weathering steels)

These low alloy steels (alloyed with nickel, chromium and copper) are designed to give increased resistance to atmospheric corrosion. Additionally, they combine high strength with good weldability.

Minimum yield strength is 340 MPa (UTS 480 MPa) and corrosion resistance is four to seven times that of structural carbon steel. Whereas plain carbon steel will oxidise, and eventually rust away if left unprotected, weather resistant steels develop a tough purplish oxide on the surface which protects the steel against further oxidation. Weathering steels are used for structural purposes, and for other applications such as transport equipment where the high strength-to-weight ratio can be used to advantage.

Weathering steels are readily weldable with both hydrogen-controlled and non-hydrogen controlled electrodes. However, if the corrosion resistance of the weld metal is required to match that of the parent metal, an electrode containing 2.5% nickel should be used.

# AS/NZS 3678 – grade designation

The grade designation of weather resistant steels is by:

- the prefix WR indicating weather resisting
- the specification of yield strength
- low temperature impact properties where appropriate.

Available grades are:

- WR 350/1
- WR 350/1L0.

## **Chemical composition**

Grade	Product analysis %											
	С	S	Si	Mn	F	0	S	C	r	Ni	С	u
	max	min	max	max	min	max	max	min	max	max	min	max
WR350/1 and WR350/ 1L0	0.12	0.15	0.75	1.70	0.055	0.16	0.040	0.35	1.05	0.55	0.15	0.05

Table 4.2 – Chemical composition of weather resistant steels

## **Mechanical properties**

Grade	Minimum yield strength MPa	Minimum tensile strength MPa	Min % elongation
WR350/1 and WR350/1L0	340	450	20

Table 4.3 – Mechanical properties of weather resistant steels







AS/NZS 3678 – WR 350/1L0 indicates weather resistant steel with 350 MPa minimum yield strength, and impact tested at 0  $^\circ\text{C}.$ 

# **Quenched and tempered steels**

Quenched and tempered steels are high strength, low alloy steels, which as the name suggests are heat treated during manufacture. Quenched and tempered steels are available in both structural and wear resistant grades. The properties that result in these steels are a product of chemical composition and heat treatment.

Quenched and tempered steels offer several advantages over structural carbon steels.

- **High strength** The tensile strength of quenched and tempered steels is about three times greater than that of structural carbon steel.
- **Corrosion resistance** The atmospheric corrosion resistance of quenched and tempered steels is about three times that of structural carbon steel.
- **Toughness** Quenched and tempered steels are tougher, and in particular display good low temperature notch toughness.
- Abrasion and impact resistance Some grades of quenched and tempered steel are heat treated to give high hardness with good abrasion and impact resistance. These grades are used as wear plates.
- **Economy** For structural fabrication purposes, thinner sections of quenched and tempered steels can offer the same strength as much thicker structural carbon steel sections. Apart from the design advantages of lighter weight, thinner sections make handling easier, and welding and cutting faster.

# Applications

Quenched and tempered steels, because of their strength, toughness and lighter weight (reduced thickness), are being widely used for such fabrications as bridges, crane jibs, dump truck bodies, gas and liquid tanks, and even the structural members for large buildings.

When supplied in the higher hardness grades, quenched and tempered steels are widely used in quarries, mines and ore treatment plants on components such as excavator buckets, ore chutes, and wear plates.

# Composition

Sala Toronto

The chemical composition of Bisalloy quenched and tempered steels is as follows.

Grade	Typical chemical composition %										
	С	Р	Mn	Si	S	Cr	Мо	ΑΙ	Ti	В	
Bisalloy 80	0.18	0.015	1.15	0.40	0.003	0.85	0.20	0.030	0.030	0.0015	
Bisalloy 320	0.18	0.015	1.15	0.40	0.003	0.85	0.20	0.030	0.030	0.0015	
Bisalloy 360	0.18	0.015	1.15	0.40	0.003	0.85	0.20	0.030	0.030	0.0015	
Bisalloy 500	0.28	0.015	0.50	0.35	0.003	0.95	0.15	0.030	0.040	0.0015	

Table 4.4 – Chemical composition of Bisalloy quenched and tempered steels

# Availability

Quenched and tempered steels are produced both in Australia (by Bisalloy Steels) and overseas. A brief list of manufacturers and their product name is given below.

Manufacturer	Product
Bisalloy Steels	Bisalloy
Nippon Steel	WEL-TEN
Sumitomo	Sumiten and Sumihard
Kawasaki Steel	Riverace
Kobe Steel	K-Ten
Nippon Kokan	Hiten and Everhard
United States Steel	T1

Bisalloy steels are produced in Australia, and tend to be the most commonly encountered. These are followed closely by the USS T1 steels, due to the fact that machinery such as cranes and earthmoving equipment produced by American-based companies is common in Australia.

Common structural grades are:

- T1 A
- Bisalloy 60, 70, 80, 80PV
- WEL-TEN 60 and WEL-TEN 80c.

Common wear resistant grades are:

- Bisalloy 320, 360, 400 and 500
- WEL-TEN AR430, AR360C and AR500E.

# **Mechanical properties**

The mechanical properties of Bisalloy steels can be seen in Table 4.5. Low carbon steel has been included for comparison purposes.

Grade	Quench °C	Temp °C	Yield strength MPa	UTS MPa	Elongation %	CE %
AS/NZS 3678 250	_	_	250	410	22	0.44
AS/NZS 3678 350	_	_	350	450	21	0.48
Bisalloy 60	900	680	500	590	20	0.42
Bisalloy 70	900	640	600	690	20	0.42
Bisalloy 80	900	600	690	790	18	0.58
Bisalloy 360	900	400	1190	1260	13	0.58
Bisalloy 500	900	175	1580	1640	10	0.60

Table 4.5 – Mechanical properties of Bisalloy steels



# Metals<sub>& Fabrication</sub>

# Weldability

Quenched and tempered steels are readily weldable, particularly the structural grades, and can be welded by a range of welding processes. The most widely used are MMAW, FCAW, GMAW and SAW. The cooling rate of welds made with these processes is such that the mechanical properties of the weld are close to those of the parent metal.

Welding processes with high heat inputs such as ESW or OAW are not recommended, as excessive heat input will destroy the mechanical properties.

Quenched and tempered steels are hardenable, and rapid cooling will cause a loss of ductility and possible cracking in the weld zone. Above 12 mm plate thickness, pre-heat should be considered. Hydrogen-controlled consumables should always be used.

# Fabrication techniques for quenched and tempered steels

- Flame cutting Pre-heat to 100–200 °C max is required where flame cutting is carried out in very cold conditions (below 10 °C) or in heavy plate thickness.
- Gouging Flame gouging of quenched and tempered steels is not recommended, due to the high heat input. Arc-air gouging is the preferred method.
- Poor fit-up is to be avoided.
- Close control of heat input and interpass temperature must be exercised.
- Minimise joint restraint when welding.
- Stringer beads are preferred when welding. When weaving techniques are employed, the maximum width of the weave should be 2x the electrode diameter.



# Chrome/molybdenum (Cr/Mo)

Chrome/molybdenum steels (or chrome/moly steels, as they are more commonly known) are also known as **'creep resisting steels'**. Creep is the slow yielding (or stretching) of a metal at high temperatures, even though the stresses involved are below the yield strength of the material. The addition of molybdenum as an alloying element imparts 'creep resistance' to steel to counteract this tendency.

Chrome/moly steels have excellent mechanical properties. The high strength-to-weight ratio of these steels makes them ideal for applications where a combination of high strength and light weight are needed. Such applications are aircraft frames, race car chassis and motorcycle frames. Pipes and tubing are by far the greatest form of this product. Processing plants, refineries, power stations and other locations that transmit fluids at high temperatures and/or pressures make extensive use of chrome/moly piping.

Popular name	С	Nb	Si	Cr	Мо
1⁄2 Cr – 1⁄2 Mo	0.10 to 0.20	0.30 to 0.60	0.10 to 0.30	0.50 to 0.81	0.44 to 0.65
1 Cr 0 ½ Mo	0.15 max	0.30 to 0.60	0.50 max	0.80 to 1.25	0.44 to 0.65
1–¼ Cr – ½ Mo	0.15 max	0.30 to 0.60	0.50 to 1.00	1.0 to 1.50	0.44 to 0.65
2 Cr – ½ Mo	0.15 max	0.30 to 0.60	0.50 max	1.65 to 2.35	0.44 to 0.65
2–¼ Cr – 1 Mo	0.15 max	0.30 to 0.60	0.50 max	1.90 to 2.60	0.87 to 1.13

Commonly encountered chrome molybdenum steels are given in Table 4.6.

Table 4.6 – Common Cr/Mo steels

## Weldability

As the alloy content of Cr/Mo steels increases, so does the hardenability and the tendency towards cracking. These steels should be welded using dry, hydrogen-controlled electrodes that deposit weld metal of similar composition to the parent metal. These electrodes are classified in AS/NZS 4857.

Pre-heating and interpass temperature control is also employed in addition to post-heat treatment (stress relieving) when welding creep resisting steels. Also, the completed weld joint is usually subject to stringent non-destructive testing (ie radiography, ultrasonic testing, and/or dye penetrant testing). Non-destructive testing is generally carried out after post-weld heat treatment.

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# Nickel steels

Nickel as an alloying element enables ductility and toughness to be maintained in steels, even at very low temperatures. Consequently the major use for nickel steels is for cryogenic applications (storage vessels for liquified gases). The cryogenic steels described below are intended for use below -60 °C.

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The commonly recognised grades are:

- **3.5% nickel** for service temperatures –60 to –80 °C
- **5% nickel** for service temperatures down to –160 °C
- **9% nickel** for service temperatures down to –196 °C.

The 3½% and 5% nickel grades are not commonly encountered, as they have little cost advantage over 9% nickel steels which have lower service temperatures and superior mechanical properties.

#### 9% nickel steels

9% nickel steels are in common use in storage vessels for LNG (-164 °C) and for liquid oxygen and nitrogen (-196 °C).

9% nickel steel is available as quench and tempered – **QT**, and double normalised and tempered – **NNT**. Available grades are as follows.

ASTM type	Tensile strength	Yield strength
A353–QT	689–827 MPa	517 MPa
A553–NNT	689–827 MPa	586 MPa

Table 4.7 – Available 9% nickel steels

#### Fabrication and welding of 9% nickel steels

9% nickel steel can be formed hot or cold. It is readily flame cut, and weld preparation can be applied by flame cutting or machining. Flame cut surfaces are usually ground, to remove the shallow layer of overheated steel which results.

9% nickel steel does not suffer from hardening of the heat affected zone, and is readily weldable. It can be welded without pre-heat up to at least 50 mm of plate thickness by the common arc welding processes.

The surface oxide melts at a temperature 600 °C higher than that of the base metal and should be removed by grinding, followed by degreasing, prior to welding.

The most commonly used consumables are of the NiCrMo type, and interpass temperatures should be kept low.

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# Chapter 5 – High alloy steels

High alloy steels are steels where the total alloy content exceeds 5%.

The high alloy steel groups most commonly encountered by the fabricator are:

- stainless steels
- austenitic manganese steel.

# Stainless steels

Stainless steels are essentially iron/chromium alloys where the chromium content exceeds 10.5%, carbon content is less than 1.5%, and the iron content is greater than that of any other element. The chromium oxides, which form rapidly on the surface, render the metal impervious to further corrosive attack.

There are various types and grades of stainless steel, aimed at providing corrosion resistance over a wide range of applications.

Stainless steels are divided into four main groups:

- austenitic
- ferritic
- martensitic
- ferritic/austenitic duplex alloys.

Stainless steels are classified under a three digit classification system established by the 'American Iron and Steel Institute' (AISI), for example:

- 200 series non-hardenable austenitic
- 300 series non-hardenable austenitic
- 400 series hardenable martensitic or non-hardenable ferritic.
- 500 series a hardenable, low chromium (4 6%) alloy which is corrosion resistant rather than stainless.

Austenitic stainless steels are also commonly referred to by their chromium and nickel content (eg 18/8 or 20/12). The chromium content is always stated first, followed by the nickel content.



# Austenitic stainless steels (300 series)

These are the commonly fabricated grades, and are consequently of the most importance to the welder. They:

- are essentially non-magnetic, and are thereby easily distinguished
- have high strength
- have excellent weldability relative to other high alloy steels (except the free machining types)
- do not harden by heat treatment
- can be cold worked to a high degree of hardness
- may be annealed by heating to 1040–1120 °C, and quenching
- have good resistance to scaling at high temperatures
- have a high rate of thermal expansion
- have low thermal and electrical conductivity
- range in analysis from 16–26% chromium and 6–22% nickel.

18/8 stainless steels are by far the most widely used.



Common grades of austenitic stainless steel, their analysis, and applications can be found in Table 5.1.

AISI steel type	%Cr	%N	%C	%other	Description/use
301	17.0	7.0	0.05	_	General purpose structural applications used where work hardening is desirable, eg rail cars and wagons.
302	18.0	9.0	0.08	_	General purpose – food, domestic, structural architectural.
					Good corrosion resistance.
303	18.0	9.0	0.12	0.25S	Free machining.
304	18.5	8.5	0.06	_	Similar to 302.
304L	18.5	9.5	0.03	_	Low carbon, less susceptible to weld decay.
					Chemical plant food processing.
305	18.0	12.0	0.08	_	Cold forming.
309	23.0	13.5	0.15	_	Resists high temperature oxidation.
310	25.0	20.0	0.12	_	Resists high temperature oxidation to 1100 °C.
316	17.0	12.0	0.06	2.25Mo	Used where high corrosion resistance is required.
					Marine and chemical industries.
316L	17.0	12.0	0.03	2.25Mo	Low carbon version of 316.
					Minimal susceptibility to intergranular corrosion.
306Ti	17.0	12.0	0.08	2.25Mo	Titanium stabilised version of 316.
				0.5Ti	High temperature strength, good resistance to intergranular corrosion.
317	19.1	13.0	0.07	_	For chemical plant.
					Greater corrosion resistance than 316.
321	18.0	10.0	0.06	0.5Ti	Heat resistant to 800 °C.
					Heavy weldments in chemical and other industries.

Table 5.1 – Common austenitic stainless steels



The factors that limit the weldability are:

- the tendency of the weld metal, weld fusion line, or HAZ towards hot cracking
- the precipitation of chromium carbide, leading to intergranular corrosion (weld decay)
- the formation of undesirable structures (eg sigma phase) within a certain range of temperatures and chromium concentrations.

# Cracking

Occurs when cooling from high temperatures, and follows the boundaries of the dendrites as solidification progresses. Cracks can affect a large part of the weld zone. Austenitic stainless steels are sensitive to micro-cracking of the grain, however this sensitivity decreases if there is ferrite present in the microstructure. Ferrite is needed to minimise micro-cracking, however >3% ferrite is desirable to completely eliminate micro-cracking of the grain structure.

Various diagrams such as the 'Scheaffler diagram' and the 'DeLong diagram' have been used to predict levels of ferrite in deposited weld metal. However the currently favoured method of calculating ferrite levels in deposited weld metal is by use of the 'WRC–1992 diagram'.

## Intergranular corrosion (weld decay)

The carbon present in austenitic stainless steels is normally dissolved within the grains. During slow cooling in the range from 900 - 500 °C, the carbon combines with the chromium carbides along the grain boundaries; this is referred as carbide precipitation. Chromium carbides are themselves not corrosion resistant. Additionally the material along the grain boundaries is depleted of chromium, leaving it subject to corrosive attack.

This form of corrosion is generally known as intergranular or intercrystalline corrosion. When associated with the weld HAZ, it is normally called weld decay.



Fig 5.1 – Weld decay





There are two methods of reducing the occurrence of weld decay.

- The production of steels with extra-low carbon content (about 0.03%). This reduces the amount of carbide formed. These steels are designated with an 'L' suffix (eg 316L).
- The addition of 'stabilising elements'. These elements have a higher affinity for carbon than does chromium. They combine with the carbon present, leaving the chromium free to form the chromium oxides which provide corrosion resistance. The most commonly used stabilising elements are molybdenum (Mo), titanium (Ti), and niobium (Nb).

# Sigma phase precipitation

When steels containing high concentrations of chromium are subjected to prolonged heating at 600–900 °C, some of the chromium forms an intermetallic compound (FeCr) with iron. This compound is extremely brittle and leads to cracking, particularly in heavy, multi-run weldments, or when heat treatment is carried out. The remedy is to ensure quick cooling between runs.





## **Recommendations for welding austenitic stainless steels**

- Low heat input high travel speeds, low currents, stringer beads, low interpass temperatures.
- Ensure good fit-up.
- Allow for approximately 50% more distortion than for carbon steel.
- Tack at intervals half of those used for mild steel.
- Feather tacks.
- The weld area must be clean. All possible sources of carbon pick-up must be removed. Use iron-free grinding disks.
- Use sequence welding, chill bars, or jigs to minimise distortion.
- Use a short arc length to reduce the loss of alloying elements.
- Fill craters.
- Avoid heat build-up.
- Ensure rapid cooling.

## Consumables

There is a wide range of austenitic welding consumables available. In general, consumables are chosen that give weld deposits which match the base metal chemistry. If in doubt, consumables slightly richer in nickel and chromium should be selected.

Higher grade consumables should also be used where dilution may reduce the corrosion resistance, or increase the hardenability of the steel.

## Distortion

Austenitic stainless steels suffer from high levels of distortion, particularly in thin plates. This is due to the combination of its high co-efficient of linear expansion and low rate of thermal conductivity, which causes significant local upsetting of the metal. It is essential that this problem is addressed when formulating welding procedures.

Correction of distortion in austenitic stainless steel is difficult and expensive. Prevention measures must be adopted. Measures to minimise distortion include low heat input, chill bars, jigs and fixtures, tacking at frequent intervals and sequence welding.

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# Ferritic stainless steels

Ferritic stainless steels contain between 13% and 30% chromium (typically around 16%) and less than 0.15% carbon. When heated, there is no transformation to austenite, as the grain structure is essentially ferrite at all temperatures up to the melting point. The relationship between the chromium content and the carbon content is important in maintaining a ferritic grain structure.

Ferritic stainless steels have been developed in what are essentially three 'generations'.

The first generation are almost never fully ferritic, due to the comparatively high levels of carbon present. Steels in this group are as follows.

#### **Typical composition**

430	0.08%C	17%Cr
442	0.20%C	21%Cr
446	0.25%C	25%Cr

The second group are the relatively inexpensive, stabilised ferritic stainless steels. This group comprises the following.

#### **Typical composition**

405	0.05%C	13%Cr0.2%Al
409	0.05%C	11%Cr0.5%Ti

Commonly used for auto-exhaust systems – especially 409. It is usually welded with a low heat input and matching filler using the GMAW process, or when in sheet form, by resistance welding.

The newest group are the modern, low interstitial ferritics or so-called 'super ferritics'.

# Typical composition

	С	Ν	Cr	Мо	Ni	Other
18-2	0.02	0.02	18	2.0	—	0.25Ti, 0.3Nb
26-1	0.003	0.008	26	1.0	-	—
SEA-CURE™	0.01	0.025	26	3.0	2.5	0.4Ti
29-4	0.005	0.01	29	4.0	—	—
29-4-2	0.005	0.01	29	4.0	2.0	_

These steels have outstanding corrosion resistance, particularly to chlorides, which cause problems for the austenitics.



## Weldability of ferritic stainless steels

Ferritic stainless steels are non-hardenable, but are embrittled by grain growth and secondary phases which form in the grain, such as the sigma phase.

Generally speaking, the weldability of the ferritic stainless steels can be described as fair when compared with austenitic stainless steels. The grain growth problem can be minimised by ensuring low heat input.

For best results when welding ferritic stainless steels, the following general procedures may be adopted.

- Pre-heat to 120–200 °C.
- Low heat input to limit grain growth.
- Slow cooling from 450 °C to room temperatures.



Where full corrosion resistance is required, full annealing at 800 °C will be necessary.

#### Consumables

Ferritic stainless steel consumables are available, however they produce welds of low ductility. For this reason, austenitic stainless steel consumables are generally used, as they ensure ductile weld metal in the as-welded condition.

When the use of austenitic consumables is contemplated, consideration should be given to whether:

- they will have no effect on possible corrosion in the HAZ
- problems may be encountered with colour match and differences in thermal expansion.

Post-weld heat treatment (PWHT) can cause weld metal embrittlement, and corrosion susceptibility, unless stabilised electrodes are used.





# Martensitic stainless steels

Martensitic stainless steels contain 13%–17% chromium, and 0.1% carbon or above. Chromium in excess of 17% tends to form excessive ferrite in the grain structure.

These steels have good corrosion and oxidation resistance, and good high temperature strength up to 600 °C. Their rate of thermal expansion is similar to that of mild steel, and some grades may be fabricated by welding.

Grade	%C	%Cr	%Ni	%Mo	Use
403	0.10	12	_	_	_
410	0.10	12	0.5	_	turbines
410 NiMo	0.04	12	4.0	0.5	turbines
420	0.20	12	-	_	steel mill rolls
440A	0.70	17	—	_	blades for shears
440B	0.90	17	_	_	or where abrasion
440C	1.10	17	-	-	resistance is required

Common martensitic grades are as follows.

## Weldability of martensitic stainless steels

Martensitic stainless steels may be supplied in a variety of heat treated forms, from fully annealed to fully hardened and tempered. Irrespective of the condition, welding will create a hardened, martensitic HAZ. The hardness of this zone will depend on the carbon content, and susceptibility to cracking will increase accordingly. Normally, steels with less than 0.15% carbon such as 403 and 410 will not require PWHT, whereas those above 0.15% carbon, such as 420, or 440 should be post-weld heat treated to ensure freedom from cracking.

Welding procedures for these steels usually involve pre-heat to 250 °C, except where the carbon content is less than 0.1%. The maximum interpass temperature for all grades is 350 °C, and where the carbon content exceeds 0.15%, PWHT at 650–700 °C is recommended.

# Consumables

Martensitic consumables such as ISO3581-B-ES-410 or 430 and E420X are available. However, the weld metal lacks toughness, so austenitic consumables such as ISO3581-B-ES308L or Mo are generally used. Reference should be made to AS/NZS 4854.

Austenitic consumables produce welds of lower strength and greater ductility. These steels are susceptible to hydrogen-induced cracking, and austenitic consumables also help in this regard, keeping the hydrogen in solution.

# **Duplex alloys**

Ferritic/austenitic stainless steels contain 18–28% Cr, 4.5–8% Ni, and 2.5–4% Mo. In these steels there is insufficient nickel to produce a fully austenite grain structure, and a mixture of ferrite and austenite results.

# **Basic properties**

- High resistance to stress corrosion cracking.
- Higher tensile strength than austenitic or ferritic stainless steels.
- Good formability and weldability.

These steels are commonly used where chloride concentrations are high, as a means of minimising stress corrosion cracking.

Duplex alloys are generally specified by proprietary names (eg SAF 2205).

# Welding of stainless steel clad steels

Where corrosion resistance is only required on one side of the plate (for example in a storage vessel), stainless clad steels are commonly selected for use. Stainless clad steels are produced by bonding a thin sheet of stainless steel to a sheet of carbon steel via the rolling process. The cladding is usually of the 18/8 or 18/10 stainless steel types, and usually represents 10% to 20% of the total plate thickness.

Advantages of stainless clad steel include:

- cost the cost of clad steels is cheaper than stainless steels of the same thickness
- distortion distortion levels are similar to carbon steels
- they can be oxy-cut from the carbon steel side.

#### Welding procedure

The mild or alloy steel backing should be welded first, making sure that the root run does not come in contact with the stainless cladding. This can be achieved either by welding with a fairly close butt weld preparation and a large root face, or by cutting the cladding away from both sides of the root.

After the welding of the steel backing has been completed, the back is grooved out by grinding or carbon-arc gouging. The first run on the clad side is welded with a stainless steel of matching composition and with minimum dilution. A more highly alloyed electrode, such as a 25/20, is often desirable to overcome the effect of dilution. The remainder of the joint is completed with an electrode of matching composition.



For the best corrosion resistance, at least two layers of stainless steel weld metal are recommended. If the cladding is thin and it is only necessary to deposit a single layer, it would be best to use an electrode of higher alloy content.



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Fig 5.2 Welding procedure of clad materials



# Austenitic manganese steel

As discussed previously, manganese is used in carbon/manganese steels that are used primarily for the construction of pressure vessels. These steels contain manganese in the range of 0.5-1.7%.

If manganese is added to steel in the range of 11–14%, a steel called 'austenitic manganese steel' is formed, so called because when manganese is within the range of 11–14%, the grain structure remains in the austenite condition at ambient temperatures.

## Composition

The composition of manganese steel is as follows.

Carbon	1.00-1.40%
Manganese	11–14%
Silicon	0.30-1.00%
Sulphur	0.60% max
Phosphorus	0.10% max

Austentitic (11–14%) manganese steel, when quenched in water from temperatures around 1050 °C, is soft, but very strong and ductile. It is readily work hardenable, and has the ability to form a hard, wear resistant surface when pounded, scraped or cold worked in any manner. This property of maintaining a tough ductile interior with a work hardened surface makes it ideal for applications such as wearing parts of earth moving and crushing equipment.

Austenitic manganese steel can be identified by its non-magnetic properties. It may become slightly magnetic due to cold working, and produce a bright bushy spark when touched on a grinding wheel. To join austenitic manganese steel by welding, the electrode recommended is 18/8 chrome/nickel (stainless steel). For building up worn parts, an electrode depositing 11–14% manganese can be used.

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# Weldability

The following precautions should be taken during welding.

- Deposit short welds well dispersed to affect rapid cooling. Use the smallest gauge electrode, and lowest welding current consistent with adequate fusion.
- Allow the parent metal to cool between runs it can be quenched or cooled with wet rags. The body of the component should not be hotter than can be borne by the bare hand, before depositing another run.
- To reduce cracking due to contractional stresses, peen each weld bead as it is completed.
- **Do not** let manganese steel cool slowly from high temperatures.

Manganese steel as cast is brittle, and it will return to this embrittled state following slow cooling from high temperatures. Toughness and ductility can be restored by quenching from 1050 °C.



Austenitic manganese steel must be arc welded and pre-heating must be avoided, otherwise it will become brittle. It can be cut with the oxy-acetylene gas flame without any serious hardening effect on the cut surface. It is suggested however, that oxy-cut surfaces be ground prior to welding.

Hardfacing electrodes with a carbon steel core must never be deposited straight onto manganese steel; the manganese steel must first be buttered with an electrode depositing 18/8 stainless steel. Otherwise, the carbon steel weld metal will be diluted by the parent metal, resulting in extremely brittle welds.

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# Chapter 6 – Non-ferrous metals

Non-ferrous metals are metals which contain no iron at all, or those in which iron forms only a minor part of the alloy.

The major groups of non-ferrous metals commonly encountered by the fabricator are:

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

## Aluminium and its alloys

The material commonly referred to as 'aluminium' encompasses a wide range of aluminium alloys, whose properties vary remarkably. While pure aluminium is soft, weak and ductile, some aluminium alloys have mechanical properties that are superior to those of steel.

## Properties of aluminium

**Density** – Aluminium has a density of 2700 kg/m<sup>3</sup>, approximately one third the density of steel. Aluminium is widely used in applications where weight is a factor.

**Melting point** – The melting temperature of commercially pure aluminium is 660 °C. Alloying (particularly with silicon) lowers the melting temperature of aluminium, with most commercial alloys melting in the range of 520-650 °C.

**Corrosion resistance** – Aluminium resists atmospheric corrosion, and is resistant to corrosion by some other media. This corrosion resistance is gained by the formation of a tough oxide, which forms on the surface of the metal. The melting temperature of this surface oxide is 2040 °C. The oxide must be removed prior to welding. This is usually accomplished by vigorous brushing with a stainless steel wire brush, and the action of the welding arc when the polarity is electrode positive.

**Tensile strength** – The tensile strength of pure aluminium is around 90 MPa UTS (mild steel 300–450 MPa). However, this can be improved substantially by alloying and/or heat treatment. By this means, the tensile strength can be raised to in excess of 700 MPa.

**Electrical conductivity** – Aluminium is second only to copper among the commercial metals in electrical conductivity, where:

- Cu = 100
- AI = 60
- Mild steel = 10
- Stainless steel = 2.



**Thermal conductivity** – The thermal conductivity of aluminium is about five times that of mild steel. While this makes it suitable for applications such as heat exchangers, it tends to lead to a lack of fusion defects when welding.

**Co-efficient of thermal expansion** – The co-efficient of linear expansion of aluminium is 0.000026, ie for each °C of temperature it rises or falls, it will expand or contract that fraction of its length. This is twice as much as for mild steel (0.000012).

**Hot shortness** – Aluminium alloys lack ductility at elevated temperatures. This, combined with high thermal expansion, tends to cause hot cracking when welding.

**Hydrogen solubility** – Aluminium will dissolve substantial amounts of hydrogen in the molten state. Upon cooling, this hydrogen is forced out of solution, resulting in weld porosity. For this reason it is essential that weldments be cleaned thoroughly prior to welding, and that there is no possibility of hydrogen being introduced via the welding process or consumables.

**Colour change** – Unlike many metals, aluminium does not change colour when heated; neither does the surface oxide change colour.

#### Identification of aluminium

Aluminium can be identified from other metals by testing, as follows:

- magnetism non-magnetic
- spark test non-sparking
- colour silvery-white
- weight lighter than lead, tin, zinc alloys
- grain structure uniform light grey grains
- oxy-flame test does not 'flare'.

Aluminium is often difficult to distinguish from zinc die castings and magnesium alloys. However zinc die casts, when fractured, often exhibit shiny pores (fish eyes) in their grain structure, and magnesium filings 'flare' and burn when subjected to the oxy flame test.

#### Uses of aluminium

Aluminium is often selected for use in the fabrication industry where its properties of light weight and corrosion resistance can be used to advantage.

Typical uses of aluminium alloys are aircraft, boats, truck bodies, storage vessels, lightweight castings and extrusions.

Certain factors may limit the usage of aluminium. Among these are:

- high temperature service
- where hardness is required
- where fatigue stresses are present
- corrosive media such as hydrochloric acid, sodium hydroxide or nitric acid
- cost.





# **Classification of aluminium alloys**

At least eight elements, in various combinations, are commonly used to produce aluminium alloys. The aluminium alloys available to industry offer a remarkably wide range of properties. To aid the selection of an appropriate aluminium alloy, the Aluminium Development Council of Australia (ADC) has produced a system of classification.

Aluminium alloys are divided into eight basic groups (or series), according to alloy composition, as follows.

Alloy	Major alloying element	Alloy series		
aluminium (	1000			
	copper	2000		
	manganese	3000		
	silicon	4000		
Aluminium alloys grouped by major alloying elements	magnesium	5000		
	magnesium and silicon	6000		
	zinc	7000		
	other elements	8000		

#### Table 6.1 – Aluminium alloys by composition

These alloys can be briefly described as follows.

1xxx series	Pure aluminium for applications requiring excellent corrosion resistance, high conductivity and good workability.
	Low strength and readily weldable.
2xxx series	High strength but lower corrosion resistance.
	Difficult or impossible to weld by the common welding processes.
3xxx series	Good workability, moderate strength, and readily weldable.
4xxx series	Silicon lowers melting point without producing brittleness.
	A major use is for filler rods for welding and brazing.
5xxx series	Moderate to high strength – good corrosion resistance in marine environments.
	Readily weldable.
6xxx series	Moderate strength, good formability, corrosion resistance.
	Readily weldable.
7xxx series	High strength – difficult to weld.
	Medium strength – limited weldability.
clad alloys	Cladding is a means of having a highly corrosion resistant surface with a high strength centre.
	Weldability depends on alloys used and type of joint.

#### Table 6.2 – Properties and uses of aluminium alloys



Of the aforementioned groups, the 2000, 6000 and 7000 series are heat treatable, and may be heat treated to produce high strength alloys. Of these, the 2000 and 7000 series alloys exhibit poor weldability and are generally not welded.

## **Common grades**

There are many commercial aluminium grades available. However, the range available 'ex-stock' is generally limited to the following.

	Alloy characteristics	Corrosion resistance	Form	Temper	Tensile strength MPa	Yield strength MPa min	Elongation min %	Typical application
5005	moderate strength	very good	sheet plate	H14	160	150	6	general purpose material
	anodises well	9000	pierce	H36	180	165	6	
5251	medium	very	sheet	0	185	75	24	general fabrication
	strength	good	sheet	H36	270	230	6	and pressure vessels
5083	high	very	plate	0	290	145	22	structural plate and
	strength	good	plate	H321	315	230	16	marine fabrication
	good weldability			H323	325	250	10	
6063	extrudes	very	ext	T1	150	90	20	general purpose
	well	good		T5	220	180	12	and architectural extrusions
	good weldability			T6	240	215	12	

Table 6.3 – Availability of aluminium alloys



- The above 5000 series alloys are supplied as sheet and plate.
- 6063 is supplied in the form of extrusions.
- Sheets supplied up to 4 mm thick may be plastic coated.

# Weldability of aluminium alloys

The commonly fabricated 5000 series and 6000 series alloys are readily welded by the inert gas shielded arc welding processes, and by other processes to a lesser extent.

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Factors which tend to reduce the weldability of aluminium alloys are:

- surface oxide
- low melting point
- high thermal conductivity
- high co-efficient of linear expansion
- hot shortness
- solubility of hydrogen.

#### Surface oxide

Aluminium gains its corrosion resistance from the oxide film that forms on the surface when exposed to the atmosphere. While pure aluminium melts at 660 °C, the melting temperature of the oxide is much higher at 2040 °C. This leads to welding problems in two major ways.

- Lack of fusion defects where the oxide film prevents adequate fusion to the base metal.
- Collapse of the weldment particularly where heat input is slow, such as in oxy-fuel gas welding. A considerable amount of the base metal may be melted, supported only by the surface oxide on the underside of the plate. Eventually, the weight of molten aluminium may break the oxide film, leading to collapse of the weldment.





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#### Low melting point

The low melting point of aluminium sometimes makes control of the welding process difficult.

# High thermal conductivity

The high thermal conductivity leads to rapid heat loss from the weld zone. This may lead to lack of fusion defects, particularly at the start of a weld bead. Rapid freezing of the weld metal also leads to the comparatively high levels of porosity that are associated with welds in aluminium. The high thermal conductivity may also necessitate extensive use of pre-heat.

## High co-efficient of expansion/hot shortness

Hot cracking is a common problem when welding aluminium alloys.

The high weld shrinkage and lack of ductility of the hot metal combine to render the metal unable to yield to absorb shrinkage forces. Common crack types are centreline and crater cracks.

## Absorption of hydrogen

In the hot condition, aluminium will dissolve large amounts of hydrogen. As the metal cools, hydrogen comes out of solution and forms gas pores in the microstructure. Levels of porosity may be extreme, causing a serious loss of cross-sectional area of the weld. It is essential that aluminium is cleaned prior to welding, and that all possible sources of hydrogen via the welding process are eliminated.



# Copper and its alloys

Copper is a reddish-brown coloured, corrosion resistant, highly conductive, non-magnetic metal.

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Its melting point is 1083 °C and its density is 8940 kg/m<sup>3</sup>.

Copper is work-hardenable and may be annealed by heating and quenching.

**Uses** – The main uses of copper are electrical, plumbing and heat exchanger applications.

**Grades** De-oxidised copper – good weldability.

Tough pitch copper – limited weldability.

Oxygen-free copper - good weldability.

#### Weldability

The weldability of copper is limited by three factors.

- The presence of oxygen results in cuprous oxide forming at the grain boundaries, leading to cracking. Fusion welding should be restricted to de-oxidised or oxygen-free copper.
- High thermal conductivity necessitates that pre-heat be used in most cases (400-700 °C).
- Annealing of the weld zone accompanied by a reduction in mechanical properties. Hot peening of the weld zone may be required.

Copper is commonly alloyed with other elements to produce a range of useful metals. The common alloys are:

- brasses alloys of copper and zinc
- bronzes alloys of copper and tin
- cupronickels alloys of copper and nickel.

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# Brass

**Cartridge brass** – 70% Cu/30% Zn. Ideal for cold forming operations such as stamping, drawing, or spinning.

Muntz metal – 60% Cu/40% Zn. More yellow in colour than cartridge brass. Cold short.

# Weldability of brass

The major problem associated with welding brass is the loss of zinc, as zinc boils at 910 °C. This leads to porosity and a loss of strength. To control this zinc loss, filler rods have small quantities of aluminium or silicon added. This forms a skin over the weld pool, and helps to stop the zinc boiling off.

# Formability

Brass that contains in excess of 68% copper is hot short, while brass containing less than 68% copper is cold short.

# Bronze

Bronze is an alloy of copper and tin. The addition of tin to copper increases hardness, wear resistance, and resistance to salt water corrosion.

**Tin bronze** - 1% - 15% Sn. Commonly referred to as phosphor bronze because of the addition of tin, which acts as a de-oxidiser.

**Aluminium bronze** – 5%–11% Al. Whitish in colour. Alloys containing above 10% aluminium are heat treatable to produce high strength alloys.

**Silicon bronze** – up to 5% Si. The strongest of the non-heat treatable bronzes. They have good workability, and are readily weldable.

## Weldability of bronzes

Tin bronze – oxidises easily. Phosphor de-oxidised filler is generally used.

**Aluminium bronze** – tends to be hot short, and is susceptible to cracking at high temperatures. PWHT may be required.

**Silicon bronze** – has good weldability. However, rapid cooling between 800 °C and 950 °C should be facilitated, to prevent hot cracking.



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# Copper/nickel alloys (cupronickel)

Cupronickels are alloys of copper and nickel, in which the major portion of the alloy is copper. Cupronickels may contain up to 30% nickel. They are non-heat treatable, and have excellent corrosion resistance, particularly to corrosion by salt water. The mechanical properties may be improved by cold working.

## Weldability of cupronickel

Cupronickels are readily welded by the gas shielded arc welding processes, and by silver brazing. They are prone to porosity as a result of contamination by oxygen and hydrogen during welding. Shielding gas flow rates may need to be increased slightly when compared to other metals.

Туре	Cu	Ni	Other	Description and uses
90/10 cupronickel	88	10	0.5 Mn 1.5 Fe	corrosion resistant used for coolers, tubes for salt water
70/30 cupronickel	68	30	1.0 Mn 1.0 Fe	strong resistance to corrosion and has high tensile strength used in tubes for salt water condensers, wire for electrical fuses

Table 6.4 – Copper nickel alloys





# Nickel and its alloys

## Nickel

Chemical symbol	Ni
Colour	silvery white
Melting point	1452 °C
Density	8800 kg/m³
Coefficient of linear expansion	0.000013
Thermal conductivity	between Fe and Al
Magnetism	slightly

Pure nickel is available in several grades between 94–99.95%

#### Uses

Nickel is tough, ductile, and corrosion, oxidation, and creep resistant. Common applications of nickel are:

- food handling equipment
- chemical plant
- heating coils
- evaporators
- marine fabrications.

## Monel

Composition	65% Ni
	28% Cu
	Mn and Fe

Monel exhibits high resistance to corrosion by acids and salt water. It is tougher, cheaper, and stronger than nickel.

#### Uses

- food handling equipment
- heat exchangers
- offshore structures
- turbine blades, bolts, screws, shafts.





# Nimonic

 Composition
 Ni 57% or 75%

 Cr 20%

Fe, Ti, Al, Co

Nimonics are high strength, high temperature alloys. They have excellent resistance to corrosion, creep, oxidation, and scaling at high temperatures.

#### Uses

- pumps, valves, springs
- turbine blades, aircraft engine parts
- vessels, chemical plant.

# Inconel

Composition	Ni 32–76%
	Cr 15–20%
	Fe 7–46%
	Al, Ti, Mn

Highly resistant to corrosion and oxidation, these alloys maintain strength and toughness from sub-zero to elevated temperatures.

#### Uses

- food and chemical plant
- heat exchangers
- furnace parts and equipment
- turbine blades
- aircraft manifolds.

Grade	Ni%	Cr%	Cu%	C%	Fe%	Mn%	Al%	Ti%
Nickel 200	99.5	-	_	0.06	0.15	0.25	-	-
Nickel 201	99.5	_	_	0.01	0.15	0.20	_	_
Nickel 205	99.5	_	_	0.06	0.10	0.20	_	_
Monel 400	66.0	_	31.5	_	1.35	0.90	_	_
Monel 404	55.0	_	44.0	_	_	_	_	_
Monel 500	65.0	_	29.5	-	1.00	0.60	2.73	0.60
Nimonic 80	74.5	20.0	0.05	0.05	0.05	0.55	1.30	2.50
Nimonic 90	57.0	20.5	0.05	0.05	9.50	0.05	1.65	2.60
Inconel 600	76.0	15.85	0.10	0.04	7.20	0.20	—	—
Inconel 601	60.5	23.0	_	0.05	14.0	_	1.35	_
Incoloy 800	32.0	20.0	_	0.04	46.0	_	_	_

#### Table 6.5 – Nickel alloys



# Welding of nickel alloys

#### Weldability

When nickel alloys are brought into contact with sulphur at temperatures above 240 °C, they are highly susceptible to hot cracking. Cracking can also result from the presence of lead, phosphorus and other low melting point substances that are commonly found in grease, paint, crayons, cutting fluid, inks, lacquers etc. Where possible, the use of such substances should be avoided during fabrication.

It is **imperative** that thorough cleaning is carried out prior to welding.

Distortion levels are similar to those of stainless steel. Preventative measures must be taken.

## Welding recommendations

- Thorough cleaning.
- Use of jigs and fixtures.
- Low heat input.
- Close tacks.
- Short arc lengths.

## Titanium

Titanium is a lightweight, non-magnetic metal, which is silvery-grey in colour. It has excellent corrosion resistance, and when alloyed has a high strength-to-weight ratio.

Chemical symbol	Ti
Colour	silvery-grey
Melting point	1670 °C
Density	4500 kg/m <sup>3</sup>
Ultimate tensile strength	315 MPa
Magnetism	non-magnetic

#### Grades

Pure titanium is relatively soft and weak. Its applications are generally restricted to those applications that take advantage of its excellent corrosion resistance, but do not have a high strength requirement. Titanium is commonly alloyed with elements such as aluminium, chromium, zinc, iron, manganese, tin, vanadium and molybdenum. Titanium alloys exhibit high strength-to-weight ratios, good creep resistance, and excellent corrosion resistance up to 250 °C.

## Uses

The major uses for titanium alloys are in the chemical, marine, and aerospace industries, in applications which take advantage of the strength, lightweight and corrosion resistance of titanium alloys.


#### Weldability

Processes such as RW and GMAW may be used to weld titanium and its alloys. However, GTAW has become the most popular process. Although titanium has excellent corrosion resistance up to 250 °C, above this, titanium is highly reactive with oxygen, hydrogen, nitrogen and other contaminants.

The major challenge when welding titanium and its alloys is to prevent contamination of the parent metal. The weld should be gas shielded until it has cooled to below 400 °C. To facilitate this, trail gas shielding is commonly used.

Sound welding procedures will result in welds with excellent mechanical properties.



Fig 6.2 – Trailing gas shielding device



#### Welding recommendations

- Thorough removal of all surface scale, grease and other surface contaminants is essential. This can be achieved by pickling, brushing with a clean stainless steel wire brush, and solvent cleaning with acetone or alcohol. The weldment should be cleaned for a distance equal to ten times the plate thickness on either side of the weld, with a minimum of 25 mm.
- High purity shielding gasses must be used (minimum 99.995% pure). Argon, helium, or argon/helium mixtures may be used.
- Gas shielding must completely protect the weld until it cools to below 400 °C. Trail shielding devices and welding chambers are used to facilitate this.
- Filler rods should be cleaned using a cloth wetted with alcohol or acetone and once cleaned, the filler rods and weldments should only be handled with clean cotton gloves.
- Backing gasses are essential, and weld support is desirable.
- Current for GTAW is DC negative.

Amperages are similar to those used for welding stainless steel.

#### Chapter 7 – Grain structure

#### Introduction

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

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

Additionally, metals that are composed of grains that are large in size will generally display poor mechanical properties, particularly in terms of malleability and ductility.

Grains form at elevated temperatures. Consequently the grain structure of a material can be changed by heat treatment and also by the heating/cooling cycle of welding. Control over changes in grain structure is important. Firstly it enables us to produce desirable properties in the metals we use and secondly to prevent the formation of undesirable grain structures due to welding.

Ideally, metals will have a grain structure which:

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



#### The formation of grains

- As molten steel cools, the temperature of the metal falls until the solidification temperature of around 1500 °C is reached.
- At various points throughout the metal where the solidification temperature has been reached, nuclei (or seed crystals) begin to form in the molten metal.
- Nuclei continue to form where the temperature has fallen to the solidification temperature. The addition of grain refining elements (or grain formers) such as nickel or aluminium encourage a larger number of seed crystals to form, resulting in a finer grain structure.
- These nuclei begin to grow in six directions along axes at right angles to each other. These structures are known as dendrites. As the growth of these dendrites continues (dendritic growth), secondary arms begin to grow at right angles to the first. In turn, arms grow in a third direction; at right angles to the second and so on. These dendrites will continue to grow in an outward direction, until their growth is restricted by that of their neighbours. From this point, continuing growth is internal and will continue until the space between the arms of the dendrites is packed tight and a solid grain is formed (Fig 7.1).





Fig 7.1 – Growth from a nucleus

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- If the temperature of the cooling metal falls rapidly to the solidification temperature, a large number of seed crystals will form. This means that less dendritic growth can occur before the dendrites meet their neighbours and a fine grain structure will result.
- If cooling to the solidification temperature is slow and/or uneven, the points at which seed crystal form will be fewer and considerable growth of the dendrites will occur, resulting in a coarse grain structure.

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

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

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

The crystals formed are extremely elongated, having their lateral growth greatly reduced owing to early contact being made with adjacent crystals growing in the same direction. Such crystals are known as **columnar crystals** and may often be found in some types of weld metal deposits.

The continuation of heat loss from the mass of molten metal will so reduce the internal temperature that simultaneous freezing of the remaining molten metal will now take place. Hence a third type of crystal will begin to form.

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

The sectional view of the cast ingot (Fig 7.2) clearly shows the crystal structure of the cast pure metal.



#### Fig 7.2 – Grain formation in a cast ingot



During cooling from the molten state, the temperature will fall until the solidification temperature is reached. However the temperature will not fall below this point until solidification is complete. Once solidification is complete, the temperature will once again begin to fall. The graph shown in Fig 7.3 shows temperature plotted against time during the cooling of a molten metal.



Fig 7.3 – Time/temperature graph for solidification

Once solidification has occurred, the final grain structure of the metal is dependent on chemical composition and heat treatment.







#### Effects of welding on the grain structure

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

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

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

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

The zone which has been heated to between the UCT and the lower critical temperature (LCT) will undergo partial transformation.

Adjacent to this will be parent metal which has not been heated to a temperature high enough for any transformation to take place and therefore the grain structure will remain unchanged. This can be seen in Fig 7.4.



Fig 7.4 – Changes in grain structure as a result of welding

#### Multi-pass welds

The first pass in a multi-pass weld forms a grain structure composed of columnar crystals, similar to that of a single-pass weld. Providing the next pass is made whilst there is still heat in the weld zone, the second pass has the effect of re-heating and recrystallising the first pass, thus causing a refinement of the grains. A third pass refines the second pass and so on until the weld is completed. The weld reinforcement, which is considered surplus, has a coarse grain structure, but the weld metal considered for the effective strength is composed of refined grains, see Fig 7.5.



Fig 7.5 – Grain refinement in multi-pass welds

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

#### Grain growth

Grain growth is the term used to describe the actual growth of some grains by the absorption of adjacent grains (Fig 7.6).



Fig 7.6 – Grain growth

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

- slow cooling from the liquid to the solid state
- maintaining the metal at a high temperature for an extended period of time
- heating the metal to a temperature well above the recrystallisation temperature.



#### The effect of this grain growth upon the mechanical properties of the metal is:

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

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

Examples of welding processes which produce coarse grain structures are:

- electro slag welding
- submerged arc welding
- oxy-acetylene welding.

Each of these processes has a high heat input and slow cooling rates.

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

Steel which has suffered grain growth can be restored to its original structure by re-heating to just above its recrystallisation temperature and by controlling the cooling rate.

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#### The structure of steel

Steel is an alloy of iron and carbon. Iron is also known as **ferrite**. Ferrite is soft, weak and ductile. When carbon is added to iron, a compound called **iron carbide** is formed. Iron carbide is also known as **cementite**. Cementite is a hard, strong and brittle material.

The iron carbide, or cementite, forms a layered structure within some of the grains of ferrite. The number of grains in which this structure forms is dependent upon the amount of carbon that is added. The grains that have this layered structure are known as **pearlite**. In this structure, the iron carbide is supported by the ductile ferrite. This combination of both hard and ductile material within each grain result in a tough, strong material being formed. (Fig 7.7)



Fig 7.7 – Pearlite

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

When the carbon content exceeds 0.83%, the additional iron carbide which forms cannot be taken in to the grains. It resides at the grain boundaries and is known as **free cementite**. This brittle constituent at the grain boundaries results in decreasing toughness of the steel as more free cementite is formed.

Fig 7.8 summarises the changes to the grain structure which occur with increasing carbon content and shows the accompanying properties and uses.

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Low carbon Medium High carbon steel Tensile strength (MPa) Structural sections & plate, drop forgings Springs, shears, tools Dies, drills, taps, milling cutters **Brinell hardness** Saws, razors, files Coil, nails, wire drop forgings, Elongation Axles, gears, wire rope % 0.900 30 300 Tensile strength Brinell hardness 0.600 20 + 200 or Elongation 0.300 10 + 100 0.100 Cementite 0.80 Ferrite 0.60 Pearlite 0.40 0.20 0.0 0.5 0.6 0.7 0.8 0.9 0.1 0.2 0.3 0.4 1.0 1.1 1.2 Carbon % 0.83 Ē В С D Е А

Fig 7.8 – The relationship between carbon content, microstructure, mechanical properties and uses of plain carbon steels in the normalised condition

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- (a) Pure iron is composed wholly of ferrite and is soft, ductile and weak.
- (b) 0.25%C (low carbon steel) is composed of approximately 25% pearlite distributed evenly in a matrix of ferrite. The pearlite increases the tensile strength and hardness but there is a loss of ductility.
- (c) 0.6% (high carbon steel) is composed of approximately 60% pearlite. There is a further increase in strength and hardness but a notable decrease in the ductility. Because of this, welding is more difficult as the material is brittle and tends to crack.
- (d) 0.83%C (eutectoid steel) is composed wholly of pearlite and is even more brittle and therefore difficult to weld unless close attention is paid to heat input and cooling rate.
- (e) 1.1%C (hypereutectoid steel) is composed mainly of pearlite but with cementite forming at the grain boundaries. These steels are extremely hard and can only be welded after the steel is heat treated to soften it.

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



### Metals Reprication

#### Phases in steel

Steel is allotropic in nature. This means the patterns into which the atoms of the material arrange themselves (the atomic structure) is changeable and may exist in more than one form.

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

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

The two phases present in low carbon steels at ambient temperatures are ferrite and pearlite. Other phases of steel that are important are as follows.

#### Austenite

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

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

Because austenite can only exist in plain carbon steels at elevated temperatures, as the steel cools, it reverts back to a ferrite/pearlite structure or some other phase, depending on carbon content and cooling rate.

#### Martensite

A hard, brittle constituent that forms in steels that are cooled rapidly from elevated temperatures. For martensite to form, the steel must contain **at least 0.3% carbon**. Steels containing less than 0.3% carbon are not hardenable by heat treatment, as martensite is not formed during cooling. Phase changes in steel as a result of heat treatment are time/temperature transformations. That is, changes are a result of time and changes in temperature.

If a hardenable steel in the austenite condition is allowed to cool slowly through the transformation range, migration of the carbon will cause a return to the ferrite/pearlite structure with which we are familiar. If the cooling rate is too rapid, there is insufficient time for the transformation to ferrite/pearlite to occur. The carbon is then trapped in a hard, needle-like structure within some of the grains. This structure is known as **martensite** (Fig 7.9).

Chapter 7 – Grain structure



Fig 7.9 – Martensite

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

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



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#### Time/temperature transformation

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

A relatively simple version of this diagram showing the essential features when dealing with plain carbon steels is given in Fig 7.10.



Fig 7.10 – Iron/carbon equilibrium diagram

#### Essential features of the iron/carbon diagram

#### Lower critical temperature (LCT)

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

#### **Upper critical temperature (UCT)**

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

#### Eutectoid steel

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



#### Transformation zone

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

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

The phases within the transformation zone are:

- ferrite and austenite for steels below 0.83% carbon (hypoeutectoid steels)
- cementite and austenite for steels above 0.83% carbon (hypereutectoid steels).

#### The effect of heating and cooling

- If a hypoeutectoid steel (containing less than 0.83% carbon) is heated, no change in grain structure occurs until the LCT of 723 °C is reached, whereupon the pearlite present transforms to austenite.
- As the temperature continues to rise, the ferrite grains still present begin to dissolve into the newly formed austenite, until at the UCT all the ferrite is dissolved and the grain structure is entirely austenite.
- During the cooling of steel from high temperatures, no change in the austenite grain structure occurs until the UCT is reached. At this point, ferrite grains begin to grow as the ferrite comes out of solution in the austenite. The ferrite grains continue to form until the LCT is reached, at which point the remaining austenite transforms to pearlite. These changes can be seen in Fig 7.11.



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Fig 7.11 – Phase changes in hypoeutectic steel due to heating and cooling



#### Recrystallisation

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

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

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

The phase changes in steel are summarised in Fig 7.12.



Fig 7.12 – Phase changes in steel



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- **Point 1** Ferrite/pearlite structure in steel of approximately 0.4%C. Grain is irregular due to cold working.
- **Point 2** Heating to just below the LCT no change in grain structure.
- **Point 3** Within the transformation zone grain structure is ferrite and austenite, new grains growing out of old structure.
- **Point 4** Just above the UCT transformation is complete the structure is fine grained austenite. If cooling from this point is slow, a fine grained ferrite/pearlite structure will result (**Point 7**). If cooling is rapid, a fine grained ferrite/pearlite/martensite structure will result (**Point 6**).
- **Point 5** Metal is liquid at high temperature. No grains are present.
- **Point 8** Temperature falls to the solidification temperature seed crystals form, dendritic growth begins.

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

A fine grained ferrite/pearlite/martensite structure (**Point 6**) will result if cooling through the transformation zone is rapid.

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

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

#### Heat treatment

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

The commonly applied heat treatment processes are:

- annealing
- normalising
- hardening
- tempering.

In addition, heat treatment processes peculiar to welding are:

- pre-heat
- post-heat
- concurrent heating (intermediate)
- stress relieving.

#### Annealing

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

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

Holding time is variable, but never less than one hour per 25 mm of thickness. A heating/cooling temperature curve for annealing is given in Fig 7.13.









#### Normalising

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

A heating/cooling curve for normalising can be seen in Fig 7.14.



Fig 7.14 – Time/temperature curve for normalising

Normalising yields a finer-grained, slightly harder (because of distribution of pearlite) and stronger steel.

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

#### Fig 7.15 – The effect of normalising



#### Grain size after welding



Grain size after normalising







#### Hardening

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

A heating cooling curve for hardening can be seen in Fig 7.16.



Fig 7.16 – Time/temperature curve for hardening

#### **Quenching rate**

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

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





#### Tempering

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

Temperatures of between 200 °C and 600 °C are used, followed by quenching in a suitable medium such as oil or water. The higher the temperature from which quenching is carried out, the softer and more ductile the component will become.



Tempering is carried out below the LCT. A typical time/temperature curve for tempering is given in Fig 7.17.







#### Heat treatment processes peculiar to welding

#### **Pre-heat**

Pre-heat is the application of heat to a weldment prior to welding. The prime purpose of pre-heating is to slow the cooling rate as a means of reducing the likelihood of cracking.

Pre-heat is also employed as a means of distortion control and for drying wet plates prior to welding – however these are relatively minor applications for pre-heat.

#### Post-heat

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

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

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

#### **Concurrent heating**

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

#### **Stress relief**

Residual stresses in a metal from forming processes or from welding can lead to failure of the weldment, particularly if it is subjected to live (fatigue) type loading in service. Stress relief involves heating the component to  $75^{\circ}-125^{\circ}C$  below the LCT (usually around 600 °C), holding for a minimum time of one hour per 25 mm of thickness, followed by slow and uniform cooling in the furnace. Because heating is below the LCT, no re-crystallisation occurs, but residual stresses will be removed (Fig 7.18).



Fig 7.18 – Time/temperature curve for stress relief



#### Methods of heating

- Furnace The preferred method of heating where large components are to be heat treated, or where close control of the heating/cooling cycle is required. The evenness of temperature in furnaces is a decided advantage.
- Heating coils/blankets Heating coils and blankets, which can be wrapped around the job, are particularly popular for heating sections of a fabrication. These are heated by electrical resistance and are ideal for heating butt welds in piping and for on-site applications.
- Heating torches are best suited to heating small components, for site work and for pre-heating and post-heating of welds.

#### **Temperature measurement**

The most commonly used temperature measuring devices are:

- temperature sensitive crayons and paints
- thermocouples
- pyrometers.

#### Temperature sensitive crayons and paints

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





Fig 7.19 – Temperature sensitive crayons

#### Thermocouples

A thermocouple consists of two wires of dissimilar composition joined at the ends and attached to a voltmeter. The wires are made from dissimilar metals which change their potential voltage as the temperature changes. The scale of the voltmeter is graduated in degrees of temperature, giving a direct temperature readout.

For furnace heat treatment, the thermocouple is commonly attached to a chart, which will record the temperature cycle and give a printed readout.







#### **Optical pyrometers**

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



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#### Digital thermometer and non-contact thermometer

The use of non-contact thermometers with a laser sighting (refer Fig 7.22) or a digital thermometer with probes (Fig 7.23) has introduced new technology in the industry.

Non-contact is by the use of a laser beam (8:1) distance, for a temperature range of -50 °C to 550 °C.

Digital probe-types temperature range is -50 °C to 1300 °C.





Fig 7.22 – Laser beam digital thermometer



Photograph courtesy of Jaycar Electronics

Fig 7.23 – Digital thermometer with probes

#### Surface pyrometer

Pen-sized surface pyrometers (similar in size and shape to a pen) are pyrometers used to conveniently measure the surface temperature of metals. These pyrometers make use of liquid crystal technology, which is sensitive to heat and light variations.

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Appendix 1

# Metals and fabrication competency mapping

# Introduction to metallurgy – Weldability of metals

Book title	Chapter title	Comp code	Competency title	Full < Partial *
Introduction to Metallurgy	1. Carbon steels			
		MEM 5.16C	Perform advanced welding using MMAW process	*
		MEM 5.46B	Perform welds to code standards using MMAW process	*
		MEM 5.49B	Perform routine gas tungsten arc welding process	*
		MEM 5.19C	Weld using gas tungsten arc welding process	*
		MEM 5.20C	Perform advanced welding using GTAW process	*
		MEM 5.44B	Perform welds to code standards using GTAW process	*
		MEM 5.18C	Perform advanced welding using GMAW process	*
		MEM 5.43B	Perform welds to code standard using GMAW	*
		MEM 5.48B	Perform advanced welding flux-cored arc welding using FCAW process	*
		MEM 5.42B	Perform welds to code standard using FCAW	*
		<b>MEM 5.22C</b>	Perform advanced welding using OAW process	*
		MEM 5.44B	Perform welds to code standards using GTAW process	*
		MEM 5.45B	Perform pipe welds to code standards using manual metal arc welding process	*
		MEM 5.50B	Perform routine gas metal arc welding	*
		MEM 5.26B	Apply welding principles	*







Book title	Chapter title	Comp code	Competency title	Full < Partial <b>*</b>
		MEM 5.36C	Repair/replace/modify fabrications	*
		MEM 5.24B	Perform welding supervision	*
	2. Cast iron			
		MEM 5.16C	Perform advanced welding using MMAW process	*
		<b>MEM 5.20C</b>	Perform advanced welding using GTAW process	*
		MEM 5.18C	Perform advanced welding using GMAW process	*
		MEM 5.48B	Perform advanced welding using FCAW process	*
		MEM 5.26B	Apply welding principles	*
		MEM 5.36C	Repair/replace/modify frabrications	*
	3. Low alloy steels			
		MEM 5.16C	Perform advanced welding using MMAW process	*
		MEM 5.46B	Perform welds to code standard using MMAW process	*
		<b>MEM 5.20C</b>	Perform advanced welding using GTAW process	*
		MEM 5.44B	Perform welds to code standard using GTAW process	*
		MEM 5.18C	Perform advanced welding using GTAW process	*
		MEM 5.43B	Perform welds to code standard using MAW process	*
		MEM 5.48B	Perform advanced welding using FCAW process	*
		MEM 5.42B	Perform welds to code standard using FCAW process	*
		MEM 5.51A	Select welding processes	*

Book title	Chapter title	Comp code	Competency title	Full < Partial *
	4. Classification of alloy steels			
		MEM 5.16C	Perform advanced welding using MMAW process	*
		MEM 5.46B	Perform welds to code standard using MMAW process	*
		MEM 5.19C	Weld using GTAW process	*
		MEM 5.24B	Perform welding supervision	*
		MEM 5.26B	Apply welding principles	*
		MEM 5.36C	Repair/replace/modify frabrications	*
		MEM 5.45B	Perform pipe welds to code standards using MMAW process	×
		MEM 5.47B	Weld using FCAW process	*
		MEM 5.48B	Perform advanced welding using FCAW process	*
		MEM 5.51A	Select welding processes	*
	5. High alloy steels			
		MEM 5.16C	Perform advanced welding using MMAW process	*
		MEM 5.19C	Weld using gas tungsten arc welding process	*
		<b>MEM 5.20C</b>	Perform advanced welding using GTAW process	*
		MEM 5.26B	Apply welding principles	*
		MEM 5.24B	Perform welding supervision	*
		MEM 5.45B	Perform pipe welds to code standards using MMAW process	×
		MEM 5.46B	Perform welds to code standard using MMAW process	*
		MEM 5.47B	Weld using flux-core arc welding process	*







Book title	Chapter title	Comp code	Competency title	Full < Partial <b>*</b>
		MEM 5.48B	Perform advanced welding using FCAW process	*
		MEM 5.51A	Select welding processes	*
	6. Non-ferrous metals			
		MEM 5.19C	Weld using GTAW process	*
		MEM 5.20C	Perform advanced welding using GTAW process	*
		MEM 5.44B	Perform welds to code standard using GTAW	*
		MEM 5.43B	Perform welds to code standard using GMAW	*
		MEM 5.24B	Perform welding supervision	*
		MEM 5.26B	Apply welding principles	*
	7. Grain structure			
		MEM 5.24B	Perform welding supervision	*
		MEM 5.26B	Apply welding principles	*
		MEM 5.36C	Repair/replace/modify fabrications	*
		<b>MEM 6.3C</b>	Carry out heat treatment	*
		MEM 6.7B	Perform basic incidental heat/quenching, tempering and annealing	*
		MEM 5.51A	Select welding processes	*
				*
				*

## Advanced welding

WA (customisation to suit local conditions is however encouraged). These pathways meet the guidelines of the MEM05 Training Package. This pathway was specifically designed to meet the needs of the metal fabrication and welding industry after industry consultation, WTIA involvement and TAFE WA moderation sessions held in 2006. This pathway is also designed to be common across all colleges of TAFE Certificate III in Engineering Fabrication (Welding) Certificate IV in Engineering Welding pathway across TAFE WA from January 2007. This resource is specifically designed to provide basic underpinning knowledge related to a number of competency units used in the

# Context of assessment

Assessors are reminded the individual units may be assessed on the job, off the job or a combination of both on and off the job. Where assessment occurs off the job, that is the candidate is not in productive work, then an appropriate simulation must be used where the range of conditions reflects realistic workplace situations.

# Project work, integration

These units could be assessed in conjunction with mandatory units addressing the safety, quality, communication, mathematics etc. Units may also be assessed with other units requiring the exercise of the skills and knowledge.

# Method of assessment

Assessors should gather a range of evidence that is valid, sufficient, current and authentic. Evidence can be gathered through a variety of ways including direct observation, supervisor's reports, project work, samples and questioning. Questioning should not require language, literacy and numeracy skills beyond those required in this unit. The candidate must have access to all tools, equipment, materials and documentation required. The candidate must be permitted to refer to any relevant workplace procedures, product and manufacturing specifications, codes, standards, manuals and reference materials.

# **Consistency of performance**

Assessors must be satisfied that the candidate can competently and consistently perform all elements of the units as specified by the criteria, including required knowledge, and be capable of applying the competency in new and different situations and contexts È

Metallurg

### **INTRODUCTION TO METALLURGY**

#### Weldability of Metals

#### DESCRIPTION

This resource supports learners to develop introductory-level skills and knowledge in the area of metallurgy and weldability of metals. Specifically, it explains different types of metals used in the welding and fabrication trade, and their applications. It relates to a number of competency units used in the Engineering Tradesperson Fabrication learning pathway

Topics covered include the following.

- Carbon steels
- Cast iron
- Low alloy steels
- Classification of alloy steels
- High alloy steels
- Non-ferrous metals
- Grain structure

The book is divided into separate chapters, each containing workshop-based activities that will provide opportunities for practice before assessment. Detailed graphics, technical drawings and photographs are provided throughout the book to support learners.

EDITION 2007

CATEGORY Metals & Engineering

TRAINING PACKAGE • MEM05

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