

Chapter 1

WELDING PROCESSES

1.1 INTRODUCTION TO WELDING PROCESSES

Modern welding technology started just before the end of the 19th century with the development of methods for generating high temperature in localized zones. Welding generally requires a heat source to produce a high temperature zone to melt the material, though it is possible to weld two metal pieces without much increase in temperature. There are different methods and standards adopted and there is still a continuous search for new and improved methods of welding. As the demand for welding new materials and larger thickness components increases, mere gas flame welding which was first known to the welding engineer is no longer satisfactory and improved methods such as Metal Inert Gas welding, Tungsten Inert Gas welding, electron and laser beam welding have been developed.

In most welding procedures metal is melted to bridge the parts to be joined so that on solidification of the weld metal the parts become united. The common processes of this type are grouped as fusion welding. Heat must be supplied to cause the melting of the filler metal and the way in which this is achieved is the major point of distinction between the different processes. The method of protecting the hot metal from the attack by the atmosphere and the cleaning or fluxing away of contaminating surface films and oxides provide the second important distinguishing feature. For example, welding can be carried out under a shield comprising of a mixture of metal oxides and silicates which produce a glass-like flux, or the whole weld area may be swept clear of air by a stream of gas such as argon, helium or carbon dioxide which is harmless to the hot metals.

There are certain solid phase joining methods in which there is no melting of the electrodes, though heat is produced in the process. The melted and solidified cast metal is normally weaker than the wrought metal of the same composition. In the solid phase joining such melting does not occur and hence the method can produce joints of high quality. Metals which are dissimilar in nature can also be readily welded by this process. In the normal process joining of dissimilar metals will present problems because of the brittle intermetallic compounds formed during melting. Since the work pieces are closely pressed together, air is excluded during the joining process.

The welding processes covered in this chapter are gas welding, arc welding which includes manual metal arc welding (MMA), tungsten inert gas shielded arc welding (TIG), gas metal arc welding (MIG, MIG/CO₂), submerged arc welding (SAW), etc. High energy density processes like electron beam welding, laser beam

2 Welding Technology and Design

welding, plasma welding are also dealt with. Pressure welding and some special welding techniques like electro-slag welding etc. are also discussed in detail. Figure 1.1 shows the broad classification of the welding processes.

Though the different processes have their own advantages and limitations and are required for special and specific applications, manual metal arc welding continues to enjoy the dominant position in terms of total weld metal deposited. The TIG process produces the finest quality weld on all weldable metals and alloys. The arc temperature may be upto 20,000 K. Although TIG welding produces the highest quality welds, it is a slow and expensive process. Metal inert gas welding process (MIG) is economical with consumable electrode fed at a predetermined rate.

Plasma arc welding (PAW) has made substantial progress in utilising the high heat energy of an ionised gas stream. The jet temperature can be as high as 50,000 K. Foils down to a thickness of 0.01 mm can also be welded in this process and hence this process is more useful in electronic and instrumentation applications.

All the processes like TIG, MIG and PAW can be successfully used for either semi-automatic or automatic applications. But they are all open arc processes where radiation and comparatively poor metal recovery put a limit on using high currents. High productivity and good quality welds can be achieved by submerged arc welding process with weld flux and wire continuously fed. The slag provides the shielding of the weld pool with provision for addition of alloying elements whenever necessary.

Electron beam welding and laser welding are classified under high energy density processes. Figure 1.2 shows the heat intensity (w/sq.cm) and heat consumption (wh/cm) for different welding processes discussed above.

For efficient welding the power source should provide controlled arc characteristic necessary for a particular job. In one case a forceful deeply penetrating arc may be required, while in another case, a soft less penetrating arc may be necessary to avoid "burn through". The welding process will also require a particular type of power source. Table 1.1 gives the power source required for widely used welding process. The process details are discussed in the following:

Table 1.1 Power source for arc welding process

<i>Process</i>	<i>Output Characteristics</i>	<i>Current</i>	<i>Polarity</i>
Shield metal arc, TIG, Submerged arc*	variable voltage	AC or DC	DCSP DCRP AC
Flux cored	constant voltage	DC	DCSP DCRP
Gas Metal arc	constant voltage	DC	DCRP

*In some applications, the SAW process can use constant voltage DC also.

4 Welding Technology and Design

Fig. 1.2. Heat intensity and heat consumption for different welding processes

1.2 DETAILS OF WELDING PROCESSES

1.2.1 Gas welding

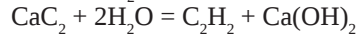
The most important process in gas welding is the oxygen in the oxygen-acetylene welding. Other fuel gases are also employed in the place of acetylene. The temperature ranges for different fuel gases are given in Table 1.2.

Table 1.2 Temperature ranges for different fuel gases

<i>Fuel gases</i>	<i>Max. Temp °C</i>	<i>Neutral Temp °C</i>
Acetylene	3300	3200
Mythyl acetylene	2900	2600
propadiene		
Propylene	2860	2500
Propane	2780	2450
Methane	2740	2350
Hydrogen	2870	2390

Oxy-acetylene welding process can be used for joining a variety of metals. Oxygen gas is produced from commercial liquefaction of air. The liquid air is allowed to boil and when nitrogen and argon escape, pure liquid oxygen is left with. The gas is compressed in cylinders at a pressure of 15 MPa.

Acetylene gas (C_2H_2) is produced by the reaction of calcium carbide (CaC_2) with water (H_2O).

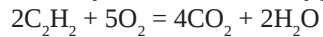


Acetylene gas has the tendency to explode if the pressure is increased. So the gas is dissolved in acetone ($CH_3-CO-CO_3$) liquid which acts as a solvent for the gas. One volume of acetone can absorb about 25 volume of acetylene per atmosphere. The acetylene gas is usually compressed at 1.7 MPa.

The acetylene cylinder will be packed with porous calcium silicate, so that the liquid is distributed in fine form and the gas is absorbed in an effective way. The cylinders are fitted with fusible safety plugs made of a low melting alloy (melting point around $97^\circ C$) which will allow the gas to escape if the cylinders are exposed to excessive heat.

Flame characteristics

When acetylene burns with oxygen the reaction can be given in the form



Thus one volume of acetylene combines with 2.5 volume of oxygen. But in practice, the volume ratio will be 1:1 from cost point of view.

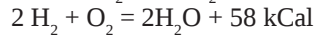
Fig. 1.3 Combustion zones in gas welding

The normal combustion zones are shown in Fig. 1.3. The flame has two zones—an inner zone where the temperature will be high and is governed by the primary reaction



6 Welding Technology and Design

and an outer zone where the carbon monoxide (CO) formed by the above reaction will combine with oxygen according to the secondary reaction



Thus combustion takes place in two stages.

1. Oxygen and acetylene (O_2 and C_2H_2) in equal proportions by volume, burn in the inner white cone. In the cone the oxygen combines with the carbon of the acetylene to form CO, while hydrogen is liberated.

2. On passing into the outer envelope of the flame, two separate reactions take place as combustion is completed. The carbon monoxide combines with oxygen from the atmosphere and burns to form carbon-di-oxide CO_2 . The hydrogen also burns with O_2 from the atmosphere to form water vapour H_2O .

Depending on the ratio of $\text{C}_2\text{H}_2 : \text{O}_2$, three types of flame can be obtained as given below:

1. Reducing flame when $\text{C}_2\text{H}_2/\text{O}_2$ is greater than one.
2. Neutral flame when $\text{C}_2\text{H}_2/\text{O}_2$ is equal to one.
3. Oxidising flame when $\text{C}_2\text{H}_2/\text{O}_2$ is less than one.

The reducing flame (also called carburising flame) will have unburned carbon which may be added to the weld during welding. Carburising flame may be fit for welding high carbon steel or for carburising the surface of low carbon or mild steel.

Neutral flame is invariably used for welding of steels and other metals. In oxidising flame the inner zone becomes very small and a loud noise will be induced. Oxidising flame gives the highest temperature possible. The maximum temperature of oxy-acetylene flame is $3100\text{--}3300^\circ\text{C}$ and the center of this heat concentration is just off the extreme tip of the white cone. Oxidising flame will introduce oxygen into the weld metal and so not preferred for steel. A slightly oxidising flame is used for welding copper base alloys, zinc base alloys, cast irons and manganese steels.

The welding torch has a mixing chamber in which oxygen and acetylene will be mixed and the mixture is ignited at the torch tip. The pressure of oxygen and acetylene can be equal and the hand valves are adjusted to get supply of gas under sufficient pressure to force in into the mixing chamber. Torches are also designed to operate with low acetylene pressure to enable to draw more completely the content from the acetylene cylinder. To extinguish the flame, the fuel gas should be turned off first followed by the oxygen. In the event of back fires, the oxygen should be turned off first to prevent the internal temperatures from being excessively high and damage the blow-pipe.

While welding plates of thickness less than 3mm, no filler wires are used. Such welding is known as puddling.

For larger thickness of plates a filler rod is used. The filler rod is held at approximately 90 degrees to the torch. When selecting the filler rod the following working formula may be used.

upto 5 mm thick (butt weld) $D = T/2$

for Vee welds upto 7 mm $D = T/2 + 0.8 \text{ mm}$

T is the thickness of the plate in mm and D is the filler rod diameter in mm.

Welding can be carried out in two ways. One is that in which the torch moves in the direction of welding with the torch inclined at 65 deg. to the weld deposit. This is known as forehand technique. In the back hand technique the torch will be inclined at 45 deg. to the unweld region as shown in Fig. 1.4.

Fig. 1.4 Welding methods in gas welding

In gas welding full penetration upto about 10 mm thickness can be obtained and a single pass welding can be done. The weld geometries for different thicknesses are shown in Fig. 1.5.

Fig. 1.5 Weld geometries for different thicknesses in gas welding
(Sources: A.C. Davies, The Science and Practice of Welding, Vol 2,
Cambridge University Press, N.Y., 1989)

8 *Welding Technology and Design*

A weld puddle is established first by the gas torch. Then the torch is moved forward in different shapes, such as circular path, zig-zag path, oscillating path etc., ensuring in each case that sufficient time is given to obtain maximum penetration.

Gas welding is more suitable for thin plates and sheets as its flame is not as piercing as that of arc welding. Welding time is also comparatively longer in gas welding and heat affected zone (HAZ) and distortion are larger than in arc welding. The gases which are generally expensive are to be properly stored.

Oxy-acetylene flame can also be used for cutting operations, known as flame cutting. When iron is heated to a temperature of about 750-870°C, it reacts rapidly with oxygen to form iron oxide whose melting point is lower than that of steel. The heat generated will be sufficient to melt iron oxides and also some free iron. The cutting torch has a central orifice of oxygen jet surrounded by several orifices of oxygen-acetylene mixture to produce the required heating. Thus oxygen supply is ensured for the formation of iron oxides during the cutting operation.

1.2.2 Fusion arc welding

1.2.2.1 Shielded metal arc welding (SMAW) and submerged arc welding (SAW)

Shielded metal arc welding

Shielded metal arc welding (SMAW) is a manual process of welding and is a common and versatile method used for joining shapes that cannot be easily set up for automatic welding methods. In this method a solid electrode with an extruded backed-on-coating material is used. A typical SMAW method is shown in Fig.1.6. The arc is struck by short circuiting the electrode with the work piece. Welding current is chosen according to the electrode diameter, type of electrode, and the kind of welding job. The arc voltage is determined as function of the arc length. In MMA it will be very difficult to keep a uniform arc length. When welding with

Fig. 1.6 Shielded metal arc welding
(Courtesy : Welding Hand Book AWS, USA, 1966)

basic electrodes, where metal transfer causes short circuit, the dynamic short circuit current has to be limited to avoid evaporation and blowing apart of the drop. The weight of the weld metal deposited per unit time is proportional to the current intensity. The electrodes are thoroughly dried or baked after production, because moisture will cause an unstable arc, heavy spatter and porosity in the weld metal.

The coating of the electrode has got several functions :

- (a) Electrode material burns off faster than the coating flux that forms a crucible and this shields the arc from the atmosphere.
- (b) Flux removes the impurities from the molten metal.
- (c) A gaseous envelope developed by the decomposition of the ingredients of the flux covers the molten weld pool, thereby protecting it from atmospheric contact.
- (d) During cooling, the slag formed on the top of the weld metal acts as a protective cover against contamination by the atmosphere.
- (e) It provides alloy addition to the weld metal.

Flux also (a) helps to start and maintain the arc, (b) helps to deoxidise and refine the weld metal, (c) helps to control the weld bead profile and reduce the weld spatter, (d) helps to control viscosity of the slag so that vertical and overhead welding is made possible. Arc voltage and current intensity, thermal energy and mode of metal transfer are controlled by the coating.

The electric power source can be AC transformer or DC generator. Carbon steels from 3 mm to 60 mm can be welded easily with work piece as one polarity. Power sources of constant current type having drooping characteristics are used for MMAW process. Power sources of the constant voltage type are not suitable.

The heat developed by the arc is given by

$$W \text{ (joules)} = V \text{ (volt)} \times A \text{ (amps)} \times t \text{ (sec)}$$

If the arc is travelling at a speed of S mm/minute, the heat input rate (HIR) of the arc will be

$$\text{HIR} = V \times A \times 60/S \text{ Joules/mm length of the joint.}$$

Though AC or DC power source can be successfully used, DC power source is suitable for all types of electrodes. With AC source some non-ferrous type and a low hydrogen ferritic type electrodes may not give a stable arc. Both starting and maintaining a short arc will be easier with DC power. Vertical and overhead welding on thick sections will be easier with DC. In DC straight polarity (*i.e.* electrode negative) can be used for MMAW of all steels; but not for non-ferrous metals. With straight polarity, more of the arc heat is concentrated on the electrode and consequently melting and deposition rates are higher, welding is more rapid and the work piece is less susceptible to distortion. Reverse polarity (electrode positive) is used with basic low hydrogen electrodes and for most non-ferrous metals. For sheet metal welding, D.C. straight polarity minimises burn-through problems because of its shallow penetration. D.C. however, can cause problems of arc blow, specially so when welding ends of joints, corners etc. A.C. does not present such problems.

10 Welding Technology and Design

The electrode size refers to the diameter of its core wire. Current range depends on the diameter of the electrode. For light job where over-heating must be avoided, small size electrodes (*e.g.* 1.6mm - 2mm) can be used with current 25 amps to 40 amps. For heavy work where maximum heat for adequate fusion is necessary, electrodes of large size and high current capacity *e.g.*, 5 mm - 6.3 mm with 240 - 320 amps can be used.

The core wire is rimming quality steel. Semi-killed or fully killed steel which gives the best performance is also used as it is cheap to produce. Rimming is the method of deoxidizing the steel in the final stages of its production. The silicon content of rimmed steel is 0.03%, in semi-killed steel it varies from 0.03 - 0.1% and in killed steel it is over 0.1%. In the selection of electrode quality wire, the silicon content should not exceed 0.03%. Rimming quality steel will give good arc stability, uniform melting, fine globular metal transfer. Sulphur in the core wire has to be controlled (0.03%) as otherwise, it will lead to hot cracking. Manganese addition (upto 1%) will suppress the harmful effects of sulphur.

Standards are available regarding the types of electrodes to be used in MMA welding for different kinds of steel. Following are some typical examples:

AWS A5.1	1981	Specifications for carbon steel covered arc welding electrodes.
IS 815	1974	Covered electrodes for metal arc welding of structural steels.
AWS A5.5	1981	Low alloy steel covered electrodes
IS 1395	1982	Low and medium alloy steel covered electrodes.
AWS 5.4	1981	Corrosion resisting Chromium and Chromium Nickel covered electrodes (IS 5206 - 1969)

The electrode standards prescribe the tensile and impact properties and other supplementary tests which are not related to the code symbols, but are meant to evaluate the performance of an electrode and its suitability for welding certain grades of steel.

In welding high carbon and alloy steels, difficulties may be encountered due to increased hardness and reduced ductility. Electrode core wire of the same composition as that of base metal should be preferred. Craters should never be left unfilled. Low alloy steel electrodes are mostly basic low-hydrogen type covering with or without the addition of iron powder.

Chromium steels should be preheated to 280-320°C and annealed after welding to restore normal hardness. Since chromium easily combines with oxygen to form oxides, the electrodes coating should produce fluid slag which can dissolve the chromium oxides.

In the case of chromium-nickel steels, the holding time at high temperature and the heat input should be reduced to a minimum. Titanium or Niobium should be added with the core wire of the electrode and titanium oxide is the usual flux material. Because of its high electrical resistivity stainless steel electrodes get rapidly overheated during welding. So the welding currents are lower (20 - 30%) for a given size than for ordinary mild steel. D.C. power supply with electrode positive is preferred for stainless steel electrodes as this will help good fusion of the electrode due to high liberation of heat. The ferrite number of stainless steel electrode should be in the range of 4 to 10.

MMA welding technique can also be used for improving surface properties of certain components like resistance to friction, wear, impact, abrasion, erosion, oxidation and corrosion. In such cases surfacing electrodes - also known as hard facing electrodes—are used as the filler rod. This technique can also be used for building of worn—out components.

Submerged arc welding (SAW)

Submerged arc welding is a method in which the heat required to fuse the metal is generated by an electric current passing through between the welding wire and the work piece. The tip of the welding wire, the arc and the weld area are covered by a layer of granular flux. A hopper and a feeding mechanism are used to provide a flow of flux over the joint being welded. A conveyor tube is provided to control the flow of the flux and is always kept ahead of the weld zone to ensure adequate supply of flux ahead of the arc.

Figure 1.7 shows a typical SAW process. The intense heat evolved by the passage of the electric current through the welding zone melts the end of the wire and the adjacent edges of the work pieces, creating a puddle of molten metal. The puddle is in a liquid state and is turbulent. For this reason any slag or gas bubble is quickly swept to the surface. The flux completely shields the welding zone from contact with the atmosphere. SAW can use much higher heat input and has slower solidification and cooling characteristics. Also the silicon content will be much higher in submerged arc welding, if care is not exercised in selecting proper flux material. SAW can be used for welding of materials in higher gauges.

SAW has the advantage of high weld metal quality and smooth and uniform weld finish. Deposit rate, deposition efficiency and weld speed are high. Smoke and arc flash are absent in SAW. The operator's skill is minimum in SAW and it is extensively used in heavy steel plate fabrications.

Fig. 1.7 Submerged arc welding
(Courtesy: Welding Hand Book @ AWS, USA, 1966)

12 *Welding Technology and Design*

Submerged arc welding can be carried out with DC source of constant voltage or constant current type and AC power sources of constant current type. The main requirement of SAW power source is that it should be capable of supplying heavy current at high duty cycle. D.C. power can give easy and accurate arc start. Control of bead shape is best with DC with electrode positive, while high deposition rate is obtained with electrode negative, though the penetration will be shallow. DC power source also gives good depth of penetration and weld speed and good manoeuvrability to weld difficult contours at high speed. DC with electrode positive (reverse polarity) can also ensure stable arc and small weld puddle. AC is generally preferred for larger diameter (> 4 mm) wires.

The power source should be rated at 100% duty cycle and not at 60% as required for manual welding. Most SAW operation is done in the current range of 200 - 1000 amps. Because of the flux cover, arc starting can be difficult in SAW; however, several starting techniques like molten flux start, sharp wire start, high frequency start etc., can be adopted to initiate the welding process.

Bare wires are used as electrodes; but in recent times flux cored wires (tubular wires carrying flux in the core) have been introduced. Since the electrodes are mechanically driven, they have to be properly tempered. American Welding Society Standards AWS A. 5.17, A 5.23 and Indian Standards IS 7280 give the required specifications for carbon steel and low alloy steel electrodes.

The flux used in SAW should not evolve appreciable amount of gases under intense heat of the welding zone. It should be of granular form and capable of free flow through the feeding tubes. Agglomerated fluxes and sintered fluxes are commonly used. Width and depth of flux will affect the shape and penetration of the weld. If the flux layer is shallow, porous weld will result. If the layer is too deep, the weld will be rough and uneven. All fluxes produce some changes in the chemical composition as the electrode is melted and deposited as weld metal. Some fluxes add alloying elements (such as moly and Nb) deliberately.

Quality of the weld deposit depends on the type of flux, the electrode, the welding current, arc voltage, speed of arc and heat input rate. Thus the process variables are:

- (a) Welding current and voltage.
- (b) Welding speed and electrode stick out
- (c) Width and depth of flux
- (d) Joint design

Welding current controls the rate of electrode melting, the depth of fusion and the amount of base metal melted. Excessively high current will produce a digging arc and the weld may melt through the backing. At high currents drops begin to transfer directly through the arc cavity into the weld pool. Other side effects are undercuts, highly narrow weld seam and a large HAZ. At low currents large droplets form on the electrode tip which get transferred to the weld pool through the slag at the periphery of the arc cavity. Too low a current will produce an unstable arc. The optimum ranges of current for different wire diameters are given Table 1.3.

Table 1.3 Optimum range of current for different wire diameter

<i>Wire diameter (mm)</i>	<i>Current range (amps)</i>
1.6	150 – 400
2.0	200 – 500
2.4	250 – 600
3.2	300 – 800
4.0	450 – 1000
5.0	600 – 1300
6.3	700 – 1400

High welding voltage will produce a wider, flatter, less deeply penetrated weld. A wider bead will increase the flux consumption. Low arc voltage will produce a stiffer arc and may improve the penetration in a deep groove joint. However, slag removal will be difficult in such cases.

The welding travel speed influences the weld size and penetration. High speed will result in undercuts, arc blow, porosity and uneven bead shapes. The bead shape is essentially controlled by the welding speed. Too low a speed will produce heavy reinforcement and cause slag inclusions.

Electrode stick out is the length of the wire extending beyond the tip of the contact tube above the work piece. Higher stick out will increase the deposition rate. However, too high a stick out will soften the wire due to heating and hence stiffness of the wire will be lost. Increased electrode stick out reduces the energy supplied to the arc, resulting in lower arc voltage and different bead shape. The depth of penetration is also decreased. Maximum electrode stick outs recommended are

75 mm for 2.0, 2.4 and 3.2 mm wire dia.

125 mm for 4.0, 4.8 and 5.6 mm wire dia.

The heat input rate (HIR) affects the microstructure of the weld metal and HAZ. The higher the heat input rate, the lower is the cooling rate of the weld and the HAZ of the parent metal. Weld and HAZ microstructure and toughness will be dependent on the HIR.

U and V weld joints can be used in SAW. Because of the high current used in SAW, a backing is always necessary for this process. The backing may be provided by means of flux, backing strip, or through the weld metal itself deposited by MMA process. The common defects encountered in SAW are slag inclusions, porosity and cracking of welds. The process variables mentioned may introduce these defects, if not properly adjusted to suit the welding condition.

Submerged arc welding is considered as an excellent and efficient process to use on nearly all ferrous metal welds of exceptionally good quality. Carbon, alloy and stainless steels upto 12 mm thick can be safely welded in single pass, while thicker cross section requires multi-pass welding. Though the arc speed and the metal deposition rates are superior to other welding processes, the only limitation is the positional welding. Because a granular flux must be used to shield the weld metal, in practice, only flat position welding is done or inclination upto 15° from flat can be used.

14 *Welding Technology and Design*

Narrow gap welding in thick plates will reduce the weld metal deposit and welding time. NGW can be successfully carried out by SAW (as well as the MIG/CO₂) process. With the SAW process good shape welds without spatter can be obtained. However, slag removal between passes, visual inspection of each individual pass may become problems. In MIG/CO₂ process of NGW, arc stability, effective gas shielding and the effect of magnetic fields on the arc may cause problems. Narrow gap welding is best suited for circumferential joints of pressure vessels. The gap width can range from 15 mm to 22 mm, and suitable electrodes for 3.2 mm to 5 mm dia are to be used. Wall preparation and joint fit-up require high level of accuracy.

Flux cored arc welding (FCAW)

It is somewhat like submerged arc and shielded metal arc welding, except that the flux is encased in a metal sheath instead of being laid over the wire. The weld metal is shielded by the metal flux and by a gaseous medium, either being externally supplied or evolved from flux. Some cored wires have been designed for all position welding, but the weld puddle is still somewhat difficult to control, specially in the overhead position. Carbon steel and stainless steel flux cored wires are available. A schematic diagram of flux cored wire welding process is shown in Fig. 1.8.

Fig. 1.8 Flux cored wire welding (Courtesy: The procedure Hand Book of Arc Welding @ The Lincoln Electric Co., Cleveland, USA, 1973).

Since the flux is in the core of the electrode wire itself, it helps in mechanisation of the welding process by introducing continuous wire feed. The flux coated electrode on the other hand fails in a situation where reeling or coiling of the wire is done. This is the major constraint in using covered electrodes in shapes of stick form.

The functions of the flux are the same as in MMA welding, *i.e.*, it provides the shielding gas through chemical decomposition, acts as deoxidiser or scavenger to produce sound weld metal, forms a slag which will float on the molten weld metal

and protect it from atmosphere when solidification takes place, stabilizes the arc and in some cases can add alloying elements to the weld metal.

Flux cored arc welding can be carried out in both semi-automatic and fully automatic method. The flux cored arc process can be adopted with or without gas shielding. The metal transfer is in the form of (a) globular, (b) spray or (c) short circuiting. The flux in the core forms a molten slag as soon as the electrode establishes an arc and subsequently a weld pool. The arc is shielded by a gas evolved during the decomposition of the flux. A separate gas shield can also be used which will ensure a positive shielding of the arc. DC is used for flux cored wire. Constant voltage power with slope and inductance control is recommended for this process. Flux wire process gives faster deposition rate and lowers welding cost. Fully automatic welding can be made in vertical seam welding. It can be a good substitute for electroslog or electrogas welding wherever the latter cannot be used effectively.

FCAW has high deposition rate due to stub elimination. Flux cored wire gives less spatter and improved weld finish due to arc stabilization and slag-forming compounds at the core, which leads to less porosity. Flux core wires use standard tube materials and the required chemistry is achieved through alloy powder introduced into the core. Flux core wires have great advantage in continuous hard facing work and also in welding steel pipes involving 360° welding.

The core will have various elements whose functions are different. The following gives the important common core elements and their functions:

Ti, Si, Al and Zr	— Deoxidiser
Calcium	— Shielding and slag formation
Carbon	— Hardness and strength
Chromium	— Corrosion resistance
Iron	— Base deposit
Manganese prevention	— Deoxidiser, Hot shortness
Moly and Nickel	— Alloy addition
Sodium, Potassium	— Arc stabiliser and slag formation.

External shielding gases are also used in many FCAW processes. CO₂ shielding gas gives deep penetration and globular metal transfer across the arc. Alloying elements like Cr, Ni, Moly in low alloy weld metals are not affected by the oxidizing atmosphere of the CO₂ gas. Deoxidising agents (Al, Ti, Zr and Si) are added to the core to compensate for the oxidising effects of CO₂. The level of oxidising agents in the cored electrode is kept sufficiently high to avoid formation of CO which can get entrapped in the weld deposit and form porosity. CO₂ shielding will give greater resistance to hot cracking. This is due to the reduction of hydrogen, phosphorus and sulphur in the deposited weld by oxidation during welding. Weld metal ductility and toughness are also improved with CO₂ shielding. If argon is added to CO₂, the Ar/CO₂ mixture gives a spray type metal transfer and penetration is moderate. Generally Ar/CO₂ mixture gives a higher tensile and yield strength of the weld metal and is mainly used for out-of-position welding of pipes of low alloy steels, because of better arc stability and manoeuvrability.

Generally welding with self shielding method gives weld deposits with lower ductility and impact strength than that with standard gas shielding method. This is

16 Welding Technology and Design

because the level of deoxidising agents like Al, Ti will be more in the former case, which may promote bainitic structure in the weld affecting its toughness. Self shielding wires are widely used in hardfacing.

AWS classification of Flux cored wires (AWS A5.20-1979) for welding C-Mn steel gives the designated figures as

E x x T – for example E 6 O T – 8

The first letter E designates electrode wire. The second letter 6 indicates the tensile strength in ksi. In the example its value is 420 MPa. The third letter indicates primary welding position. *e.g.*, O- flat and horizontal and 1 is for all positions. In the example it is flat and horizontal position. T stands for flux core wire and the last figure indicates the weldability and performance capability. In the present example it shows the high crack resistance and good notch toughness at -15°C .

The AWS specifications of the core wire are

AWS A5.20	1979	Carbon steel electrodes for flux cored arc welding.
AWS A 5.22	1980	Flux cored chromium and chromium-nickel steel electrodes
AWS A 5.29	1980	Low alloy steel electrodes for flux-cored arc welding.

In general, increasing the welding current will increase weld deposit rate and penetration. Low currents will produce large droplet transfer and spatter. Similarly, increase in arc voltage will result in spatter and a wide weld bead of irregular profile. With self shielded electrodes this will result in excessive nitrogen pick-up. Low voltage will give shallow penetration. The electrode extension must be kept at optimum length, otherwise unsteady arc and spatter will occur. Similarly low welding speed will cause overheat of the base metal and will give rise to burn-through problems in thinner plates. Too high a speed will affect the bead profile and penetration. The electrode angle to the vertical (drag angle) should be between 5° - 15° in gas shielded method and 20° - 45° for self shield method. FCAW is used extensively for large scale hardfacing through automatic processes.

The main advantages of self shielded flux cored arc welding can be summarized as follows:

- (a) The deposition rate is around four times higher than that of stick electrode welding.
- (b) It produces crack free welds in medium carbon steels, using normal welding procedures.
- (c) Mechanised welding is made easy.
- (d) It eliminates stub losses and the time required for electrode changes.
- (e) The process is adaptable to a variety of products.

1.2.2.2 Gas shielded arc welding

MIG and TIG

In gas shielded arc welding both the arc and the molten weld pool are shielded from the atmosphere by a stream of gas. The arc may be produced between a continuously fed wire and the work. This is known as metal inert gas (MIG) welding.

The arc may also be produced between non-consumable tungsten electrode and the work piece. This process is known as tungsten inert gas (TIG) welding. In TIG welding extra metal must be supplied separately to fill the joint. For TIG welding the shielding gas is usually argon or helium, but for MIG welding the inert gases can have additions of either oxygen or carbon-di-oxide depending on the metal being welded. Carbon steels can be welded with carbon-di-oxide alone as shielding gas and the process is then called " CO_2 welding".

MIG welding (gas metal arc welding)

Gas metal arc welding is a gas shielded process that can be effectively used in all positions. The shielding gas can be both inert gas like argon and active gases like argon-oxygen mixture and argon-carbon-di-oxide which are chemically reactive. It can be used on nearly all metals including carbon steel, stainless steel, alloy steel and aluminium. Arc travel speed is typically 30-38 cm/minute and weld metal deposition rate varies from 1.25 kg/hr when welding out of position to 5.5 kg/hr in flat position.

MIG welding is a well established semi-automatic process. Continuous welding with coiled wire helps high metal depositions rate and high welding speed. MIG gives less distortion and there is no slag removal and its associated difficulties like interference with accurate jiggling. Because of the good heat input control, MIG can be used for non-ferrous welding with good results. However, since the torch has to be very near to the job, there is a constraint where accessibility is limited. Spatter is high and so deposition efficiency is less. Absence of slag in solid wire welding processes allows a higher cooling rate of the weld zone and hence joints made with the process on hardenable steels are susceptible to weld metal cracking.

The filler wire is generally connected to the positive polarity of DC source forming one of the electrodes. The work piece is connected to the negative polarity. The power source could be constant voltage DC power source, with electrode positive and it yields a stable arc and smooth metal transfer with least spatter for the entire current range. AC power source gives the problem of erratic arc. So is DC power source also with electrode negative. Power sources are rated at 60 per cent duty cycle for semi-automatic and at 100 per cent duty cycle for automatic continuous operation with maximum amperage of 600 amps and 1000 to 2000 amps respectively.

AC constant voltage power source, pulsed current constant voltage power source or pulsed current power source with voltage feedback controlled wire system are also in practice. Among these, constant voltage power source is generally used. With a constant voltage power source, the welding current increases when the electrode feeding rate is increased and decreases as the electrode speed is decreased, other factors remaining constant. When the current value is increased the melting rate of the electrode will also increase.

Inert gas usually argon, helium or a suitable mixture of these is used to prevent the atmosphere from contacting the molten metal and HAZ. The core of the gas column ionized by the arc heat helps to maintain the arc. The metal transfer is accomplished by (a) Short circuit transfer (dip transfer), (b) Globular transfer or

18 *Welding Technology and Design*

(c) Spray transfer: The current requirement will be of the order of 50 - 300 amps, and the voltage in the range from 16 to 45 V, depending on the type of metal transfer.

Schematic diagram of the MIG process is shown in Fig. 1.9

Fig. 1.9 Gas metal arc welding MIG (Courtesy: The Procedure Hand Book of Arc Welding @ The Lincoln Electric Co., Cleveland, USA, 1973)

CO₂ gas is used as the shielding gas in GMA welding of steel plates. The flow characteristics of CO₂ are such that the gas issues in a non-turbulent manner from the MIG gun. With CO₂ shielding the metal transfer will be globular and non-axial at low current densities. Hence there will be considerable spatter. The non-axial transfer is caused by an electromagnetic repulsive force acting on the bottom of the molten drop. MIG/CO₂ welding with spray type arc (current density 350 amps) is best suited for welding relatively thick parts. For thin sheets dip transfer technique is used with low arc voltage (16 - 22 V) and low current (60 - 180 amps). The low arc voltage results in a reduced arc length and the molten droplet gets transferred into the weld pool by direct contact. With pure argon or a mixture of argon + 20% CO₂, the metal transfer is globular at low current density, but changes to spray type when the current density increases. In the spray type transfer the metal travels across the arc in the form of fine droplets which is induced by the magnetic force acting on the molten electrode tip.

100 per cent pure argon is used for almost all metals except steels. Helium has higher thermal conductivity. So it gives higher arc voltage for a given current and higher heat input. However, helium being lighter (than argon and air) rises in a turbulent manner and tends to disperse into air. So higher flow rate will be required in the case of helium shielding.

Addition of O₂/CO₂ with argon or helium causes the shielding gas to be oxidising and may give rise to porosity in some ferrous metals. CO₂ is widely used for welding of mild steel and it gives sound weld deposits. In these cases the electrode must contain appropriate balance of deoxidisers such as Al, Ti, Si and Zr.

MIG/CO₂ process is extensively used for welding steels of different kinds. Filler wire specifications are given in standards AWS 5.18/79 and AWS 5.20/79.

Aluminium alloy can also be welded by MIG and TIG processes. The standard filler rods are given in AWS A 5.10 and IS 5897. Aluminium alloys welding is normally done with spray type arc using steady current or pulsed current. Deep penetration with proper root fusion can be obtained. Plates of different thicknesses can be welded easily with pulsed current welding technique. MIG can also be used for copper and its alloys. The filler rod specifications are given in AWS A 5.7 and IS 5898.

Pulsed MIG welding

In MIG there is a transition current below which the metal is transferred in a few large drops by gravity and the penetration is shallow. Above the transition current the metal is transferred in many small drops by electromagnetic forces and the penetration is deep. The power can thus be supplied in a pulse mode which can enable the current just high above the transition level and long enough time to transfer small droplets accompanied by deep penetration. The metal deposition takes place when the current is at peak level. During low level current in the pulse period, no transfer of metal will occur. This process is known as pulsed current MIG welding. Pulsed MIG can be used for all positions, for root pass without backing and for joining thin plates. Pulsed MIG is best suited for aluminium and copper with high thermal conductivity where rapid solidification occurs, which may cause lack of fusion in normal dip transfer MIG technique.

Hot wire MIG

The filler wire can be heated to increase the metal deposition rate. This process is known as hot wire MIG welding.

The current passed through the filler wire in MIG has to

- (a) heat the filler to the melting condition,
- (b) set up an electromagnetic force which helps in drop detachment, drop size and rate of transfer of the drop to the work piece,
- (c) maintain the plasma
- (d) wet-in the weld bead and the work piece to have proper penetration.

Plasma MIG

A non-consumable electrode with a suitable torch and a nozzle can be used to produce the necessary plasma. With the help of a high voltage high frequency spark, an arc can be initiated between the non-consumable electrode and the work piece. The filler metal can be fed from a different convenient position. The non-consumable electrode and its constant current arc form the plasma MIG process. In addition there will be an auxiliary outer stream of a shielding gas, CO₂, argon, helium, nitrogen, or a mixture of these gases. The additional plasma sheath in plasma MIG process makes it possible to use large electrode extension increasing the deposition rate. Wetting-in of the base metal is improved. In aluminium welding, the quality of weld metal is improved by the cleaning action of the plasma arc on the work piece. Table 1.4 gives the shielding gas for different base metals.

Table 1.4 Shielding gases for MIG

Argon	For most metals except steel
Helium	Aluminium and copper alloys
A+He(50%)	Aluminium and copper alloys
A + 25%N ₂	Copper and its alloys
A + 1.2% O ₂	Alloy steels and stainless steels
A + 3.5 % O ₂	Carbon steels, alloy steels, requires deoxidised electrodes
A + 25% CO ₂	Various steels, used with short circuiting arc
A + 5% O ₂ + 15% CO ₂	Various steels, requires deoxidised wire
CO ₂	Steels, requires deoxidised electrodes.

TIG welding

A non-consumable tungsten rod is used as the electrode with inert gases shielding both the molten metallic pool and the red hot filler wire tip. Argon or helium gas is used for shielding purposes. Argon is preferred for a wide range of materials, and as no flux is used, corrosion due to flux inclusions cannot occur. Almost all metals can be welded using TIG process. Dissimilar metals can also be welded by TIG choosing the appropriate combinations. These non-consumable tungsten electrodes are alloyed with zirconium or thorium (around 1%). Zr alloyed tungsten is used in alternating current applications and it has high resistance to contamination and has got good arc starting characteristics. Typical TIG process is schematically shown in Fig. 1.10.

Thoriated Ti electrodes have high emissivity, better current carrying capacity and longer life and normally preferred in DC welding. Pure Ti electrodes are usually preferred for AC welding of aluminium and magnesium. The current carrying capacity is lower than that of alloyed electrodes.

The current carrying capacity of the electrode depends on the type of shielding gas, the length of electrode, the cooling of the holders, position of the weld type etc. If the electrode is large for specified current, the arc will become erratic and welding will be difficult. However, selection of smaller diameter rods would increase the chances of electrode melting.

Tungsten Electrode
(Non-consumable)

Fig. 1.10 Gas tungsten arc welding TIG
(Courtesy : Welding Hand Book @ WAS, 1970)

TIG welding of stainless steel, nickel and its alloys may be carried out with argon and 5 per cent hydrogen. The hydrogen helps to increase the arc heating efficiency and reduce the amount of oxides formed with stainless steel. In the case of aluminium alloys a mixture of argon and helium can be used.

TIG welding can be done in almost all positions. Metal thickness ranging 1 to 6 mm is generally joined by TIG process. TIG is often used for root pass in pressure components and other critical applications, as it gives a clean and accurate weldment. In aerospace work the welds are made totally by multipass TIG welding, owing to the high quality demanded there. Aluminium alloys are generally welded by TIG welding. Argon is the main shielding gas with some amount of helium. Preheating of aluminium alloys is necessary when TIG process employs AC power supply. High alloy steels, copper, magnesium, Ni, Ti and Zr alloys can be readily welded by TIG with AC power source. Pure inert gas atmosphere must be ensured as some of these alloys (Ti and Zr) are highly reactive.

Gas tungsten arc welding produces the highest quality welds most consistently. It can weld all metals in any configuration, but is not economically competitive on heavy sections. It is most popular for welding aluminium and stainless steel pipe for nearly all process uses and specially in cryogenics where fusion is very necessary. GTAW lends itself to more precise because the arc heat and filler metal additions are controlled independently. But the process is slow and the arc travel speed is 10cm/min and metal deposition rate 1 kg/hr. The concentrated heat input of the TIG process helps to increase the welding speed, minimise distortion and improve the metallurgical quality of the weld. In TIG the shielding gas (argon, helium or their mixture) gets ionised due to high frequency voltage superimposed on the welding current. The electrons which become free during the process of ionisation form a conducting path between the work piece and the tungsten electrode. Thus the arc can be started without directly touching the tungsten electrode to the work piece. In the case of DC power supply the high frequency voltage superimposition can be cut off once the arc is struck. In AC power, the high frequency voltage superimposition will be required continuously to improve the arc stability in addition to the filter capacitor to be connected in series in the output circuit.

The arc voltage may range from 10-15 V with current 50-350 amps for argon and 15-25V with current 50-350 amps for helium shielding gas.

Tungsten has high resistance to heat and a high melting point (3410°C) and is a strong emitter of electrons which provide the arc path, ionize it, facilitating the maintenance of a stable arc. Specifications of tungsten electrode are given in AWS A 5.12-1980.

TIG welding is better suited for metal thickness of 7 mm and below. DC from a constant current type power source is used with electrode negative to deposit a narrow deep penetration weld. While welding the electrode tip must not be allowed to come in contact with the molten puddle. For initiating the arc high frequency starting must be used.

Pulsed TIG welding

Pulsed TIG welding achieves a good control of heat input. The current from DC power source is supplied in pulses having a predetermined duration for the peak

22 *Welding Technology and Design*

and low values. When the current is maintained at high on-position, welding takes place with the required penetration. During the off-position, the torch is manipulated to correct the positioning. The electrode is kept sufficiently hot and the ionised column is also retained so that the arc is not extinguished. In this process deep penetration is obtained with less heat input to the joint. The pulsed arc agitates the molten weld metal and so minimises the porosity. Pulsing produces arc stiffness and hence avoids arc wander. Molten weld pool can be well manipulated and, successive solidification of the nuggets avoids cracking and burn-through. Lesser heat input improves the grain structure and the mechanical properties of the weld. There is no need for weaving because the pulsed current is sufficient to melt the required base metal area. Since the molten metal deposited in each pulse starts solidifying from the periphery towards the centre, the centre portion becomes prone to defects like segregation and shrinkage cracks. Pulsed TIG welding is suitable for the root run of the tube and pipe welding. Thin plates and foils can be effectively welded by this process.

While joining precision parts by pulsed TIG, rapid current rise and current decay with a high pulse repetition rate is used. In mechanised TIG, slower rates of current rise and fall and slower current pulse rates are used.

The advantages of pulsed TIG are

- (a) variation in joint fit-up can be tolerated
- (b) welding of sheets down to 1 mm thickness can be carried out
- (c) distortion is minimised
- (d) position welding made easy
- (e) operator requires less skill
- (f) mechanisation is possible
- (g) ideal for critical applications like root passes of pipes, joining dissimilar metals etc.

Hot wire TIG

Hot wire TIG welding is similar to ordinary tungsten inert gas welding except that the filler wire is heated prior to the deposition, either by resistance heating or by induction heating. A high quality weld is obtained at a high deposition rate which is controlled by adjusting the heating current of the wire. The dilution level is low in this welding process. Since the wire is heated before entering the welding zone, the volatile surface contaminants of the filler wire get evaporated, thus eliminating hydrogen, porosities, etc.

Spot TIG

Spot TIG is a process adopted to spot welding. Argon shielding is used in this process. The current can be supplied in pulses and by proper timing spot welds with defect free nuggets can be obtained.

Circumferential seam welding of pipes and tubes is carried out by orbital TIG welding. Welding speed must be properly adjusted to suit variations in weld position, such as vertical-up, flat, vertical-down and overhead. Pulsed current is also used for orbital TIG.

In automatic TIG welding magnetic control is used sometimes to control solidification. This control is effected by subjecting the arc and the weld puddle to a determined level of magnetic field. The arc stability is increased, defects are eliminated, penetration and dilution can be well controlled, grain refinement and mechanical properties can be improved by this method.

Both MIG and TIG can be effectively used for narrow gap welding (NGW), in which thick plates in the range of 50 mm to 350 mm thick can be welded to each other with narrow U-type gap involving only 10 to 25 mm width and 2° to 4° included angle. The groove is filled with successive layers of weld metal with one or two passes per layer.

Edge preparation in narrow gap welding is rather simple and quantity of filler material consumption is less. Due to low heat input and multipass retempering, fine grained structure of weld is obtained. Residual stresses and distortion are minimum in narrow gap welding. However, the MIG and TIG equipments meant for narrow gap welding are more complex and costly. Repair of defects will be difficult. Cleaning the weld surface after each layer is laid, is also difficult. Side wall fusion must be properly ensured. The process requires high accuracy of power supply characteristics and close tolerance for electrode tip to work distance. Slag inclusion and lack of fusion in the side wall are the most common defects in NGW. Weld quality is more sensitive to welding condition than in conventional welding methods.

Different materials, particularly those sensitive to heat input, including HSLA steels, stainless steels, aluminium and titanium alloys can be welded by NGW. Large structures, components like shells, drums, steam pipes, pressure vessels, power plant components, penstocks etc., are among the variety of products fabricated by narrow gap welding process.

1.2.3 Electrical method

1.2.3.1 Electric resistance welding

Heat is produced by the passage of electric current across the interface of the joint. It may also be induced within the metal near the joint. Typical examples of this type of joining are spot and seam welding where sheet metals are pressed together at the joint by copper alloy electrodes and, projection welding where the metal itself is shaped so that local contact at the joint concentrates the current flow, thereby producing heat. Electro-slag welding which makes vertical joints, is in effect a continuous casting process employing electric resistance heating of a bath of molten slag carried above the weld pool.

Electric resistance welding is a nonfusion welding process. Heat is generated when high electric current is passed through a small area of the two contacting metal surfaces. The heat H generated is given by

$$H = I^2 \times R \times t$$

where I is current, R is resistance of the interface and t is the time of application of current. When the rise in temperature is sufficient, a large pressure is applied at the heated interface to form a weld joint. The process variables are : current, time of application of current, pressure, duration of pressure applications, materials to be welded and their thickness.

24 *Welding Technology and Design*

There are five main types of resistance welding:

- (a) spot welding
- (b) seam welding,
- (c) projection welding,
- (d) upset butt welding and
- (e) flash butt welding

In spot welding the plates to be welded are kept one over the other, after cleaning the two surfaces in contact. Two stick electrodes are kept on both sides of the plate, as shown in Fig. 1.11. A pressure is applied to the electrodes and maintained for a particular interval known as squeeze time before starting further operation. Then the current is passed through the electrodes. The time of application of current known as weld time is measured in terms of the number of cycles, each cycle corresponds to 20 m.sec. (1/line frequency). The pressure is maintained during this time also. After the current is cut off, the pressure is maintained for a brief time known as hold time, so that the heated metal solidifies and forms a weld nugget. After hold time, the pressure will be released and an off-time is given before starting another spot welding operation.

Fig. 1.11 Schematic diagram of spot welding

Too high a current will cause weld expulsion, cavitation and weld cracking, reduced mechanical properties and electrode embedment in the surface. On the other hand, less current will result in unfused surface and poor weld. High pressure will increase the contact and decrease the contact resistance and so less heat will be generated. It may lead to distortion and reduced electrode life. More time of application of current may lead to boiling, porosity, growth of nugget upto electrode face.

When two plates of different thicknesses are welded, the weld nugget grows towards the thicker side. So also, when two plates of different conductivity are welded, the weld nugget grows towards the higher resistivity side. In these cases, the upper and the lower electrodes are chosen to be of different diameters.

In the case of plates with thickness “t”, the electrode diameter “de” is taken as

$$de = (0.1 + 2t) \text{ mm}$$

Mild steel plates upto 10 mm can be easily spot welded. In the case of aluminium the upper limit is 6 mm plates and for copper it is 1.5 mm thick. The conductivity of the materials plays an important role in deciding the thickness of the plates that could be easily welded by spot welding. Spot welding of high carbon steels requires PWHT. Spot welding is extensively used in aircraft industries, auto and instrument industries.

The main advantage of spot welding are

- (a) its adaptability to mass production,
- (b) high speed of operation,
- (c) cleanliness,
- (d) no welding rods and less operational skill

Materials having high thermal and electrical conductivities will be difficult to weld by spot welding and require special procedure.

In seam welding roller type of electrodes are used as shown in Fig. 1.12. The rollers are rotated over the job as the welding proceeds. By controlling the power supply it is possible to obtain a good heat control. The seam cools under pressure at definite intervals. The weld will have less surface disturbances.

As the welding proceeds the applied current will try to pass through the already welded portion, thus reducing the heating in the portion to be welded. One way of overcoming this difficulty is to increase the current as the welding progresses. Sometimes external heating like high frequency heating to offset the effect of reduced current due to shunting can also be adopted.

The applied pressure in seam welding may range from 3 MPa to 8.5 MPa depending on the thickness of the work piece. The current density may be as high as 775 amps/sq.mm. The heat generated during welding will be high and the rollers must be cooled by using water cooling arrangements, so that distortion of rollers can be avoided. Current interruption can also be employed so that the current shall

Fig 1.12 Seam welding

flow for a specific time to supply the requisite heat to the weld and then shall cease for another predetermined length of time before the next spot weld is begun. In this way the heating of the rollers can be controlled.

Seam welding can be carried out on steels, aluminium, magnesium and nickel alloys. Seam welding of copper and its alloys is not recommended. High frequency seam welding is suitable for finned tubes and other tubings.

Projection welding is similar to spot welding excepting that welding is carried out at places in the sheet or plates where there are projections made for this purpose. The projections are created by pressing at the selected places in the sheet. Resistance to heat being confined to the projections, welding between the parts takes place by the application of adequate pressure at the appropriate time at these point of contact. Projection welding is particularly applicable to mass production work, and is quite suitable where many spot welds are required in a restricted area. Projection welding method is used in welding brackets, heavy steel stampings, in the encapsulation of thyristers etc.

Upset butt weld is obtained by bringing two pieces of metals to end-to-end contact under pressure and then allowing current to flow from one piece to the other. The contact surfaces should be as smooth as possible. In upset welding (as also in flash butt welding) a forge structure results as against the cast structure obtained in spot and projection welding. Welding of tools to the shank is carried out by upset welding. Resistance butt welding is employed for joining tubes as schematically shown in Fig. 1.13.

Fig. 1.13 Resistance butt welding.

In flash butt welding the two pieces to be welded are pressed against each other by applying a pressure so that contact will be at points due to surface roughness. A high welding current is passed. The surfaces are heated upto molten condition, and as one piece is slowly advanced towards the other the molten metal is flashed out. After the faces attain plastic stage upsetting pressure is applied, leading to bonding of the two faces. Flash butt welding is different from resistance pressure welding in the sense that in flash butt weld contacts between the two surfaces are made at some point only due to the roughness of the surface. In resistance butt weld a smooth full contact surface is preferred.

In flash butt welding surface contaminations are removed in the spatter during flashing and molten metal is expelled in the final upset of forging operation. A small fin is created at the weld joint consisting of the remaining molten metal and oxides. This fin can be trimmed off by grinding. The advantage of this process lies in the fact that the molten metal and the arc afford an efficient protection to the plastic metal which ultimately forms the weld, so that the danger of oxidation can be avoided.

The applied pressure in the cold (not preheated) condition may range from 70 MPa for low alloy and mild steels to 110 MPa for medium carbon steel and 177 MPa for stainless steel and tool steels. With preheating, the applied pressure can be reduced to approximately half the above values.

Flash butt welding is easily applied to highly alloyed steels which cannot be welded by other process satisfactorily. Flash butt welding is cheap and simple. It can be readily used for small sub-assemblies as in motor car industries. The cost of current per weld is small and production rate will be high.

Fig. 1.14 Electro-slag welding process

28 *Welding Technology and Design*

Flash feed rate must be properly controlled. Insufficient or intermittent flashing will result in poor heating. Flash time and flashing current should also be to the optimum level. Plasticity induced due to heating should not be very high or too low. Too high an upset force will result in too much of flashing leading to poor weld. If upsetting force is less oxides, inclusions and voids can be found in the weld.

Flash butt welding is used in solid and tubular structural assembly, gears and rings, super heater tubes in boiler etc.

1.2.3.2 Electro-slag welding (ESW)

Electro-slag welding offers good productivity and quality in heavy structural and pressure vessel fabrications. The weld metal in ESW process is obtained by fusion of electrode wire under the blanket of flux layers. The heat for melting is obtained as resistance heat by passage of current through slag pool covering the complete surface of the weld metal. The schematic diagram of the ESW process is shown in Fig. 1.14. A pool of molten slag is formed between the edges of the parts to be welded and the travelling moulding shoes. The metal electrode is dipped into the molten slag. The current passing through the electrode and the molten slag heats up the slag pool. The slag melting point is higher than those of the wire and the parent metal. Hence the electrode wire melts and the molten metal settles at the bottom of the slag pool and solidifies to form the weld metal. To keep welding stable, it is necessary for the slag pool to maintain its temperature.

In electro-slag welding the slag pool is 40-50 mm deep and it offers a conductive path between the electrode and base metal. Thus the current flow is maintained after the arc is extinguished. In contrast, in the case of submerged arc welding which appears to be similar to ESW, the arc remains stable under the molten slag, as the arc voltage is around 25-30 V, and the slag layer is rather shallow.

Both non-consumable and consumable guides are used in ESW. The first method has a contact tube which directs the wire electrode into the slag bath. The welding head moves upwards steadily along with the shoes as the weld is deposited. In the consumable guide arrangement, a consumable tube is used. The welding head remains fixed at the top of the joint. The axis of the weld is vertical. The welding machine moves upwards consistent with the deposition rate. The amount of slag remains constant. A small amount of flux has to be added to the slag. When the weld is complete the welding machine can be withdrawn.

The welding wire chosen must match with the base material and the diameter is generally of the order of 3-4 mm. The flux should have high boiling point to enable melting of base metal and the welding wires. It must have good conductivity and viscosity so as to maintain the temperature of the slag pool and to prevent the flow of the slag through gaps between work piece and the cooling shoes.

The ESW process is completely continuous and so productivity will be faster. No edge preparation of the parts to be joined is necessary. There will be saving in the quantity of filler metal and the flux. After the welding process, the welded components require heat treatment. The process should be continuous and should not be interrupted due to power failure etc. Otherwise the molten metal will shrink forming a cavity at the centre. Normally other defects like slag inclusions, porosity, undercuts, notches etc., are not encountered in ESW process.

Constant potential power source with 750-1000 amps at 100 per cent duty and with an open circuit voltage of 60 V minimum is used. The electrode could be solid or flux-cored fed at a rate of 20-150 mm/second.

The quality of weld in ESW depends on (a) the ratio of width of the weld pool and its maximum depth, known as Form Factor, (b) weld current and voltage, (c) electrode extension and oscillation, (d) slag depth, (e) number of electrodes and their spacing etc. The weld will be more crack-resistant if the form factor is high. Weld voltage controls the depth of fusion. Increasing voltage increases the depth of fusion and the width of the weld. Increasing welding current will increase the deposition rate and also the depth of molten weld pool. However, too high a current may result in deposits which will be crackprone.

Oscillation of electrode will ensure proper heat distribution and fusion. The slag bath depth should be sufficiently deep so that the wire enters into it and melts beneath the surface. With shallow bath the slag will split and arcing will occur at the surface. For best results the bath depth should be around 40 mm.

The electrode can be solid and metal-cored. AWS 5.25-1978 gives the specifications of flux wire combination for ESW of carbon and high strength low alloy steels. In ESW, the dilution is to the extent of 30 - 50 per cent by the base metal. Hence care should be taken to select the proper wire for a particular steel. Many of the solid electrodes are the same as with SAW and MIG/CO₂ welding.

The flux used must be conductive and must have proper viscosity to permit a good stirring action in the flux pool. The flux must have a melting range lower than that of the weld metal and metallurgically compatible with the alloy being welded. A basic flux is usually employed for carbon steel, low alloy steel and stainless steel. Fluxes are classified on the basis of the mechanical properties of a weld deposit made with a particular electrode.

Plates and other heavy sections upto 450 mm are commonly welded by electro-slag process. Heavy pressure vessels for chemical, petrochemical and power generating industries are usually welded by ES process only.

In ESW, the weld metal stays molten for a long time and permits slag-refining action, namely, escape of dissolved gases and transfer of non-metallic inclusions to the slag-bath. The prolonged high temperature and the slow cooling rate in ESW result in a wide coarse grained HAZ having relatively soft high temperature transformation products. The weld itself will have columnar cast structure. As such the toughness of the weld and HAZ will not be very high and if the service condition does not require high toughness the weld as such can be made use of. However, if the service condition requires high toughness of the weld, then proper normalising heat treatment must be carried out, so that all traces of cast structure are removed and toughness properties are improved.

1.2.3.3 Induction pressure welding

This is a solid phase welding, obtained by the use of high frequency induction heating and by simultaneous application of pressure. Oxidation is avoided by purging with hydrogen gas. The surfaces to be joined are heated by induction current at 4kc/sec, produced by an inductor in series with two capacitors, powered by a transformer with two high frequency alternators. A typical seam welding of a

tube is schematically shown in Fig. 1.15. The induced current flows in a longitudinal loop along the edges to be welded, heating them uniformly through their thickness over a certain length. Forging rolls, then weld together the fused lips, leaving a slight external flash, which is removed afterwards. The normal speed of welding which depends on the power supplied, is around 15 meters per minute.

Induction pressure welding is extensively used in joining boiler grade Cr-Mo steel tubes. Figure 1.16 (a) shows the IPW process in welding of two tubes. 100 kVA, 10 kHz IPW machine is used in welding a 50 mm diameter and 5 mm wall thickness tubes of 2.25 Cr- 1 Mo steel in the boiler industries. One tube is clamped in a fixed platen, while the other tube is in a moving platen. These tubes are pressed together by applying pressure through hydraulic system. The joint is induction heated and hydrogen gas is purged around the weld joint to prevent formation of oxides and to keep the induction housing cool. A typical weld cycle including the soaking periods, is shown in Fig. 1.16(b) The peak temperature in the production is 1275°C with an upset of 2.5 to 3 mm.

Fig. 1.15 Induction pressure welding process of a tube

1.2.4 Energy method

1.2.4.1 Electron beam welding (EBW)

Electron beam welding is a process in which the heat required to produce fusion is obtained from the impact of a high velocity high density stream of electrons on the work piece. Upon impact the kinetic energy of the electrons is converted to thermal energy causing both vapourisation and melting. The vapourisation of the material beneath the beam enables the beam to penetrate into the material to be welded, with the beam and the vapour forming a hole. As the beam moves along the joint, the molten metal flows round the hole leaving the welded joint in the wake of the beam. A schematic diagram of the process is shown in Fig. 1.17.

Fig. 1.16 IP welding of Cr-Mo boiler tube. (b) Variations in Weld parameters

Fig. 1.17 Electron beam welding process

The EB weldings have depth to width ratio of more than 10:1 due to the extremely high heat concentration. The beam is very narrow, less than 0.25 in diameter and the welding speed is high. The net heat input is very low.

The electron emitter is a cathode - anode system in a very high vacuum chamber. The cathode is made of tantalum or tungsten and heated to about 2560°C. Electron

32 *Welding Technology and Design*

cloud is thus created near its surface. A metallic shield, known as Wehnelt, is fixed near the cathode to make the electric field sharper and regulate the electron flow.

The electric field between cathode and anode accelerates the electrons and sets them free with considerable energy. Thus an electron beam is created which is made to impinge on the parts to be welded. Magnetic lenses are used to focus the beam on the work piece. Magnetic coils are also used for beam deflection and manipulation of the beam spot on the work piece.

The speed of welding which depends on the width and depth of the weld must be properly controlled as, otherwise, it will lead to either incomplete penetration or overheating. As the fusion zone in the weld joint is very narrow, there will be very small disturbances in the base material. Shrinkage allowance to be given in the design is small compared to other arc welding and the residual stresses produced in the component are also small. As the focal length of the EB system is quite high, the EB gun can be placed at a distance, as far as one meter from the work pieces, unlike in electric arc or plasma jet welding. Thus welding narrow and restricted area is possible with EBW. Welding can be done over a wide range of thicknesses (0.1 mm to 100 mm) and dissimilar metals can be easily welded by the process due to precise heat control. Welding speed in EB is much higher than electric arc methods, thus reducing the welding time. Also the repeatability of EB welds is high compared to other processes.

In EB welding the weld zone narrows down from the upper bead to the lower bead. The metal vapour generated at the centre of the molten column may not be able to escape through the narrow slot at the bottom of the joint interface. Thus when the molten metal solidifies, root porosity may form in EB welds.

In deep penetration welds, it will be difficult to achieve fusion of the whole depth. To get heating lower beads, weld parameters selected should be greater than those set for truly narrow weld. Backing support to the lower bead will help in achieving a full penetration joint. The backing can be removed after welding.

The gun-to-work piece distance depends on the vacuum in the gun chamber. At about a vacuum of 10^{-4} torr, a sharp focus over a greater gun-to-work piece distance can be achieved. When the chamber pressure is 10^{-3} torr, electron scattering becomes significant, resulting in wide bead with lower penetration. Thus welds made in a high vacuum are narrower with narrow HAZ than those welds made in medium vacuum (10^{-1} to 10^{-2} torr) or at atmospheric pressure. High vacuum welding, though takes longer time (to achieve the required vacuum level) is good for reactive material welding.

Because of the narrow welds and HAZ, the residual stress and strain fields produced are comparatively small and this reduces the cracking tendency of the weld. High welding speed attainable in EBW helps in achieving a weld with grain boundary condition almost free from liquation in the HAZ. Thus cracking can be avoided immediately after welding or on PWHT. When welding refractory alloys of high melting point, EBW reduces the grain growth substantially leading to improvement in tensile strength and ductility.

The fusion zone in the EB weld is effectively a fine grained cast structure, often with directional solidification towards the centre line of the weld. The solution treated areas are narrow and the overaged regions in the base metal is almost

undetectable. A low temperature ageing treatment is sufficient to recover the original strength after welding. This property of EBW is very useful for welding of aluminium alloys.

Non-ferrous metals such as aluminium and titanium alloys are welded at above 50 mm/second welding speed to suppress gas evolution, and steels at lower speeds to allow adequate time for vacuum degassing of the weld pool. Due to the faster cooling rate of EBW, hardness in the weld zone will be high. This may not be desirable in some steels, as it will lead to quench cracking. To avoid such cracking PWHT has to be carried out.

In case EB weld does not penetrate fully, a blind weld results. In such situations, the molten metal is unable to flow into the penetration cavity and wet the side walls of the work pieces. This will result in cracking, known as “Necklace Cracking” and has been noticed in all materials such as Ti alloys, stainless steels, nickel base alloys and carbon steels. This defect can be eliminated by widening the weld, which will enable the material to flow into the cavity and reduce temperature gradient and the cooling rates. Initial cost of EBW machine is very high. Further, EBW can be used only in an automatic operation owing to high speed of welding. However, significant machine time and material saving can be achieved by EBW.

1.2.4.2. Laser beam welding

Laser beam welding is a high energy density welding process with low heat input. A wide variety of metals and alloys can be welded by this process. The heat source is a focussed beam of high energy monochromatic and coherent stream of photons and this process does not require vacuum chamber.

Fig. 1.18 Laser beam welding process

34 *Welding Technology and Design*

Figure 1.18 shows the essentials of the laser beam welding unit. The welding unit consists of

- (a) Laser generator
- (b) Power supply
- (c) Capacitor bank
- (d) Microscope

The important component is the ruby rod which is enclosed in a pump cavity. The cavity encloses a flash tube installed parallel with the ruby rod and fired by a high voltage applied to its ends. On the inside the cavity is polished to serve as a light reflector. The ruby rod is cooled by compressed air fed into the pump cavity. The light energy emitted by the ruby rod is approximately shaped and directed onto the work by optical system, consisting of a prism, a lens and an additional lens system which can include several accessory lenses to converge the beam to a spot of 0.25 to 0.05 mm diameter.

In laser welding the pulse should have maximum duration and minimum spacings—high pulse repetition frequency. Present day lasers have the PRF (pulse repetition frequency) ranging from 1 to 100 per minute.

Ruby laser (solid state laser) is used for making extremely small spot welds (0.8 mm dia.) in dissimilar metals. Gas laser using CO_2 is also employed which produces continuous or pulsed infra-red beam of around 10 microns. The density of energy obtained at the focussing point of a lens concentrating a laser beam, can be as high as 5000 kw/sq. cm.

When the high power laser beam impinges on the surface of the metal, the energy that is absorbed, heats up the surface and melting occurs. The laser beam sharp and well focussed as it is, melts a small cylindrical volume of material through the thickness of the plate. A column of vapour is surrounded by a liquid pool and as the column is moved along the joint of the two plates, the material on the advancing side of the hole throughout its depth is melted. As the column is narrow, the molten metal at the rear end of the hole solidifies, thus resulting in the welded joint. The vapour column is stabilized by the balance between the energy density of the laser beam and the welding speed. It is important to choose proper energy density and the corresponding welding speed. Too high energy density will result in an unstable hole which can cause drop through. Too low energy will not permit vapourisation and the formation of liquid cylindrical volume. A welding speed too fast will result in incomplete penetration and a slow speed will give rise to wide fusion zones and possible drop-through. The depth to width ratio of the laser weld should be greater than 4 to 1.

The hot fusion zone can absorb gases like hydrogen, oxygen and nitrogen. Absorption of these gases is minimised by protecting the fusion zone by inert gases as is done in gas metal arc welding.

Deep penetration welds produced with high power CO_2 laser are similar to electron beam welds. However, laser beam welding offers several advantages:

- (a) A vacuum is not required for the work piece since the laser beams can easily be transmitted through the air.
- (b) X-rays are not generated in the laser beam/work piece interaction.

- (c) The laser beam can be readily focused, aligned and redirected by optical elements.
- (d) Due to the slightly lower energy density of the focused laser beam, the tendency for spiking, underbead scatter, incomplete fusion and root porosity is reduced.
- (e) Simple geometry of weld joint.
- (f) No necessity for preheat, post heat or any interpass temperature.
- (g) Generally no filler material is required.
- (h) Distortion is less.
- (i) Autogeneous weld upto 15 mm thick can be made.

The process has to be automated.

Variety of metals and alloys including hot and cold rolled steels, HSLA and stainless steels, aluminium alloys, titanium alloys, refractory and high temperature alloy can be welded by laser beam welding process. The weldment is free from porosity and generally ductile in nature. The cooling rates of the laser beam welds are high as a consequence of low heat input. As a result high hardness due to the resulting microstructure corresponding to the cooling rate can be obtained. Figure 1.19 shows the relationship between power on work piece (kW) and the travel speed for different thorough thickness weldments of steel. For joining thinner plates large range of speed and power can be used. The high power density of the laser

Fig. 1.19 Relation between laser beam power and the welding speed for different through thickness weldments (*Courtesy: Welding Hand Book, AWS*)

36 *Welding Technology and Design*

beam welding process and the resulting rapid cooling rate have a strong influence on the microstructure and in turn on the properties of the welded joint, specially in high strength low alloy steels. Hence the speed and the power combination must be carefully chosen for a given material to get the optimum mechanical properties.

Laser welding is widely used in automobile industries for parts such as transmission gear cluster, box beams etc. In heavy industrial applications, pipe line welding and welding in ship building, nuclear plant fabrication are typical examples where laser welding process is used extensively.

1.2.4.3 Plasma welding

Plasma means a gas that has been heated to a sufficiently high temperature so that it is transformed into an ionised condition and is able to conduct an electric current. Plasma arc welding is an inert gas non-consumable electrode welding method, utilizing a transferred, constricted arc. As the orifice gas passes through the torch to the work piece, it is heated by the arc, gets ionized and passes through the arc constricting nozzle at an accelerated rate. Since too powerful a jet would cause a turbulence in the molten puddle, the jet effect on the work piece is softened by limiting gas flow rates through the nozzle. Since this flow alone may not be adequate to protect the molten puddle from atmospheric contamination, auxiliary shielding gas is provided through an outer gas cup on the torch. Fig. 1.20 shows a typical plasma arc welding method.

Fig. 1.20 Plasma arc welding process (*Courtesy: A.C. Davies, The Science and Practice of Welding, Vol 2, Cambridge University Press, N.Y., 1989*)

Plasma arc welding gives rise to what is known as keyhole effect when performing square butt joints in the thickness range of 2 to 6 mm. A keyhole is formed at the leading edge of the weld metal, where the forces of the plasma jet displace the molten metal to permit the arc to pass completely through the work piece. This keyhole is an indication of complete penetration. In the key hole technique, the molten pool is prevented from spilling by its surface tension. So no backing is required for support. When a filler metal is required it is added to the leading edge of the pool formed by the keyhole. The molten metal flowing around the keyhole forms a reinforced weld bead. Square butt joints upto 6 mm thick can be welded in a single pass by this method.

For heavier plates which require multi-pass welding partial beveling is done and the root pass of the largest size is deposited with the keyhole technique without using filler wire. The rest of the passes are then carried out with normal melt-in technique with filler wire addition. PAW process is limited to around 25 mm thick plates. Continuously formed stainless steel tubes are welded by plasma arc welding process without filler metal. This process has high rate of welding particularly for thick tubes. The welding speed is approximately twice that of gas tungsten arc welding for the same tube thickness.

Constricting orifice gives the stability of the plasma jet and increases its effectiveness. The plasma arc is columnar in nature due to the constriction provided by the nozzle. So this arc is less sensitive to the arc length variation, as compared to TIG. The area of heat input and intensity is almost constant. There are two types of plasma arc welding. (a) transferred arc and (b) non-transferred arc. The transferred arc is formed between the electrode and the work piece. The non-transferred arc is formed between the electrode and the nozzle. The transferred arc imparts greater energy to the work piece than the non-transferred arc and produces heat both from the anode spot on the work piece and plasma stream. The transferred arc generally is used for welding applications. The positive lead is connected to work as well as to the orifice body for pilot arcing. The main arc strikes between the electrode and the work piece. This type of connection is used for welding and cutting applications where more arc energy is to be transferred to the work piece. The non-transferred arc is used for special applications like surfacing, where lower energy concentration is desirable and, also used for joining of non-conductive materials. The arc is confined between the electrode and the nozzle and the arc energy is transferred to the work piece by the hot gas.

A mixture of argon-hydrogen (or pure argon in the case of reactive materials such as Zr and Ti) is used as the plasma and the shielding gases for stainless steel. For mild steel, CO₂ as the auxiliary shielding gas is used. In multilayer welding for second and subsequent passes, helium is used. For welding a plate of say, 6 mm stainless steel, the current of 240 amps with voltage of 38 V may be required. The welding speed will be around 350 mm/min and the plasma gas will be 0.6 cubic meter/hr and the shielding gas 1.4 cubic meter per hour.

The salient features of plasma arc process are:

- (a) narrow weld beads and HAZ
- (b) greater penetration and less distortion
- (c) less heating of surrounding parent metal and less current required than TIG.

(d) less arc wandering.

PAW process as compared to TIG process has the following advantages:

- (a) greater concentration of energy
- (b) improved arc stability at low currents
- (c) higher heat content
- (d) higher velocity of plasma
- (e) less sensitivity to variations of arc length
- (f) solid backing is avoided by adopting keyhole technique
- (g) no tungsten contamination.

In normal TIG, the arc is of conical shape and so the area of heat input to the work piece varies as the square of the arc length. Thus in TIG, a slight variation of arc length will cause appreciable change in unit area heat transfer rate. But the plasma jet is cylindrical and so changes of arc length have no effect on the area of heat input and the arc intensity. In normal TIG, the arc plasma spreads over a large area of the work piece and the arc is easily deflected by weak magnetic fields. In plasma process, the arc is stiff and very little affected by magnetic fields. The constriction of the arc in PAW results in higher plasma temperature and arc power.

However, in PAW

- (a) equipment cost is high
- (b) life of constricting nozzle is short
- (c) consumption of inert gas is increased.

A comparison of the different energy processes is of welding with tungsten inert gas welding is shown in Table 1.5.

1.2.5 Special methods

1.2.5.1 Explosive welding (EW)

Explosive welding is a process based on the controlled application of enormous power generated by detonating explosives. The surfaces of the parts to be joined must be clean without contamination of oxides etc. These clean surfaces are pressed at pressure of the order of million kg/sqcm generated by the explosive. Combination of dissimilar metals-aluminium to steel or titanium to steel - can be readily obtained by this process.

Metals which are too brittle to withstand the impact of explosion cannot be welded by this process. EW is a well suited process for cladding application. There is no upper limit for the thickness of the backer plate. EW can also be used for cladding the inner or outer surfaces of right cylinders.

The principle of operation is schematically shown for pipe welding in Fig. 1.21. The prime metal (external pipe) is oriented to the backer plate (internal pipe) with a small air gap, maintained by support metallic inserts. The backer plate rests on the anvil. The explosive in plastic liquid or granular form is placed uniformly over the prime metal and a moderating layer of polythene, water or rubber may be placed in between the explosive and the prime plate. This protects the surface of the prime plate from the explosion effects. The explosion is initiated by means of a detonator attached to it. Once the detonator is ignited, the wave front progresses forward and welds the prime plate with the backer.

Table 1.5 Comparison of different parameters of energy welding processes and TIG welding (plate thickness 6 mm)

<i>Parameter</i>	<i>Laser</i>	<i>TIG</i>	<i>Plasma</i>	<i>EB</i>
Power absorbed by work piece.	4 kW	2kW	4kW	5kW
Total power used	50kW	3kW	6kW	6kW
Traverse speed	16 mm/s	2 mm/s	5.7 mm/s	40 mm/s
Positional welding	yes; but requires optics to move the beam	serious penetration	serious penetration	yes; but requires mechanisms to move the gun
Distortion				
axial	minimum	significant	significant	minimum
shrinkage	small	yes	yes	minimum
angular	minimum	yes, in V-shaped weld	yes, in V-shaped	parallel sidedness
Surface profile defects	very fine flow lines	underside protrusion held in by surface tension	weld under side protrusion held in by surface tension	ruffled swarf on back face
Special requirements for process	safety interlock against misplaced beam reflection	normal light screening	normal light screening	vacuum chambers, X-ray screening
End defect	slight surface protrusion	smooth	slight surface protrusion	slight surface protrusion
Start finish	smooth	-do-	-do-	-do-

Fig. 1.21 Explosive welding parameters

40 Welding Technology and Design

The important variables of the process are

- (a) collision velocity and angle
- (b) mechanical properties of the metals to be welded.

The detonating velocity of the explosive in combination with the preset angle between the plates determines the collisional velocity. Below a certain collisional velocity welding will not occur. For welding to occur, the collisional velocity should be nearly equal to the sonic velocity of the plates.

The following Tables 1.6 and 1.7 give the metal and the sonic velocity and the detonating parameters of different explosives.

There is a maximum collision angle above which no welding will occur regardless of collision velocity. In parallel plates cladding, this angle is established by the distance between the plates called stand-off distance. In the case of angle cladding the preset angle and the stand-off will give the collision angle.

Table 1.6 Sonic velocity of different metals

<i>Metal</i>	<i>Sonic velocity meter/sec</i>
Aluminium	5370
Copper	3970
Magnesium	4493
Nickel	4667
Molybdenum	5173
Titanium	4786
Zirconium	3771
Steel	4600

Table 1.7 Detonating parameters of different explosives

<i>Explosive</i>	<i>Detonating temperature °C</i>	<i>Detonating velocity m/sec</i>	<i>Detonating pressure kg/sq.cm.</i>
BDX	5450	8400	263,500
Nitropenta	5400	8300	232,000
Tetryl	4440	7800	204,000
Pertit	3900	7300	186,000
TNT Dynamite	3900	6900	158,000
Dynamite	3900	6000	107,000

When the explosion occurs and the pressure on the prime plate builds up, jetting takes place at the collision point and brings together the two materials under high pressure and extreme plastic deformation. The original surface layer will be swept in the jet. Thus a direct metal to metal contact is achieved and a weld results.

The bond obtained can be

- (a) straight direct metal to metal bond
- (b) wavy bond
- (c) straight but with a continuous layer between the plates.

The type of bond depends on the collision velocity. Normally a wavy type of bond represents a good defect free welding. EW is used in chemical process equipments to clad corrosion and erosion resistant thin materials to the inner surface of the pressure vessels. In the coin industry, cupro-nickel is clad on thick copper

and the the billets are rolled. The cladding is done by explosive welding. Dissimilar metal welds can be easily made by explosive welding method. Such welding process is commonly used is electrical and cryogenic applications.

Pipes can be welded by explosive welding process with lapped joint through the simultaneous initiation of external and internal explosive charges as indicated in Fig. 1.21. The process can be easily applied under pipe line construction conditions. The charges progressively denote from the apex outwards to the open end of the angular gap established by the overlapping or bell and spigot configuration. The intense pressure generated at the point of collision, in combination with the angular collision geometry, causes severe flow of the surface layer of the pipes and the formation of a jet. The jet—a mixture of the two surface layers and their contaminants—is expelled from the collision zone leaving uncontaminated metal surface in intimate contact for the formation of a metallurgical or solid phase bond.

Another method of joining two pipes by explosive method is based on an inner ring welding. A backing outer ring is placed outside the joint to take up the detonating

Fig. 1.22 Explosive welding of two pipes with inner ring.

force. The inner ring along with the explosive is placed at the junction of the two pipes as indicated in Fig. 1.22. When the explosive detonates, the inner ring expands and gets welded on to the inner surfaces of the two pipes. The entire force is taken care of by the back outer ring. By suitable dimensioning and controlled deformation, the inner bore diameter can be properly adjusted to suit the pipes. As all the

explosions are inside the pipe, the noise and environmental problems will be easier to solve.

Fig. 1.23 Friction welding process

1.2.5.2 Friction welding

Friction between the two welding faces is used to create heat to the extent that the material at the two surfaces become plastic. Welding is effected by applying axial force. A schematic diagram of the friction welding process is shown in Fig. 1.23.

The friction welding process is divided into two distinct modes:

- (a) conventional drive friction welding, and
- (b) inertia welding

In the conventional drive friction welding, the pieces are axially aligned. One component is rotated at a constant speed by a direct drive while the other is moved into contact with the former under axial pressure. Sufficient time is allowed for heat generation, so that the interfacial temperature will make the material plastic and permit the components to be forged together. At this stage the rotation is rapidly stopped while the pressure is still maintained to consolidate the joint.

Though the basic principle is the same, in the inertia welding kinetic energy from a rotating flywheel system is used to heat the faces of components to be welded. One component will be attached to the flywheel rotating at high speed. The other component will be brought to face the first, so that friction between the two will generate heat. The flywheel energy will be utilized to obtain a good bond between the components.

The principal variables in this process are the relative velocity, heating and forging pressure and the duration of heating. The secondary factors are pressure build up during heating and forging, deceleration during braking and the properties of the material being welded. Peripheral speeds in the range of 75 to 105 meters per minute appear to give satisfactory welds. Too high a speed may result in a wide HAZ. Lower speeds will not be able to generate sufficient heat and raise the temperature upto the required level. The forging pressure depends on the hot

strength of the alloy being welded. The pressure chosen must be sufficient to weld the surfaces.

Duration of the heating time depends on rotational speed, friction and the pressure. Heating time determines the heat input. Steels of all varieties, stainless steels, copper and its alloy can be easily welded by friction welding process.

In inertia welding the initial peripheral velocity of the rotating work piece, axial pressure and the flywheel size are the main factors to be considered for good welding. The peripheral velocity must be above a minimum *e.g.*, for mild steel it is 1.5 meter/sec. The axial pressure influences the heating. As a thumb rule, the value of the thrust pressure can be chosen as about 25 per cent of the room temperature yield strength of the material being welded. The flywheel size and the surface speed of the material control the energy required for the inertia welding process. The power capability of the flywheel is limited only by the rate at which it can be retarded.

The peak power demand is met by the flywheel by stopping in about 0.5 sec for steel, 0.2 sec for copper and 0.1 sec for tungsten. In addition the flywheel supplies the torsional forging force towards the end of the welding cycle. To keep the thermal disturbances to a minimum, and to avoid over upsetting, welding times are usually reduced to a few seconds. However, the time is dependent on the material to be welded and the size of the weldments and hence the maximum time may be up to a half a minute.

The type and shape of the joint made by friction welding are limited by the very nature of the welding process. Round-bar butt joints, tube butt joints, bar or tube tee-joints can be made in a wide range of materials. Joints between dissimilar metals can also be made: for example, copper to steel, copper to aluminium, aluminium to steel or brass and bronze to aluminium or steel. Special steel alloy with differing properties can also be successfully welded. Welding of certain plastics is also possible.

Special friction welding machines which provide a high degree of control over the variables in the welding process, namely, time, surface speed and axial pressure to suit a wide range of materials are available and the welding of parts can be repeated without any defect or difficulty.

Tables 1.8 and 1.9 give the typical parametric values for frictional welding and inertia welding.

Table 1.8 Typical parameter of frictional welding

<i>Material</i>	<i>Diameter of surface mm</i>	<i>Rotational speed rpm</i>	<i>Axial pressure kg/sqmm</i>	<i>Upset mm</i>
Low carbon steel	20	1500	5 - 12	5
Medium carbon steel	10	3000	4 - 10	3
Stainless steel	10	1500	12 - 30	3
Dissimilar weld				
High speed steel + carbon steel	15	1500	12 - 30	6

Table 1.9 Typical parameters for inertia welding

<i>Base material</i>	<i>Peripheral speed meter/s</i>	<i>Minimum weld energy kg.m./sqmm</i>	<i>Axial pressure for 15 mm kg/sqmm</i>
LC steel	2.5 - 5	6.6	11.2
MC steel	2.5 - 5	7.7	12.0
S.S.	3.0 - 4.5	8.2	13.8
S.S. to carbon steel	3.0 - 4.0	3.2	13.8

Radial friction welding of pipes

Radial friction welding is a one-shot welding process with great potential for the joining of pipe lines. It operates on the principle of rotating and compressing a solid ring on two stationary pipe ends producing a solid state bond. Radial friction welding is essentially a forge welding process where heat is provided by relative rotary motion of the ring and the pipe. The pipes to be joined are clamped stationary and the welding action is provided by the rotating solid ring located around the pipe ends. A simple form of the process is shown in Fig. 1.24. The rotating ring is compressed radially and welding of the pipe ends is initiated by the heat produced due to friction and the plastic flow of the material. After a predetermined heating period, ring rotation is stopped and an increased level of compressive force is applied to consolidate the weld. Throughout the weld sequence, the two pipes are securely clamped to prevent axial and rotational movement. A support mandrel can be inserted in the bore of the pipes to prevent pipe collapse and flash metal penetration. Experience has shown that defect free welds are readily produced in carbon-manganese steel and duplex stainless steel.

Fig. 1.24 Radial friction welding of pipes**1.2.5.3 Diffusion bonding**

Diffusion bonding is a joining process which requires high temperature to enhance diffusion, but involves very little macroscopic deformation; the joint is formed without any filler metal and the microstructure and composition at the interface are the same as those of the base metals. Pressure is applied which will

cause local plastic and creep deformation at the temperature of operation. Bonding will take place due to diffusion and will depend on temperature, time and the pressure applied. An interlayer foil or coating may be used to improve the bonding characteristics. Recrystallization and grain boundary migration at the interface will occur at the final stages of bonding and these processes are essential for obtaining high strength joints and to eliminate the planar boundary interface.

The pressure can be applied on the surfaces to be joined through a platten. Gas pressure can also be used to achieve the same. To preserve the clean surface the bonding can be carried out in vacuum. If gas pressure is employed for the application of load, then an argon gas chamber can be used. The major advantages of diffusion bonding are:

- (a) Joint strength can approach that of the base metal.
- (b) Sintered products, dissimilar materials including metal and ceramics can be joined by this process.
- (c) Bonding involves minimum deformation and distortion and hence close dimensional control is possible.
- (d) In metal ceramics joints residual stresses can be reduced by multiple interlayers.
- (e) Thin sheets of fine grained superplastic materials can be easily joined and formed to any desired shape and contour by diffusion bonding.
- (f) Large area bonding is possible and thick and thin sections can be easily joined. Process time is independent of area or number of components.
- (g) Machining cost is reduced and no flux or electrode is necessary.

The important variables that will affect the bond quality are (i) surface roughness, and (ii) surface oxide films. Stable oxide films such as Al_2O_3 or Cr_2O_3 , nitride or carbide films make solid state bonding difficult and need to be removed by spatter cleaning. However, unstable oxides such as Ag_2O or oxides soluble in the base metal such as TiO_2 , allow good bonds to be made if the operating temperature is above the oxides' instability temperature.

Some typical examples of diffusion bonding are presented in the following:

Titanium alloys: The operating temperature is kept above 850°C so that the surface oxide film TiO_2 will dissolve in the parent metal. The environment must be free from oxygen and moisture. For thick sheet a pressure of 14 MPa may be applied for bonding. Void defects in diffusion bonding joints usually originate from grinding or machining grooves on the surface. In inert gas environment voids can be caused by entrapped gas. Good surface finish of the base materials and bonding in vacuum will reduce the chance of void formation. Typical joint shear strength for Ti-6Al-4V sheet will be 575 MPa (almost the same as the parent metal strength), for diffusion bonded joint, as compared to 10 MPa for rivetted joints and 40 MPa for adhesive bonded joints.

Aluminium alloys : The presence of tenacious surface oxide film makes diffusion bonding of aluminium alloys very difficult. Introduction of soft interlayers in the form of cladding coating or foil inserts enables bonds to be made with small overall deformation. 7475 aluminium alloy sheets can be successfully welded using 5052-Al-Mg alloy as an interlayer and the operating temperature and applied

pressure as 500°C and 2.75 MPa respectively. The maximum shear strength is obtained with the bonding time of around 4 hours. The production of oxide free surfaces on aluminium alloy can be possible by using argon-ion spatter cleaning, followed by coating by silver. Such surfaces are readily bonded above the dissociation temperature of Ag_2O ($\approx 200^\circ\text{C}$).

Dissimilar metals: The need to have physical and chemical compatibility between the two material to be joined, makes it necessary to have interlayers in diffusion bonding of dissimilar metals. Use of multiple layer is more common to obtain good and sound bonding. The interlayers must exhibit mutual solubility without the formation of intermetallic compounds, wide temperature range for bonding (0.5 to 0.7 T_m), compatible thermal expansion, and Young's moduli. Joining of Ti alloy with stainless steel can be achieved by having interlayers made of Ni/Cu/V combination. Thus the joint will have stainless steel/Ni/Cu/V/Ti-Al-4V interface. Such a bond made at 850°C under a pressure of 10 MPa gives a tensile strength of around 400 MPa (70% of the UTS of stainless steel).

Metal matrix composites (*e.g.* Ti alloy with SiC fibres) are also produced by diffusion bonding methods, similar to the dissimilar metal joining. Titanium alloy components joined by diffusion bonding are widely used in aerospace applications. Dissimilar metal (Ti/S.S., Ti/Al) diffusion bonded components find their application in cryogenic tube constructions. Al/Zr joints are used in nuclear fuel element constructions. Metal/ceramics joints are used in high temperature applications as in engine valves and fuel nozzles.

1.2.6 Selection of welding process

There are a number of welding processes available; however, their application is dictated by the material properties, type of weld joints, their quality required in the service condition, cost and availability of the machine and operator's skill. The following gives a comparative study of the different processes discussed and their applicability to different materials.

(a) *Oxy-acetylene gas welding:* This process can be used for carbon steel, copper, aluminium, bronze welding. Sheet metal welding and small diameter pipe welding can be effectively carried out. Control of the flame is important. Plates of thickness upto 8 mm - 10 mm can be welded.

Red brass and yellow brass are preferably welded by oxy-acetylene process to minimize vapourization of zinc.

(b) *Shielded metal arc welding:* This process is widely used. All engineering materials can be welded. However, low melting and high reactive metals will be difficult to weld. This process is easy to operate and plates of thickness ranging from 1 mm to 25 mm can be easily welded. Preheating will be required in some alloy steels. Welding can be done in flat, inclined, vertical and overhead position. Edge preparations are essential in welding thick plates.

Manual metal arc welding is commonly used in the erection of structural works like storage tanks, bridge etc. In open breezy conditions flux cored self shielded welding is better suited. Heavier plates are usually groove welded.

MMA and MIG/CO₂ processes are used for welding nozzles and other attachments in pressure vessels. MMA and TIG are extensively used for welding cupronickel (70:30 alloy) for water pipe and condenser tubes.

While welding carbon and low alloy steel pipes by MMA process for steam power plants, backing rings are commonly used. However, backing rings are rarely used for piping in oil refineries and chemical plants.

(c) *Submerged arc welding*: Carbon and alloy steels and copper alloys can be welded by this process; generally applied for plate thickness above 10 mm. Best suited for automatic welding in boilers, pressure vessels, ship building where high quality welds for larger thickness plates are required. This process is generally used for flat and horizontal positions. Not suitable for cast iron. With U-type of grooves, narrow gap welding can be carried out by this process and, plates as thick as 300 - 400 mm can be welded. In such cases of pressure vessel cylinders and pipes made of large thick plates, automatic submerged arc process is preferred.

(d) *Gas metal arc welding (TIG and MIG)*: All engineering materials except Zn can be welded. The thickness of the plates ranges from 1mm to 6mm. TIG is applied to all non-ferrous and alloy steel welding and also for root pass in pipe welding. Welding equipment is more complex and costly. Difficult to weld small corners and, out-door applications are limited. MIG process in semi-automatic or fully automatic form is used for non-ferrous and stainless steel pressure vessel parts.

In the manufacture of boiler units, large number of tube butt welds have to be made with the tubes positioned at any angle from horizontal to vertical, with restricted access. In such cases automated orbital TIG welding with automatic cold wire feed is used.

Titanium alloy tubes with wall thickness 1.6 mm and below are normally welded by TIG process without filler wire. For heavier pipes, filler metals are used.

(e) *Plasma arc welding*: This process is used mainly for reactive metals. The thickness of plates is usually upto 1.5 mm

Plasma arc welding equipments are costly and, mechanised PAW is restricted to flat and horizontal positions. Operating conditions are quite difficult. Large amount of ultra violet and infra-red rays are emitted. Thus PAW is used for welding Ni-alloys and refractory metals for special applications. It is also used for refractory metal coating, alumina (Al₂O₃) and titania (TiO₂) on graphite nozzle for rockets.

(f) *Spot, Projection and Seam welding*: These processes meant for sheet metals are widely applied in automobile parts, tube manufacturing and sheet metal industries. All engineering metals can be welded. Precautions are necessary in the case of copper and aluminium alloys which are good thermal and electrical conductors.

Flash or induction welding is used for tubular joints in boiler construction. At site, such welds are made by TIG for the root pass and MMAW for subsequent passes.

In automotive industries, radiators are either brazed or resistance seam welded. Upset seam welding is used for exhaust and tail pipes. The side seams are usually spot or seam welded. Seam welding is normally limited to sheets upto 5 mm thick.

Baffles and other interior parts are spot welded in place. A typical application of projection welding is in the manufacture of honey comb panels.

Propeller and drive shafts are commonly made from resistance welded tubing with the end forgings arc welded by submerged arc or MIG/CO₂ process.

(g) *Electro-slag welding*: This process is for thick section welding, 50 mm and above, of alloy steels. This is mainly used for pressure vessel parts, steel plant equipments, large shafts etc. Both ESW and SAW are best suited for thick plates; however, ESW is more specialized in its application and less flexible compared to SAW.

(h) *Electron and laser beam welding*: Stainless steel, nickel base alloys, Ti and Zr and other reactive metals upto 10 to 25 mm can be welded. Special applications are in electronic industries, nuclear and aerospace industries. The process is rather costly.

Laser welding has the ability to make tiny spot welds. So it is applied in microelectronic circuits. Laser beam can weld metals on silicon and germanium.

(j) *Diffusion bonding*: This is widely used in the manufacture of metallic components for electronic tubes.

1.3 CLASSIFICATION OF ELECTRODES

1.3.1 Electrode coating

Electrode covering has a large effect on its performance. The functions of the electrode include the following; it

- (a) provides a vapour shield to protect the molten metal from reaction with the oxygen and nitrogen of the air.
- (b) provides an ionised path for conducting current from the electrode tip to the work and for maintenance of an arc.
- (c) provides flux for cleansing the metal surface of oxides and tying up any oxides as slags that float to the top and may be removed from the finish weld.
- (d) controls the weld profile, especially on fillet welds.
- (e) controls the melt-off rate of the electrodes
- (f) controls the penetration properties of the arc.
- (g) provides filler metal in addition to that supplied by the core wire.
- (h) adds alloy materials to the weld deposits where a particular chemical composition is required.

Materials used in the electrode covering for fluxing and slag formation, vary in their abilities to clean dirty or rusty plate and provide the thickness of the resultant slag covering. These materials remove undesirable elements, and form slags that

rise to the surface of the pool, freeze before the metal below freezes and thus aid in the protection of the molten metal from reaction with the atmosphere. Deoxidizers in the covering serve to reduce oxides that might have been present on the work or inadvertently formed by oxidation of the molten metal through imperfect shielding or slagging. Oxides would tend to make the weld metal brittle. The most commonly used deoxidizing agents are silicon, aluminium and manganese.

Arc stabilization is another important function of the electrode covering. With AC current, which reverses its direction, there is tendency for the arc to “cut-off” every time the current flow is reversed. This problem is solved in the AC electrode by incorporating potassium compounds, such as potassium titanate in the covering. Thus DC electrodes are not useable with AC currents, but AC electrodes can be used with DC current.

The electrode covering is also used for adding filler metal ingredients to the weld deposits. Thus iron powder is extensively used in electrode covering-adding iron to the weld, in addition to the iron supplied by the core wire. A small percentage of iron powder, in some E6010 electrodes, stabilizes and quiets the arc without loss of penetration characteristics. Iron powder added in large amount increases the deposition rate, increases the optimum current and, with thick covering, facilitates the use of the drag technique in welding. The electrode covering can also be a source of alloying metals, such as manganese, nickel, chromium, and molybdenum. When mixed with iron from the steel wire core, an alloy weld is created during the welding process.

There are four main types of electrode coatings on which all mild and low alloy steel electrodes are based.

- (a) *Gas shielded (cellulosic) electrodes* : These coatings developed originally nearly 60 years ago contain over 30 per cent of organic material such as alpha flock, wood flour or other cellulose. In the arc the coating breaks down to give a voluminous gas shield of H_2 , CO and CO_2 which give good protection of the molten weld metal with consequent good weld metal properties. These electrodes develop a strong plasma jet which gives excellent penetration. Burning off rate of the electrode is low and the coating constitution leads to only a small amount of thin friable slag being formed, which makes the electrode very suitable for positional welding, including vertical position. Direct current is necessary.
- (b) *Rutile electrodes* : This coating contains 50 per cent titania (TiO_2) as the minerals rutile or ilmenite. This compound gives good arc stability and low operating voltage so that it can readily be used with alternating current. Protection against contamination is effected by a gaseous atmosphere containing hydrogen, oxides of carbon nitrogen together with an acidic slag, whose viscosity can be varied by minor mineral additions. The easily controllable slag, low spatter, medium penetration and high deposition rate make this electrode type ideal for general engineering. Weld appearance is also good and uniform and mechanical properties are generally sound. However, ductility is lower than that with other coatings.

(c) *Iron oxide/silicate electrodes* : The coating is based on iron oxide and manganese oxide and associated silicates. This gives very little gas shielding but a voluminous acidic slag which can result in intense slag metal reactions. Depending on other constituents of the coating, the high oxygen content can lead to a very low carbon weld deposit of low strength or a well deoxidised deposit with good strength and ductility. A low operating voltage makes the electrode suitable for a.c or d.c. The slag makes control, and therefore position welding difficult, but gives good weld appearance with a slightly concave profile which is excellent for fillet welds and deep grooves. Deposition rates are high, penetration good and spatter low. Although mechanical properties (strength and ductility) and soundness are good, the high oxygen content of the weld metal gives low notch ductility. Additionally, the acid slags cannot cope with high sulphur contents which lead to weld metal cracking.

(d) *Basic electrodes* : This type, also known as low hydrogen, lime-ferritic or lime-fluorspar electrodes, has a complex coating containing a high proportion of limestone (CaCO_3) and Fluorspar (CaF_2). Clays, asbestos and other minerals with combined water are kept to a minimum to ensure very low hydrogen contents in the weld deposit. For this reason basic electrodes are also baked at a higher temperature than other types and are stored under dry conditions.

Protection against contamination is by CO_2 -CO gas yield (with no H_2) and a fluid basic (or semi basic) slag which allows good deoxidation of the metal which has low oxygen content. Mechanical properties including ductility and notch toughness are superior to other types, soundness is excellent and the deposit has a high resistance to hot and cold cracking which is very good for welding higher strength steels (most alloy electrodes have basic coatings). Basic electrodes are also less sensitive to plate quality than other types and they are used for high carbon or high sulphur containing steels.

The arc voltage of basic electrodes is fairly high, and most electrodes require direct current electrode positive. But the addition of potassium salts to the coating leads to potassium ions in the arc atmosphere and allows the use of alternating current. It is necessary to maintain a short arc length. The slag is fluid and gives the weld bead a convex to flat profile which can lead to deslagging problems. These electrodes give medium speed of deposition, moderate penetration and good bead appearance. They are generally more difficult to use than rutile electrode and require short arc lengths and care in weaving, stopping and starting, if porosity and slag inclusions are to be avoided. Dampness in the coating must be avoided.

Table 1.10 gives the comparison of the four electrodes. The differences are only marginal.

Table 1.10 Comparison of four types of electrodes

<i>Electrode class</i>	<i>Rutile</i>	<i>Gas shielded</i>	<i>iron oxide silicate</i>	<i>Basic</i>
Ductility	4	2	3	1
Penetration	4	1	2	3
Absence of undercut	1	4	3	2
Absence of spatter	2	4	1	3
Deposition efficiency	1	4	3	2
Deposition rate	2	4	1	3
Soundness	3	4	1	2
Ease of handling	1	3	4	2
Ease of re-striking	1	2	3	4
Resistance to cracking	2	3	4	1

Note : 1 indicates the best results; 4 the worst.

The division of electrode coatings into four main types gives only a general picture of coatings and it is worthwhile considering further subdivisions or combinations of these types:

- (a) *Cellulosic electrodes* : Little variation is possible with this major type of electrode. The original coatings restrict use to direct current; however, minor additions or arc stabilisers allow the use of a.c. with some electrodes. Spatter losses remain high and the weld bead is coarse with uneven ripples. Mechanical properties of the weld are good.
- (b) *Medium rutile electrodes* : With an average coating thickness i.e., outer diameter less than one and a half times the core wire diameter, it is based on titanium dioxide, with around 15 per cent of cellulosic material present in the covering to give some gas shielding. These electrodes are suitable for positional welding. Hot cracking can occur with small throat thicknesses although the weld metal is not so susceptible as iron oxide/silicate deposits.
- (c) *Heavy rutile electrodes* : Thicker coverings with less, below 5 per cent, cellulosic additions result in a heavy compact self detaching slag. The weld appearance is smooth and mechanical properties are quite good.
- (d) *Iron oxide acid electrodes* : These electrodes have a medium to heavy covering that produces an iron oxide, manganese oxide-silica acidic slag. Further, the covering contains deoxidizers (generally ferromanganese) to give sound weld deposits with good mechanical properties. The solid slag has a characteristic honey comb structure and is readily detached. Deposition rates are high and deep penetration can be achieved with thick coverings. Though the welds can be made in all positions, the nature of the molten slag (voluminous and often fluid) makes these electrodes best suited in the flat position.
Weld deposits from these electrodes are more susceptible to hot cracking than from other types and care must be taken with the parent material. Carbon content should not exceed 0.24 per cent nor sulphur content exceed 0.05 per cent for killed steels or 0.06 per cent for rimmed steels. Crack susceptibility is most marked in horizontal-vertical or vertical fillet welds.
- (e) *Rutile acid electrodes* : With replacement of iron and/or manganese oxide by titania upto a maximum of 30 per cent, a somewhat more fluid acid slag is

52 Welding Technology and Design

produced. Mechanical properties and weld soundness are similar to iron acid electrodes.

(f) *Oxidising electrodes* : A thick covering based on iron oxide and possible manganese oxide without deoxidants produces an oxidising slag which gives a weld deposit with very low carbon and manganese contents and low strength. Penetration is low and molten weld metal fluid, restricting use to horizontal/vertical or flat fillet welds. The slag is heavy, compact and self detaching and gives excellent weld appearance.

(g) *Basic electrodes* : These electrodes have thick coverings containing considerable amount of basic carbonates (generally calcium or magnesium) and calcium fluoride, which give CO_2 gas shielding and an active basic or semi-basic slag. Deoxidation is generally effected by ferro-silicon and ferro manganese. The deposited weld metal is low in oxygen, hydrogen and nitrogen, retains alloying additions and has excellent mechanical properties, particularly ductility and toughness. A medium quantity of dense slag forms on the weld giving a reasonably good appearance. Slag inclusions are rare.

The coatings are often hygroscopic and must be stored under warm dry conditions to prevent moisture. Otherwise hydrogen in the weld metal can lead to porosity, fissuring and underbead cracking in susceptible steels. Moisture content should not exceed 0.6 per cent.

The high ductility and low hydrogen content of the weld deposits lead to excellent resistance to hot and cold cracking and basic electrodes are particularly suitable for welding heavy or highly restrained structures.

(h) *Iron powder electrodes* : Iron powder can be added to all types of electrode coverings; so it is not strictly a single type.

The main advantages of the addition of iron powder are :

- * it allows nearly twice the deposition rate;
- * the iron powder is recovered in the weld deposit so that a specified electrode length will give a longer arcing time and a large bead.

Iron powder also reduces the operating voltage; this can be an advantage, and for example, it allows cellulosic electrodes to be used with alternating current; however, 50 per cent iron powder in the coating reduces operation. Iron powder also increases slag fluidity which leads to manipulation difficulties for positional welding. However, electrode coverings are often slightly conducting and this allows 'touch' welding in the flat position. To get high deposition rates, particularly at the lower operating voltages, these electrodes use high current which can lead to a decrease in weld metal ductility. Ductility improves after a post weld tempering or stress relieving heat treatment.

A recent development has been the introduction of low hydrogen rutile iron powder electrodes which offer an electrode that is easy to use in the flat position and gives a low hydrogen content in the weld deposit. There is some indication that certain of these electrodes can give porosity in positional welds and require a high level of operator skill for position welding.

1.3.2 Classification of electrodes

The American classification system (AWS Designation A.5.1. ASTM A 2233 for mild steel and A5.5 ASTM 316 for low alloy steel) is different from the British system. Classification consists of a prefix letter E specifying an electrode, a group of two or three digits specifying weld metal strength in ksi in the 'as-weld' or stress relieved condition, and a final two digits specifying type of covering, weld position and current characteristics. Typical examples are given in Table 1.11

Table 1.11 Nomenclature of electrode specification

E60xx	60ksi (420MPa)
E70xx	70ksi (490 MPa)
E80xx	80ksi (560 MPa)
E90xx	90ksi (630 MPa)
E100xx	100 ksi (700 MPa)

Typical electrodes (those in brackets are widely used) are given in the following:

Exx10	Cellulosic covering for the use with DC reversed polarity
(E6010)	only. Deep penetration and all positions electrode for general purpose.
Exx11	Cellulosic covering for AC or DC., all position.
(E6011)	Deep Penetration and thin slag, X-ray quality weld.
Exx12	Rutile covering AC or DC, all positions.
(E6012)	Medium penetration, good choice for fit-up work.
Exx13	Rutile electrode, AC or DC, all position.
(E6013)	Good performance in sheet metal welding.
Exx14	Iron powder rutile covering giving same characteristic as Exx 13, but with a higher welding speed.
Exx15	Basic low hydrogen covering requiring use of DC only, all positions for steel welds.
(E7015)	Good for high sulfur steels.
Exx16	Basic low hydrogen covering as Exx15 but with addition of potassium salts to allow operation with AC.
(E7016)	
Exx18	Low hydrogen electrode as Exx 16, but with 30% iron powder to give better welding speeds and recovery. All position use, AC or DC reverse polarity.
(E7018)	
Exx20	Typical mineral (iron oxide/silicate) covering for use in flat and
(E6020)	horizontal positions. AC or DC, produces a spray type arc and a heavy slag that can be easily removed.
Exx24	Rutile and 50 per cent iron powder covering similar to Exx12, with
(E7024)	better recovery and suitable for touch welding. F and Hz positions only. High deposit rate, AC or DC straight polarity.
Exx27	Mineral plus 50 iron powder covering with similar
(E6027)	characteristics to Exx20. Very high deposition rate, Spray type of arc and AC or DC straight polarity.
Exx28	Low hydrogen basic plus 50 per cent iron powder covering with high
(E7028)	deposition rate. F and Hz positions only. AC or DC reverse polarity.

54 Welding Technology and Design

Exx30 Mineral covering similar to Exx20 but high deposition rates. F position only.

Note : The use of mineral or iron oxide/silicate covered electrodes is decreasing in the USA and UK.

Several high tensile low hydrogen electrodes are classified with extra suffixes *e.g.*, Exxxx-A1-B2 etc., which indicate the chemical composition of the deposit, and gas content of manual metal arc weld deposits.

AWS-specification A5.5-69 prescribes the chemical requirements for low alloy shielded metal arc weld metal. Classification is similar to that the mild steels covered electrodes with the addition of a suffix to indicate the alloy constituents of the deposited weld metal. *e.g.*, E7010-A1 or E 8016-B1. A1 for carbon molybdenum steel and B1 for chromium-molybdenum steels.

Electrodes - IS and AWS classifications and codes.

In the following are given some of the IS and AWS specifications for electrodes. For details the reader is advised to consult the specifications which cover the chemical compositions, mechanical properties, impact strength and other requirements.

IS 814 - 1991 Covered electrodes for manual metal arc welding of carbon and carbon manganese steels.

This standard is primarily concerned with the mechanical properties of the weld metal and no limits have been specified on the chemical composition of the weld metal.

For weld metals with tensile strength higher than 610 MPa reference can be made to IS 1395-1982 "Low and medium alloy steel covered electrodes for MMAW".

The classification of electrode is given by letter and numerals as give below :

Ex xxxx

E R 4211

The first letter "E" indicates a covered electrode for MMAW, manufactured by extrusion process,

The second letter "R" indicates type of covering *e.g.*, R = Rutile, A = Acid, B = Basic, C = Cellulosic, RR = Rutile heavy coated, S = any other type not mentioned here.

The first numerical "4" indicates strength (UTS = 410-510 MPa) in combination with the yield strength of the weld metal deposit YS = 330 MPa.

The second numerical digit indicates percentage elongation in combination with the impact value of the weld metal deposited. Thus "2" means 22 per cent minimum elongation with impact 47 J at zero °C.

The third digit "1" shows welding position in which the electrode may be used. "1" means all positions.

2 = all position except vertical

3 = flat butt weld horizontal/vertical fillet weld

4 = flat butt and fillet weld

5 = vertical down and flat butt

6 = any position not mentioned here.

The fourth digit indicates the current condition in which the electrode it to be used. Other IS and AWS standards are:

IS 815	1967	Classification and coding of covered electrodes for metal arc welding of structural steel.
IS 1387	1967	General requirement relating to supply of covered electrodes for metal arc welding.
IS 1395	1982	Low and medium alloy steel covered electrodes for MMAW.
IS 5206	1969	Specification for corrosion resisting chromium nickel steel covered electrodes.
IS 5511	1969	Covered electrodes for MMAW of cast iron
IS 5898		Copper and copper alloy bare solid welding rods and electrodes.
IS 6419	1971	Welding rods and bare electrodes for gas shielded arc welding of structural steels.
IS 7280	1974	Specification for bare wire electrodes for SAW of structural steels.
IS 8666	1977	Specification for copper and copper alloy covered electrodes for MMAW.
IS 9595		Recommendations for metal arc welding of carbon and carbon -Mn steels.
AWS A 5.1	1981	Specification for carbon steel covered arc welding electrodes.
AWS A 5.3	1988	Aluminium and aluminium alloy electrodes
AWS A 5.4	1981	Corrosion resistant chromium and Cr-Ni steel covered welding electrodes.
AWS A 5.5	1981	Low alloy steel covered arc welding electrodes
AWS A 5.6	1984	Covered copper and alloy arc welding electrodes.
AWS A 5.7	1984	Copper and copper alloy filler rods suitable for TIG, Plasma, and MIG welding process
AWS A 5.9	1981	Corrosion resisting Cr and Ni-Cr steel filler wires suitable for TIG, MIG, and SAW processes.
AWSA 5.10	1988	Aluminium and aluminium filler wires suitable for oxyacetylene, TIG, Plasma arc and MIG processes.
AWSA 5.11	1990	Nickel and nickel alloy covered welding electrodes.
AWS A 5.12	1980	Tungsten arc welding electrodes.
AWS A 5.13	1980	Solid surfacing welding rods and electrodes.
AWS A 5.14	1989	Nickel and nickel alloy bare welding rods and electrodes.
AWSA 5.15	1990	Welding rods and covered electrodes for cast iron.
AWSA 5.17	1980	Carbon steel electrodes and fluxes for submerged arc welding.
AWS A 5.16	1990	Titanium and Titanium alloy filler wires.
AWS A 5.18	1979	Carbon steel filler metals for TIG, Plasma arc and MIG/CO ₂ processes.
AWS A 5.19	1980	Magnesium alloy filler wires.
AWS A 5.20	1979	Carbon steel electrodes for flux-cored arc welding.

56 *Welding Technology and Design*

AWS A 5.21	1980	Composite surfacing welding rods and electrodes
AWS A 5.22	1980	Flux cored Cr and Cr-Ni steel electrodes
AWS A 5.23	1990	Low alloy steel electrodes and fluxes for submerged arc welding.
AWS A 5.24	1990	Zr and Zr alloy filler metal.
AWS A 5.25	1991	Flux wire combinations used for electroslag welding of carbon and high strength low alloy steels.
AWS A 5.26	1978	Consumables used for electro-slag welding of carbon and high strength alloy steels.
AWS A 5.28	1979	Bare solid wire of low alloy steel for use with TIG, MIG and PAW processes.
AWS A 29	1980	Low alloy steel electrodes for flux covered arc welding.

Matching electrodes must be used for alloy steels and stainless steels. For corrosion resistant base metals the electrode must also be corrosion resistant. Chromium-nickel steel electrodes are classified on the basis of chemical composition of the filler metal. AWS - A5.5--69 and AWS A5.5-69 specifications give the composition for stainless steel electrodes.

Hydrogen, oxygen and nitrogen can be present in mild and low alloy steel weld deposits; all are detrimental even in small amounts.

Hydrogen lowers the ductility and notch ductility of weld deposits. It is believed to cause fissuring (Micro-cracking) in non-hardenable weld deposits and cold (underbead) cracking in the heat affected zones of hardenable steels. It can also cause porosity. Hydrogen is considered to affect notch ductility and cracking in amounts above 0.0087 per cent.

Oxygen can lead to poor notch impact performance possibly by acting as a catalyst for precipitation reactions such as strain ageing. In larger amounts it can react with carbon to give carbon-monoxide and hence porosity.

Nitrogen is believed to contribute to weld metal fissuring and in larger amounts it leads to reduced ductility and the formation of hard needles of iron nitride. It can have a deleterious influence of creep behaviour, and in larger amounts cause porosity.

Basic covered electrodes give weld deposits low in hydrogen, oxygen and nitrogen. Cellulosic electrodes also give deposits with good mechanical properties and weld metal low in oxygen and nitrogen.

Some electrodes are compounded to deposit weld metal that solidifies rapidly after being melted by the arc, and are thus used specifically for welding in the vertical and overhead positions. They are known as Fast Freeze Electrodes. Commonly used Fast Freeze Electrodes in the welding of steel are E 6010, E 6011, E 7010-A and E 7010-G. The deposition rates are not very high with these electrodes. These electrodes provide deep penetration and maximum admixture. Slag formation is light and the arc is easy to control.

There are electrodes which are compounded to deposit metal rapidly in the heat of the arc, and are thus well suited to high speed welding on horizontal surface. These electrodes are known as Fast-Fill Electrodes. The weld metal solidifies somewhat slowly and so these electrodes are not suitable for out-of-position

welding. The arc penetration is shallow with minimum admixture. The bead is smooth, free of ripples. Spatter is negligible and slag formation is heavy; but it peels off easily. The commonly used Fast-Fill Electrodes in the welding of steel are E 7024, E 6027, and E 7020-A1.

Some electrodes known as Fill-Freeze Electrodes, provide a compromise between Fast Freeze and Fast-Fill characteristics and thus give a medium deposition rate and penetration. The commonly used Fill-Freeze electrodes are E 6012, E 6013 and E 7014.

Conventional electrodes may not be suitable for high quality welds which should not have any defects. In such cases low hydrogen electrodes are used. Typical examples are E 7018 and E 7028. These electrodes give :

- (a) X-ray quality welds requiring high mechanical properties.
- (b) Crack resistant welds in medium or high carbon steels; welds that resist hot-short cracking in phosphorus steels and welds that minimise porosity in sulfur bearing steels.
- (c) Welds in thick sections or in restrained joints in mild and alloy steels where shrinkage stresses may promote weld cracking.
- (d) Welds in alloy steels with strength of 500 MPa.
- (e) Multipass, vertical and overhead welds in mild steels.

Low hydrogen electrodes must be used in dry condition, if they are to give good result.

Fluxes : Fluxes are classified on the basis of the mechanical property of the weld deposit made with a particular electrode. The classification designation given to flux consists of a prefix “F”, indicating a flux, followed by two digit numbers representative of tensile strength and impact requirements for test welds made in accordance with the specification. This is followed by a set of numbers corresponding to the classification of the electrode used with the flux.

Flux cored electrodes are tubular wire containing within it the flux with all the ingredients for shielding the arc and weld pool, fluxing, deoxidizing and conditioning the molten metal. Specifications for flux cored arc welding electrodes are given in AWS A5.20-69 code.

1.3.3 Selection of electrodes

The selection of electrodes for any particular job has always been a compromise between the requirements of weld quality and the overall cost of fabrication.

Where quality is important it is necessary to select an electrode type which will give the appropriate weld metal properties. However, the skill of the operators and conditions of electrode storage and usage must also be considered. In many cases it may be preferable to sacrifice the maximum quality to ensure that sound defect-free welds can be obtained under prevailing conditions of fabrication. Once the required quality has been defined it is possible to select the electrode type and make which will give the lowest fabrication cost or highest production rate.

Trends in electrode selections have been apparent for many years. For the highest quality in mild and low alloy steel deposits, basic electrodes are selected. If the parent plate quality is dubious or unknown, basic electrodes are again used. The

58 Welding Technology and Design

use of iron powder basic coatings can help the ease of the use and deposition rate although it may prevent positional weldings.

Aluminium and aluminium alloy welding rods and bare electrodes are made in accordance with AWS A5.10.69 specifications. The filler metals are classified on the basis of their chemical composition as manufactured and their useability. Types ER 5356, ER 4043 and ER 5183 can be used for large variety of welding applications.

Some typical metal arc welding electrodes for welding alloy steels are given in Table 1.12.

Table 1.12 Electrodes and their uses

1. <i>Mild steel heavy duty electrodes</i>	Rutile or basic coated for medium and heavy duty fabrications. The latter is suitable for carbon and alloy steels, mild steel, high strength steels under restraint and for root runs.
2. <i>High tensile alloy steel electrodes</i>	Austenite rutile or basic coated; used for high strength steels including armour plates, joints between low alloy and stainless steels.
3. <i>Structural steel electrodes</i>	Basic coated: used for high strength structural steel and copper bearing weathering quality steels.
4. <i>Ductile steel electrodes for low temperature</i>	Basic coated: used for Ni base steels, 2.5% Ni-C-Mn steels.
5. <i>Creep resistant steel electrodes</i>	Ferritic and basic coating: can be used Cr-Mo boiler steels with pre-and post-heating.
6. <i>Heat and corrosion resistant steel electrodes</i>	Rutile or basic coating : for 19%Cr9% Ni extra low carbon stainless steels. Basic coated for Nb or Ti stabilised 18/8 stainless steels. Rutile or basic coated for Mo bearing 18/10 Mo steels. Rutile or basic coated low carbon stainless steels electrodes for low carbon Mo bearing steels. Basic coated austenitic electrodes for 25% Cr-11% Ni steels and for joints in stainless steel clad to mild steel. Rutile coating austenitic for 23%Cr-11% Ni heat resistant steel containing tungsten. Basic coated 25% Cr-20% Ni (non-magnetic) for welding austenitic 20/20 steels.
7. <i>12-14% Mn steel electrodes</i>	Basic coating for Mn steel parts-steel excavators and mining equipments. Tubular type electrodes for hardfacing Mn steel parts.

1.4 WELD JOINT CONSIDERATIONS

1.4.1 General procedure

For every welding job there is one procedure which will give the best including the cost considerations. The main factors that must be considered are :

- type of joint to be made, included angle, root opening and land (root face).
- type and size of electrode.
- type of current, polarity and amperage.
- arc length and speed.
- position of welds (flat, horizontal, vertical and overhead).

The designer must consider problems and include them in his analysis of the joint design.

A root opening is used for electrode accessibility to the base of the joint. The smaller the angle of the bevel, the larger will be root opening to obtain good fusion at the root. Back up strips are used on larger root opening, specially when all weldings have to be carried out from one side. Spacer strips may be used specially in the case of double -Vee joints to prevent burn-through.

A land is provided to have additional thickness of the metal. A sharp feather edge preparation is more prone to burn through than a job with a land, especially if the gap is a bit too large. A land usually requires back gouging, if a perfect weld is required. A land is not recommended when welding into a back up strip, since a gas pocket will be formed.

Fig. 1.25 Basic type of welded joints and welds (Courtesy: American Welding Society, Standard Welding Symbols: A2.0-68)

1.4.2 Type of welded joints

1.4.2.1 General

The important consideration of designing a weldment is the selection of the best type of edge preparation for the given application. During the selection the following main factors must be considered.

1. Magnitude and type of loading *i.e.*, static compression or tension, fatigue, bending, impact etc.
2. The effect of warping on cooling.
3. The thickness of the material to be welded.

The basic type of welded joints are: butt, tee, corner, lap and edge, as shown in Fig. 1.25. The basic types of welds are: fillet, square, bevelgroove, J-groove and U-groove. The type of joints does not affect the weld. The definition of a welded joint must include description of both the joint and the weld.

1.4.2.2 Groove-welds

The commonly used groove welds have a number of typical properties :

- (a) Single groove welds welded from one side only should not be used for bending or fatigue loading. It may fail due to stress concentration at the weld root.
- (b) Single or double groove welds which are welded from both sides can develop full strength.
- (c) If welds do not extend completely through the thickness of the members joined, the joint should not be used for fatigue loading.
- (d) With single or double bevel type of groove, it may be more difficult to obtain sound weld.
- (e) If backing strip is used during welding, it must be removed if the joint is subjected to fatigue type of loading.

1.4.2.3 Various types of groove welds

- (a) Square grooves may be used with butt, corner Tee and edge joints. Complete penetration of square groove weld is obtained by welding from both sides on material upto 3 mm thick without any root opening and on materials upto 6 mm with adequate root opening.
- (b) Single Vee groove joints are suitable for materials of 6 mm to 19 mm thick with a minimum root opening of 60 deg. Single Vee groove joints are suitable for most loading conditions.
- (c) Double Vee groove joints are applicable to butt joint for materials with thickness ranging from 12 mm to 38 mm. Control of distortion is also achieved by using double Vee groove joint and welding on alternate sides of the joint and so balancing the heat input.
- (d) Single Bevel groove joints include butt, Tee and corner joints. This joint may be used for thickness between 6 mm to 19 mm. However, the narrow included angle (35 to 45 deg.) of the bevel groove joint makes it one of the least desirable types of joint.
- (e) Double Bevel groove joint may be used for thickness upto 38 mm.

Fig. 1.26. Different types of edge preparation

- (f) Single U-groove applies to butt and corner joints. U-groove joint consumes less weld metal and gives reduced distortion. U-groove can be successfully applied to thickness range of 19 mm. The weld metal width is uniform. Because of rounded bottom at the root, it is easier to achieve a better side wall fusion at the root than in the V-groove type of weld.
- (g) Double U-groove joint is suitable only for butt joint. It is economical for plate thicknesses greater than 38 mm and has all the advantages of single U-groove joint.
- (h) Single J-groove joint may be used for butt, Tee and corner joints. It is applicable particularly when the thickness exceeds 19 mm. The common root opening angle is 15 to 25 deg.
- (i) Double J-groove joint is capable of withstanding loads of all types in heavy plates. This joint is recommended when the thickness is more than 38 mm.

Figure 1.26 gives summary of different types of edge preparation for various welding processes.

1.4.2.4 Fillet welded joint

Though fillet weld may require more filler metal than groove welds the edges for the fillet welded joints are very simple to prepare and to fit up. Figure 1.27 shows the different fillet weld joints. The following are considered in fillet welded joint.

Fig. 1.27 Combined groove and fillet joint

- (a) Single fillet welded joint is employed in Lap, Tee and Corner joints. The strength of these joint depends on the size of the fillet. If loading is not severe, these joints are suitable upto 12 mm of plate thickness. In fatigue or bending the joint will be weak.
- (b) Double fillet welded joint is used for Tee, lap and corner joints. It develops full strength of the base metal and hence can be used for fatigue type of loading also.
- (c) Combined groove and fillet joint may be used in certain applications to improve the stress distribution within the joint, specially in Tee and corner joints.

1.4.2.5 Comparison of joints

In general butt joint is preferable to the single and double fillet or lap joint when

- (a) the joint undergoes appreciable tension, bending and shock or fatigue stresses.
- (b) overlapping parts would decrease thermal conductivity where this is a most important factor.
- (c) there is a possibility of corrosion between the overlapping structures.
- (d) a maximum saving in weight is desired.

The main disadvantages of the butt joint are :

- (a) Greater cost of preparation.
- (b) Higher assembly cost in some of the products.
- (c) Lack of design flexibility in weld size.
- (d) Greater skill required.
- (e) Use of smaller electrodes or filler rods and lower currents for the root layers.
- (f) Greater shrinkage and higher residual stresses.

1.4.3 Welding symbols

The welding symbols denote the type of weld to be applied to a particular weldment. These symbols will indicate to the designer, draftsman and the welder the exact welding details established for each joint or connection to satisfy all conditions of material strength and service required.

Figure 1.28 (a) shows the different weld joints and the symbols used to represent them.

Figure 1.28 (b) shows the practical application of these symbols to various typical joints.

The welding symbols are indicated in conjunction with an arrow connected at an angle to a reference line. This reference line is usually drawn parallel to the bottom base plate. If the weld symbol is placed below the reference line, the weld face is on the other side of the joint. If the symbol is above the reference line, the weld face is on the other side of the joint. A circle where the arrow line meets the reference line indicates that it should be a peripheral (around) weld. A numerical figure before the symbol for a fillet weld indicates the leg length. A fork at the end of the reference line with a number in it, indicates the welding process to be employed. For example 111 is metal arc welding with covered electrode; 121 for

Fig. 1.28 (a) Welding sysmbols

Fig. 1.28 (b) Welding Symbols

SAW; 131 for MIG; and 141 for TIG and so on. These numerical indicators for different types of welding processes have been standardized and are given in welding societies publications.