1

Introduction

Welding processes have become increasingly important in almost all manufacturing industries and for structural fabrication. The major industries employing welding processes extensively are the following :

1. Ship building,
2. Thermal and nuclear power plant,
3. Oil pipe line construction,
4. Chemical process plant,
5. Automobile and
6. Aerospace.

While these industries involve welding large components or structures, we employ welding of thin strips, foils, wire and components of microcircuits in electronic industries.

Further welding techniques are widely employed for maintenance and repair of equipments. Metal surfacing by welding processes is applied to several components in various industries for improving wear and corrosion resistance.

Welding processes, with modifications of operating conditions, can be used to cut metals. Thus gas torch, metal arc, plasma arc and electron beam can all be employed for cutting metals as well.

1·1. Classification

Welding processes can be broadly classified into two categories :

1. fusion welding and
2. solid state or non fusion welding.

In fusion welding, actual melting of the metal is involved in forming the bond. Examples are gas welding and arc welding processes. In solid state welding, heat energy and pressure are applied to the workpieces to be joined and bonding occurs primarily due to *diffusion* of atoms and intimate contact of clean surfaces. No melting process is involved. Examples of solid state welding are cold welding, diffusion bonding and friction welding.

In this book fusion welding processes are given greater emphasis. The solid state processes are briefly discussed in chapter 13.

Brazing and soldering processes which involve the use of filler metals in molten condition and capillary action are discussed in chapter 19.

Fusion welding requires an intense source of heat for the melting of both parent metal and filler or electrode. The most important sources of heat energy for welding are :

1. combustion of a fuel with an oxidiser, (an in oxygen-acetylene gas welding)
2. electric arc,
3. electrical resistance heating,
4. arc plasma,
5. a beam of electrons and
6. a laser beam.

Among these, gas welding employing a mixture of oxygen and acetylene, and electric arc welding processes have attained the major position. The equipments required for both these processes can be relatively simple and they are flexible to perform welding in a variety of situations.

Table 1·1 provides a comparison of different fusion welding processes.

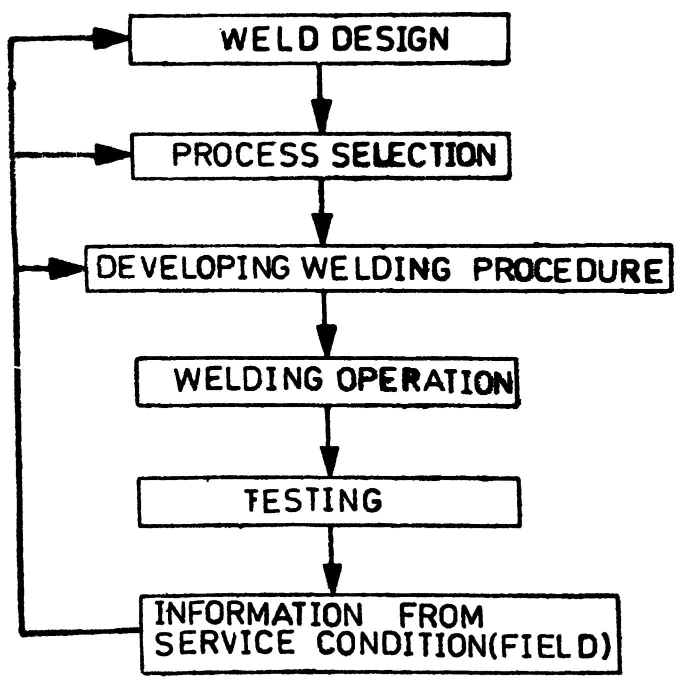


Fig. 1·1. Flow chart for a welding process model.

Table 1·1. Comparison of Fusion Welding Processes

Process	*Metals*	*Thickness Range*	*Industrial Use*
Oxy-fuel gas (Chapter 2)	Carbon steel, Copper, aluminium, zinc, lead, Bronze welding	Sheet metal and Small diameter pipe upto mm	Sheet metal welding Small diameter pipe
Shield metal arc (Chapter 4)	All engineering metals and alloys except copper, low melting and very reactive metals	1 mm upwards	All fields of engineering
Submerged arc (Chapter 5)	Carbon and low and high alloy steels, copper alloy	1 mm upwards (Generally over 10 mm)	Joints suitable for automatic welding ; boilers, pressure vessels, storage tanks, ship building
Gas tungsten arc (Chapter 6)	All engineering metals except Zn	1 mm upto about 6 mm	Non-ferrous and alloy steel welding in all engineering fields ; root pess in pipe welds
Gas metal arc (Chapter 7)	Carbon steels, low alloy, stainless, heat resistant steels, aluminium, nickel alloys	1 mm upwards	General engineering, all fields.

(*Contd.*)

Process	*Metals*	*Thickness Range*	*Industrial Use*
Plasma arc (Chapter 8)	All engineering metal except Zn	Usually to about 1·5 mm	Mainly for reactive metals : root runs.
Stud arc (Chapter 9)	Carbon, low alloy and high alloy steels ; aluminium	Stud diameters upto about 25 mm	Ship building, railway and automotive industries, furnace tubes.
Resistance (Spot, Seam and projection) (Chapter 10)	All engineering metals except Cu and Ag ; Al requires special treatment	Sheet metals upto about 6 mm	Automobile and aircraft industries ; pipe and tube manufacture ; sheet metal industries.
Electroslag	Carbon, low and high alloy steels	50 mm upwards	For thick sections of press frames, pressure vessels, shafts, steel plant equipment.
Electron beam (Chapter 12)	All metals ; particularly for stainless steels, nickel, titanium, zirconium and other reactive metals	Upto about 25 mm 100 mm (max)	Nuclear and aerospace industries ;
Laser beam (Chapter 13)	Same as above	Upto 10 mm	Special applications, electronic industries.
Thermit (Chapter 13)	Steels, Copper alloys steel/copper joints	Upto about 100 mm	Welding rails ; Copper conductors ; Copper/steel joints.

1·2. Process Modeling

The various steps in executing a welding fabrication are described here as a process model (Fig. 1·1).

1. *Weld design.* This involves the identification of welds, their geometry and preparation of suitable drawings. Stress analysis may be important to arrive at a satisfactory design. (The drawing prepared should contain proper weld symbols).

2. *Selection of an appropriate welding process.* This step would include the cost comparison for different processes, availability of equipment, time required to complete the welding job, skill of the available personnel, metallurgical and quality requirements of the completed weldment.

3. *Developing the welding procedure.* This step includes determining the welding parameters, test methods, welding sequence, use of jigs and fixtures, and process planning. This is the main task of a welding engineer.

4. *Actual welding operation.* This involves the execution of shop floor or outdoor welding work with proper supervision and inspection at the required stages.

5. *Testing.* This step may be of two kinds : test made on test coupons prepared during the welding and tests on actual weldments. The tests can be destructive tests (suct as tensile, bend and fracture toughness test) or non-destructive tests such as X-ray radiography, gamma ray radiography and ultrasonic inspection.

6. *Feedback from service conditions.* This step involves feedback information from the performance of the welded structure in service conditions or from the field. It is possible that cracking and distortion may develop in welded structures even after a few years. The corrosion resistance of the welds can be analysed in most cases only from service performance. The feedback information would be helpful in suitably modifying the various steps listed earlier.

It should be emphasized that successful weldments can be produced only if *design, materials and fabrication procedures* are considered together and properly integrated.

1·3. Welding Procedure

Now we can consider step 4—the actual welding operation. This would point out the elements of welding cost as well as the variables in considering different welding processes. The welding procedure may involve the following stages :

1. Cleaning and cutting the plates, sections or castings ;
2. Use of fixtures, positioners or manipulators ;
3. Fit-up assembly (and inspection) ;
4. Welding operation ;

5. Slag removal (if required), weld dressing (grinding, machining etc.) ;

6. Post weld treatments (stress relieving by mechanical means or heat treatment, peening, specified heat treatments) ;

7. Inspection (dimensional, mechanical and metallurgical testing, crack detection etc.) ;

8. Painting, spraying etc. for surface protection.

Many welded constructions involve joining large castings or several forgings. Cast-weld and forged-weld fabrications enable economical construction of large systems.

1·4. Abbreviations for Welding Processes

The commomly accepted terminology and abbreviations for several welding processes (as given by American Welding Society) are listed here :

1. Shielded metal arc welding—SMAW, (includes manual arc welding, stick welding, coated-electrode welding),
2. Submerged arc welding—SAW,
3. Flux cored arc welding—FCAW,
4. Gas tungsten arc welding—GTAW, (includes the tungsten inert gas (TIG) welding)
5. Gas metal arc welding—GMAW, (includes the metal inert gas (MIG welding)
6. Plasma arc welding—PAW,
7. Electrioslag welding—ESW,
8. Electron beam welding—EBW,
9. Resistance welding—RW,
10. Atomic hydrogen welding—AHW,
11. Carbon arc welding—CAW,
12. Stud arc welding—SW,
13. Induction welding—IW,
14. Laser beam welding—LBW,
15. Thermit welding—TW,
16. Oxyfuel gas welding—OFW,
17. Oxyacetylene welding—OAW,
18. Flash welding—FW,
19. Friction welding—FRW,
20. Ultrasonic welding—USW.

1·5. Welding Terms and Characteristics

Most of the common terms used in welding technology and certain characteristics of welding processes are given here.

Welding Terms

The *parent metal* or *base metal* is the metal to be joined by welding. The weld metal is the deposited metal, derived from a filler rod or electrode or from the original base metal (Fig. 1·2).

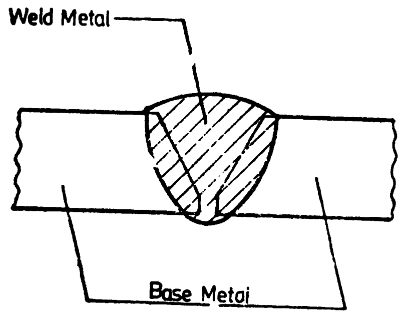


Fig. 1·2 Base metal and weld metal.

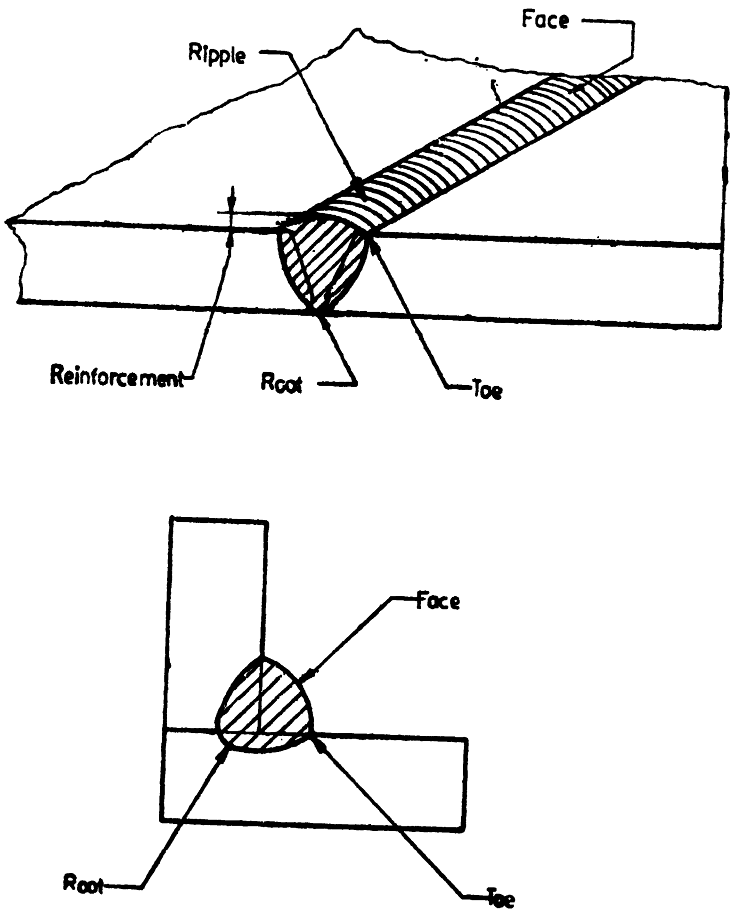


Fig 1·3. General terms.

The *face* of the weld is the outer, top surface of the deposited metal. The bottom of the weld is called the *root*. Ripples are wavy formation of the metal in the face. The *toe* region is shown in Fig. 1·3.

The *reinforcement* is the excess metal above the surface of the base metal.

In the case of fillet welds, the face can have flat, convex or concave contour (Fig. 1·4). Note that the throat is the perpendicular

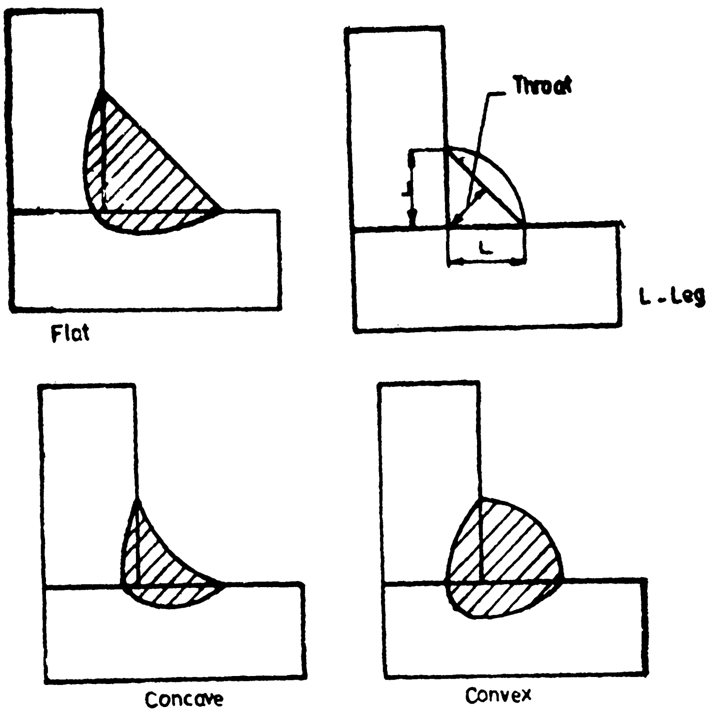


Fig. 1·4. Fillet weld terms.

distance between the face and root of the weld. For a fillet weld with equal leg on both sides, throat=0·707×leg.

In the case of welding with grooved geometry, the terms groove angle, groove face and root gap can be noted (Fig. 1·5).

In multipass welding, the first pass is called the root pass.

If *weld backing* is employed, a back up plate or grooved back-up bar is used (Fig. 1·6). Sometimes *chill bars* are kept at the sides of the weld and clamped.

Process Characteristics

Deposition rate is the weight of metal deposited in a given period of time, usually expressed in kg/hour. We can compare different welding processes in terms of deposition rates. (Table 1·2).

Table 1·2. Deposition Efficiency and Operation Factor

Press	*Deposition efficiency %*	*Operation factor %*
SMAW	60—75	20—30
GTAW	90—100	(20—30)
GMAW	90—95	50 for manual ; 100 for automatic
FCAW	85—90	,,
SAW	95	,,

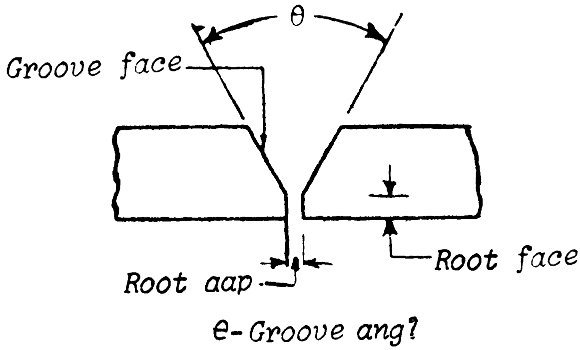


Fig. 1·5. Groove weld geometry.

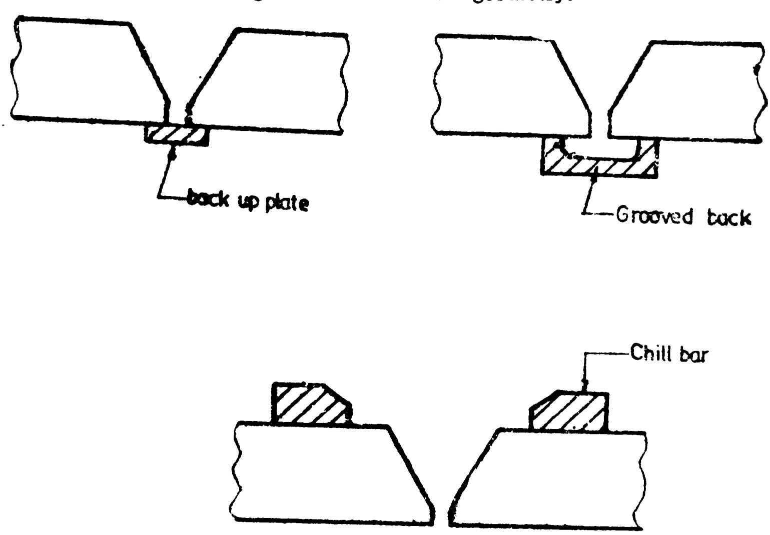


Fig. 1·6. Weld backing and chill bars.

Deposition efficiency or electrode efficiency in arc welding is calculated as follows :

$$\text{Deposition efficiency} = \frac{\text{Deposited weight}}{\text{Melted weight}} \times 100$$

Operation factor is defined as the proportion of the total welding time an operator is actually fusing electrodes.

Penetration. An important characteristic of a fusion welding process is the penetration obtained by the heat source. This is measured as the ratio of width of the weld to its depth. As a matter of comparison, consider the weld bead geometry for several processes shown in Fig. 1·7. The weld width to depth ratio is about 2·5 for SMAW and about 1·25 only for GMAW. In electron beam welding, the weld is very narrow and depth/width is about 15 or higher because of greater penetration while for plasma arc welding, depth/width is about 5.

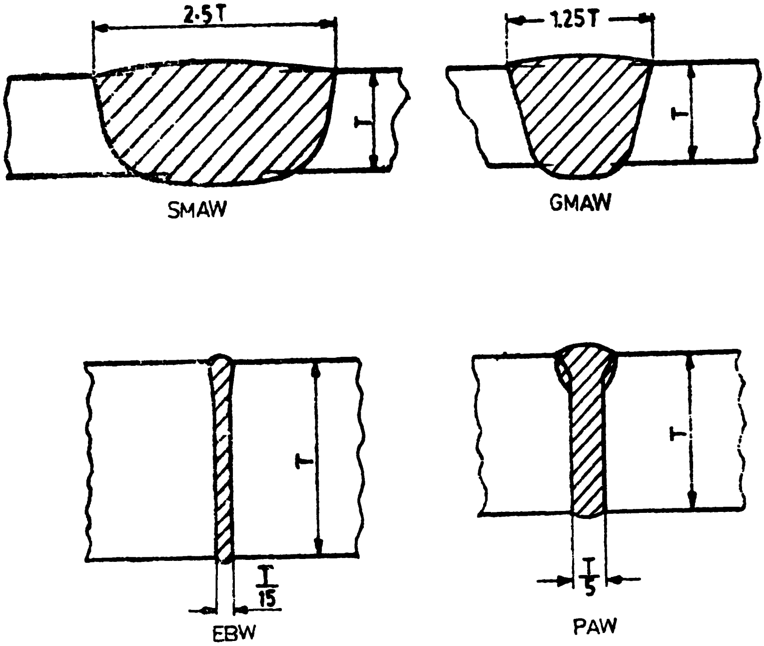


Fig. 1·7. Weld shapes-penetration characteristics.

It follows that if a process shows a greater penetrating power, a narrow groove is sufficient, *i.e.* the groove angle is smaller or a groove may not be needed at all, *i.e.*, a square weld may be possible in butt welding. Another important consequence of greater penetration is a narrow heat affected zone. The distortion would also be less. Further a narrow groove reduces the filler or electrode consumption.

Welding Speed is the speed with which the electrode moves or deposition takes place. It is expressed as mm/second or metre/hour. Note that for a given set of conditions, higher welding speed will result in lower penetration.

Heat Input. Heat input or energy input is an operation parameter of great importance for a welding process. For arc welding,

$$\text{Heat input} = \frac{V \times I}{S}$$

where V=arc voltage

I=arc current

and S=welding speed.

If welding speed is expressed in mm/sec, the unit for heat input $\left(\frac{\text{volt} \times \text{ampere} \times \text{second}}{\text{mm}}\right)$ is Joules/mm. Note that it is in terms of energy per unit length of weld. Alternately it can be expressed as Mega Joules/metre (MJ/m). Table 1·3 provides the heat input range for different welding processes.

Table 1·3. Heat Input Range

Process	*Heat input range (MJ/m)*
SMAW	0·5—3
GTAW	0·3—1·5
GMAW	0·5—3
SAW	1·0—10
ESW	5—50
EBW	0·1—0·6
LAW	0·1—0·6

Power Density. The magnitude of the heat intensity can be expressed in terms of power density, considering the cross-sectional area of an arc column or electron or laser beam. It is expressed as watts/m^2.

Table 1·4 presents the power density values for different processes. The penetration for welds depends roughly on the power density ; greater the power density, deeper the penetration.

Table 1·4. Power Density Range

Process	*Power density ($Watts/m^2$)*
SMAW	$5 \times 10^6 — 5 \times 10^8$
GMAW	$5 \times 10^6 — 5 \times 10^8$
PAW	$5 \times 10^6 — 5 \times 10^{10}$
EBW and LBW	$10^{10} — 10^{12}$

1·6. Joint Design

The basic types of joints used in welding are : (1) butt (2) lap (3) T or fillet (4) corner and (5) edge. There are several variations of each of these joints.

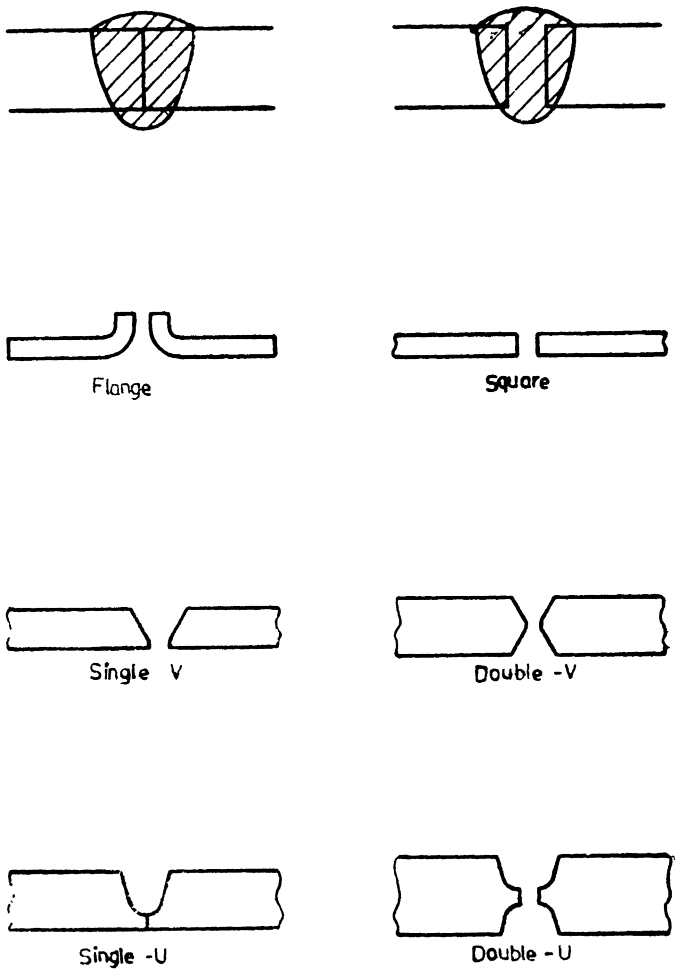
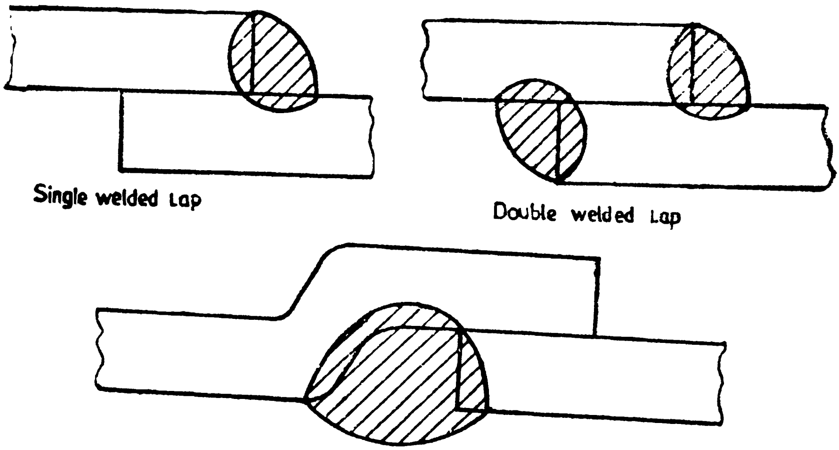


Fig. 1·8. Butt joint.

Butt Joint. The butt joint is used to join the ends or edges of two plates or surface approximately in the same plane with each other. Preparation of the edge varies according to the thickness of the plate and the welding processes. The general recommendations are given in different chapters. A general description follows :

For light gauge sections, a straight edge (square-butt) is used. For greater thicknesses a bevelled edge is needed. The groove angle is usually 60° for shielded metal arc welding (SMAW). As the thickness is greater, a double V or double U joints are made (Fig. 1·8). Note that a double-bevel V-joint requires approximately one-half the amount of filler metal or electrode that a single V would require for the same thickness and groove angle. (This can be proved by considering the area of the weld required in each case).

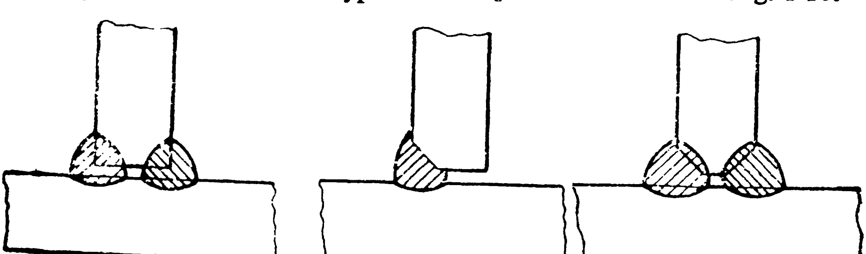
Lap Joint. The lap joint is used in joining two overlapping plates so that the edge of each plate is welded to the surface of the other. Common lap joints are single lap, double lap and offset or 'joggled' lap joints (Fig. 1·9).



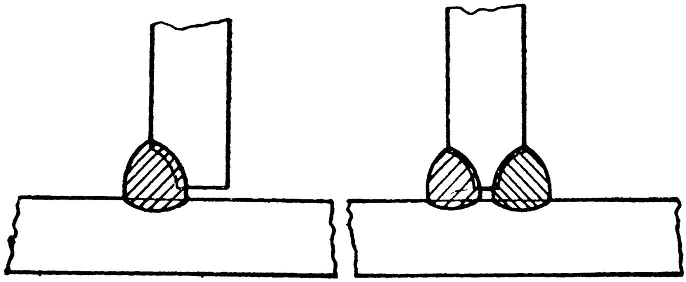
Offset Lap
Fig. 1·9. Lap joint.

The single-welded lap does not develop full strength, but it is preferred to the butt joint for some applications. For example, this is employed in tubular construction where one tube telescopes into the other and lap welded.

Fillet Joint (T-joint). Fillet joints are used to weld two plates or sections whose surfaces are at approximately right angles to each other. The common types of fillet joints are shown in Fig. 1·10.



Plain T — Single Bevel — Double Bevel



J-groove Double J

Fig. 1·10. Fillet joint.

The plates on surfaces should have good fit-up in order to ensure uniform penetration and fusion.

Corner Joint. This is used to join the edges of two sheets or plates whose surfaces are at an angle of approximately 90° to each other. Welding can be done on one or both sides, depending on the position and type of corner joint used. (Fig. 1·11).

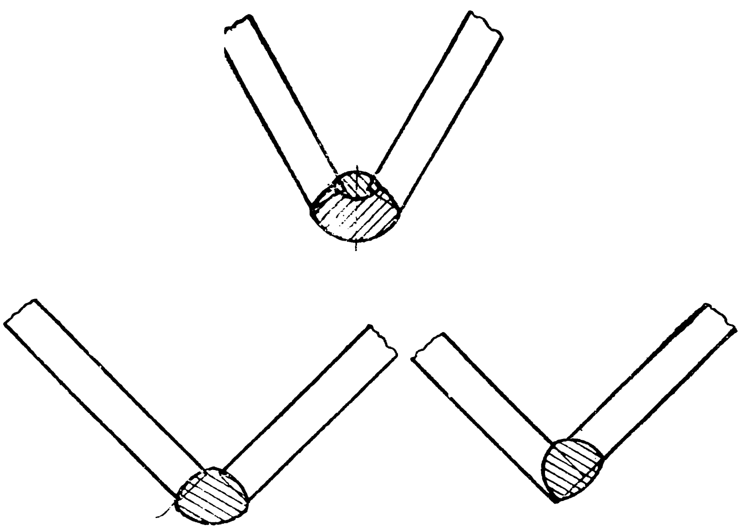


Fig. 1·11. Correr joint.

Edge Joint. This consists of joining two parallel plates by a weld. It is often used in sheet metal work. For small thicknesses the two edges can be melted down and no filler metal is required. For thicker plates, a bevelled groove is needed (Fig. 1·12).

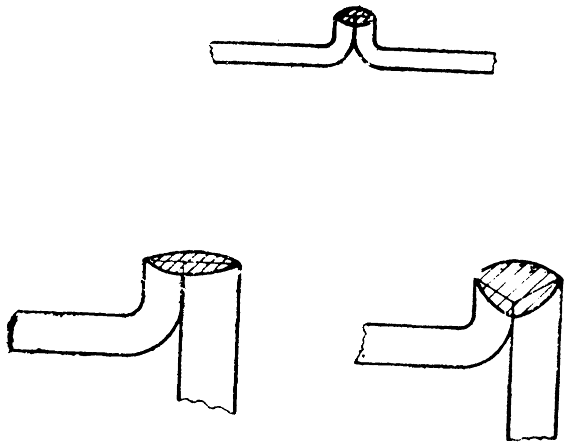


Fig. 1·12. Edge joint.

Plug Weld. This is a weld made in a circular hole in one plate onto another plate underneath it (Fig. 1·13). For plug welds, the

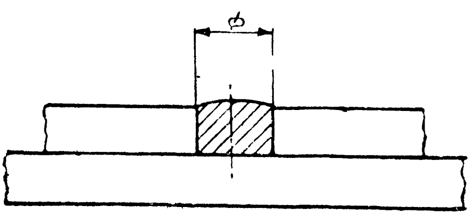


Fig. 1·13. Plug weld.

hole diameter should not be less than the plate thickness plus 8 mm and not greater than 2·25 times the plate thickness.

1·7. Safety in Welding

A number of safety measures are to be considered in a welding shop. Among these, the most important are *prevention* of fire accidents, explosions (from gas cylinders) and electric shock to the personnel. A very important measure is the use of *welding goggles* and *hand shield* for the welding operator. The goggles and shield protect the eyes from harmful ultraviolet rays and infrared rays from the oxyacetylene flame or electric arc. It is also important to prevent the passers by from looking at the arc. The goggles are provided with filter glass at the centre and plain glass on both sides. The suitable tint of the glass filter is decided on the basis of the process employed. The goggles protect the eyes from flying sparks or metal shots or from slag particles while chipping the slag.

Welding gloves are considered a necessary protection from burns. Protective clothing or apron made of leather, asbestos or non-inflammable cloth may be worn by the operator.

In shielded metal arc welding considerable fumes are produced. A proper ventilation system should be provided.

1·8. Welding Skills

It is important to emphasize that most of the welding processes require considerable skill on the part of the welder or machine operator. Certain agencies require that only certified welders are engaged for particular jobs. New processes like gas metal arc welding (GMAW) require less skill on the part of the operator and automatic machine are more widely used than ever before. Further, welding robots are increasingly coming into welding shops to replace the operators.

1·9. Welding Engineer

This book is mainly intended for engineers who may acquire training as welding engineers. Therefore the major roles of a welding engineer can be discussed here. A welding engineer is required to develop suitable welding procedures and to supervise the execution of the work. He should work closely with design engineers and metallurgists/materials engineers. He can contribute to the following major areas :

—design
—production
—metallurgy
—inspection and quality control

It should be emphasized that these areas are interrelated. A welding engineer should possess sound basic knowledge of all these areas even though he/she might specialise in one or more specific aspects. The major objective of this book is to introduce the basic concepts of all these areas in an integrated manner.

1·10. Historical Introduction

Welding technology has been a relatively recent development compared to other technologies like foundry technology. Almost all the developments have occurred in the 19th and 20th centuries, though forge welding has been known for several centuries.

The discovery of electric resistance welding—an accidental discovery—was made by Elihu Thompson in USA in 1877. The carbon arc welding was invented by Bernados in 1885. In 1890, Le chatelier, the famous French chemist, developed the oxygen-acetylene flame-torch. Interestingly, the early users of this torch were bank safe crackers. There was a move to ban the use of this torch !

Following these major break-throughs, welding technology developed with important improvements in techniques. The major landmarks are mentioned here.

1902—M.U. Schoop, a Swiss engineer developed the process of flame spraying.

1907—Kjellberg, a Swedish engineer, introduced the coated electrodes for arc welding.
1925—Gerdien developed the plasma torch device.
1926—American chemist and Nobel prize winner, Irving Langmuir invented atomic hydrogen welding.
1938—Ludwig Bergman developed the ultrasonic welding.
1953—Robert Gagu developed the plasma welding unit.

For several other processes, definite dates cannot be given. Submerged arc welding was developed in USSR and in USA around 1935. Electroslag welding and friction welding were also developed in USSR. Electron-beam welding was developed in 1950's. Laser beam welding has grown after the construction of first laser in 1959.

1·11. Welding vs other Joining Processes

An engineer has to evaluate welding against other joining processes for any specific application. The most important joining processes, besides welding are

—*Mechanical fastening*
—*Riveting*
—*Brazing and soldering*
—*Adhesive bonding*

Mechanical fastening with bolts for instance, has the chief merit of being removable—it is not permanent joining method. When components are to be disassembled, fasteners are almost always used. Further, drilling holes for bolting may reduce strength of the structure.

Riveting had been extensively used before welding technology was adequately developed. Ship building used riveting until the late 1930's, *i.e.*, before World War II. Riveting is extensively used even today for aircraft structures. (Look closely at the wing surface of any aircraft). Riveting results in a low strength joint. It has a great advantage : Any crack originating at a rivet hole will extend upto another rivet hole and end there. [On the other hand, a small crack in a welded construction can propagate throughout the structure—in this sense, weldment is a '*monolithic*' structure]. Because of this advantage and the fact that certain aluminium alloys have poor weldabilitv, riveting is still the main joining method for aircraft structures.

Brazing and soldering involve using low—melting filler metals and are often easier to apply. The strength of the joint is much lower than welded joints. The joint, however cannot be used for high temnerature service conditions. (Chapter 19 is devoted to "*Brazing and Soldering*"). A major advantage of soldering/brazing is that the metallurgical structure of the potent metal is not signi-ficently altered due to lower temperatures. These joints can be removed by desoldering for repair work.

Adhesive bonding is being increasingly used for aerospace components and for small appliances. The use of adhesives is limited to moderate temperatures of application usually less than 60°C. Adhesive bonding cannot be considered as a serious alternativet o welding for most applications.

2

Gas Welding

2·1. Introduction

Gas welding processes are technically called oxygen-fuel gas welding. The most important process is, of course, oxygen-acetylene welding. Instead of acetylene, other fuel gases can be employed. The common fuel gases and the maximum flame temperatures as well as netural flame temperatures are as follows :

Fuel gas	*Maximum temperature (°C)*	*Netural temperature (°C)*
Acetylene	3300	3200
M.A.P.P.	2900	2600
Propylene	2857	2500
Hydrogen	2870	2390
Propane	2777	2450
Netural gas/ methane	2740	2350

(M.A.P.P.—methyl actylene propadiene).

Oxy-acetylene welding is a versatile process and can be used for welding a variety of metals. Further it is also useful for brazing. The oxygen cutting process is discussed separately at the end of the chapter.

The equipment for gas welding is quite inexpensive and the cost of welding is largely determined by the cost of the required gases.

2·2. Production of Oxygen and Acetylene

Oxygen gas is produced from commercial liquefaction of air. The liquid air is allowed to boil. After nitrogen and argon boil off, pure liquid oxygen remains.

The oxygen gas is compressed in cylinders at a pressure of 15 MPa (2200 psi).

Acetylene gas (C_2H_2) is produced by reacting calcium carbide (CaC_2) with water :

$$CaC_2 + 2H_2O = C_2H_2 + Ca(OH)_2$$

Acetylene gas may explode if the pressure is increased to about 0·2 MPa. Therefore, it is dissolved in acetone ($CH_3-CO-CH_3$) liquid which acts as a solvent for the gas. One volume of acetone can absorb about 25 volumes of acetylene per atmosphere. The acetylene gas is usually compressed at 1·7 MPa and, therefore, the volume of gas stored is calculated as follows :

$$\text{Volume of } C_2H_2 \text{ stored per unit vol. of acetone} = \frac{25 \times 1{\cdot}7}{0{\cdot}101} = 420$$

The acetylene cylinder is packed with porous calcium silicate so that the liquid is distributed in fine form for effective absorption of the gas. The cross sectional view of an acetylene cylinder is shown in Fig. 2·1. The cylinders are equipped with fusible safety plugs made

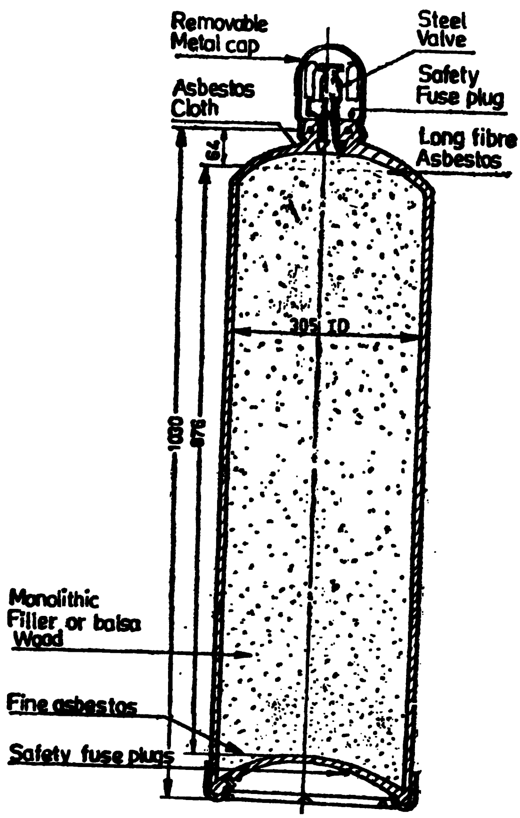


Fig. 2·1. Acetylene gas cylinder.

of a low melting alloy (melting point around 99°C) which allows the gas to escape if the cylinders are exposed to excessive heat.

In small workshops or outdoor locations, acetylene generators (a cylinder with water and a hopper for dropping calcium carbide) are employed.

2·3. Flame Characteristics

The combustion of acetylene in the presence of oxygen can be discussed here. The overall reaction is written as follows :

$$2C_2H_2+5O_2 \rightarrow 4CO_2+2H_2O$$

According to this reaction, one volume of acetylene requires 2·5 volumes of oxygen. But in practice the volume ratio of 1 : 1 is used for reasons of economy.

The flame shows two zones of combustion (Fig. 2·2). The inner zone is characterised by the primary reaction :

$$C_2H_2+O_2 \rightarrow 2CO+H_2$$

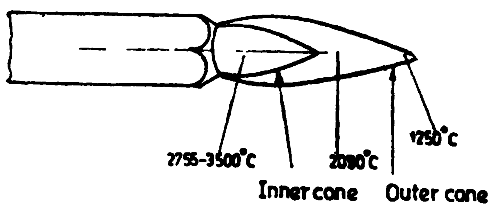


Fig. 2·2. Combustion zone.

The carbon-monoxide thus formed, combines with oxygen from the air in the outer zone or secondary reaction :

$$2CO+O_2 \rightarrow 2CO_2$$

$$2H_2+O_2 \rightarrow 2H_2O$$

The temperatures attained in the different parts of the flame are shown in Fig. 2·2.

Chemical nature of the flame. Three types of flames can be obtained, depending on the ratio of $C_2H_2 : O_2$:

1. Carburising or reducing flame : $\frac{C_2H_2}{O_2} \triangleright 1$

2. Neutral flame : $\frac{C_2H_2}{O_3}=1$

3. Oxidising flame : $\frac{C_2H_2}{O_2}<1$

Carburising flame. It has three zones. The middle cone will have feather like appearance. The unburned carbon in this type of flame may be added to the weld (Fig. 2·3). Carburising flame is advantageous for welding high carbon steel or carburising the surface of low carbon or mild steel.

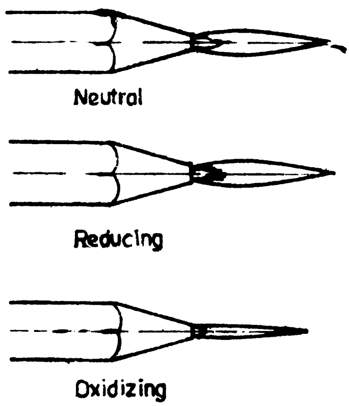


Fig. 2·3. Three types flames.

For surfacing applications, a flame of long length (3 times the inner cone length) called '*3×flame*' is used.

Natural flame. In this case, the middle cone disappears. The neutral flame is invariably used for welding of steels and other metals.

Oxidising flame. The inner cone becomes small—a loud, roaring noise is heard. Oxidising flame gives the highest temperature possible. It would introduce oxygen into the weld metal and is not preferred for steel. A slightly oxidising flame is used for welding copper-base alloys, zinc-base alloys, a few steels (manganese steel, for example) and cast irons.

2·4. Welding Torches

There are two types of welding and cutting torches in use: (1) Equal pressure type, also called balanced-pressure type. (2) Injector type.

Equal-pressure type. The welding torch consists of four main parts : (*i*) body (*ii*) hand valves (*iii*) mixing chamber (*iv*) tip (Fig. 2·4).

The equal-pressure type is used with gases stored in cylinders. Its construction necessitates that each gas is supplied under enough pressure to force it into the mixing chamber. The hand valves are of needle-type design. They are made of yellow brass with a packing of asbestos rope or impregnated leather.

The mixing chamber is usually located inside the torch body, although some torches incorporate the mixing chamber in the torch head. The size and design of the mixing chamber depend on the size of the torch.

The tips are usually made of copper but some are nickel plated as a means of reflecting the heat and keeping the tip cooler.

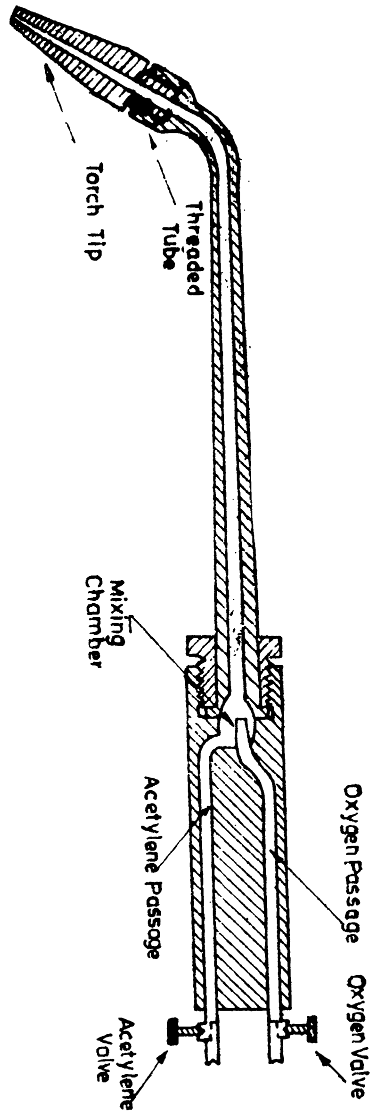


Fig. 2 4. Welding torch—Equal pressure type.

Injector type. The injector or low pressure type of torch looks the same but its internal construction is different. (Fig. 2·5). It is designed to operate using very low acetylene pressure, as from an acetylene generator. Also they have the advantage of being able to draw more completely, the content from acetylene cylinders.

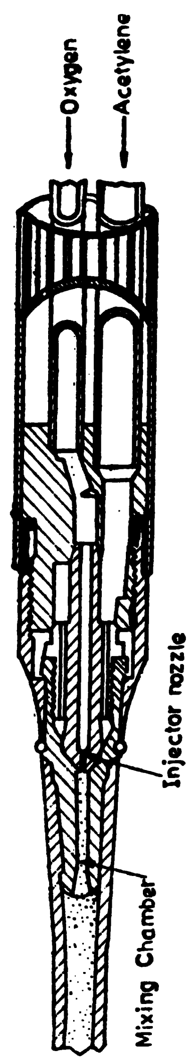


Fig. 2·5. Welding torch-Injector type.

In this type, the oxygen line enters the mixing chamber through a jet which is surrounded by the acetylene passage. The high pressure oxygen 'pulls' the acetylene into the tip.

2·5. Welding Techniques

If welding is done without a filler rod, it is called *puddling*. This is used for plates of 3 mm thickness or less. For thicker metals, a filler rod is needed. The filler rod is held at approximately 90° from the tip (Fig. 2·6). For filler rods, the tensile strength obtainable are specified.

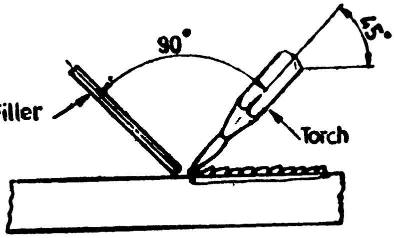


Fig. 2·6. Use of filler rod.

As for the direction of applying the torch, two techniques are possible. In *forehand* welding, the torch follows the welding direction. In *backhand* technique, the torch is facing the welding puddle and moves backward with reference to the welding direction. (Fig. 2·7).

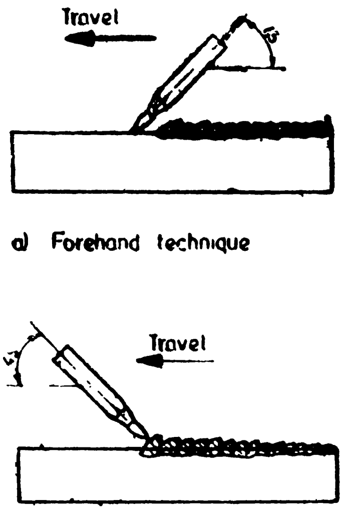


Fig. 2·7. Forehand and backhand techniques.

The forehand technique is adopted for thin sheets while the backhand method is used for thicknesses greater than 3 mm.

In gas welding it is possible to obtain full penetration upto about 10 mm thickness and a single pass welding can be done. The recommended weld geometries for different thicknesses are shown in Fig. 2·8.

Weld movement or weaving. First a weld puddle is established by the gas torch. For this, a circular or spiral movement of the torch is used. Then the torch may be moved forward in movements

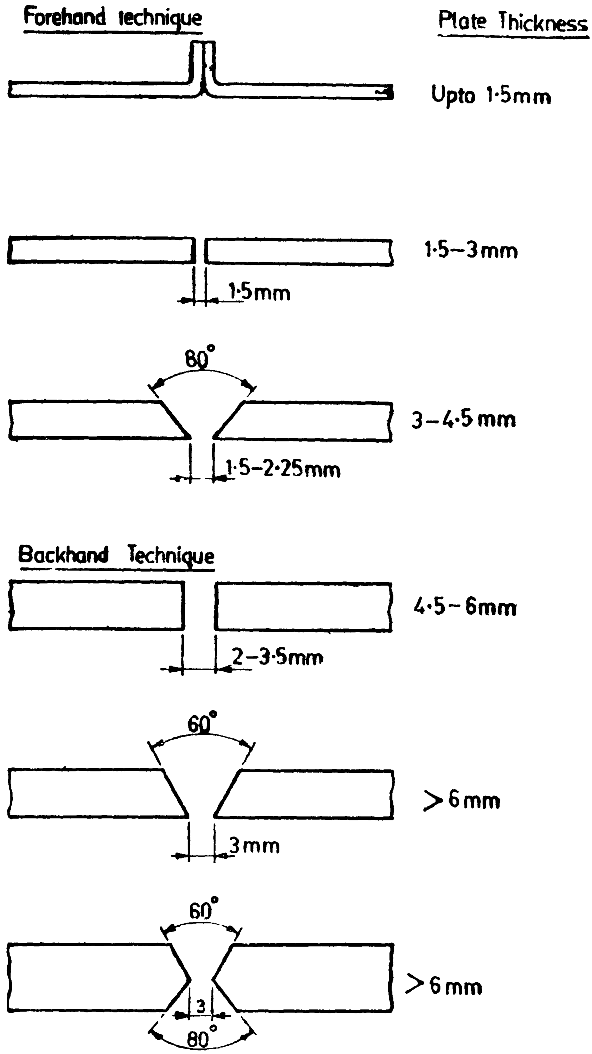


Fig. 2·8. Recomended weld geometry.

of different shapes (Fig. 2·9). During the movement, a pause is allowed to insure maximum penetration.

2·6. Advantages of Gas Welding

The oxyacetylene flame is more easily controlled and is not as piercing as arc welding. Therefore, it is more suitable for thin metals or sheets.

It is very portable ; can be easily altered (with change of torches) for brazing, cutting and heating purposes. It is very useful for outdoor, repair work.

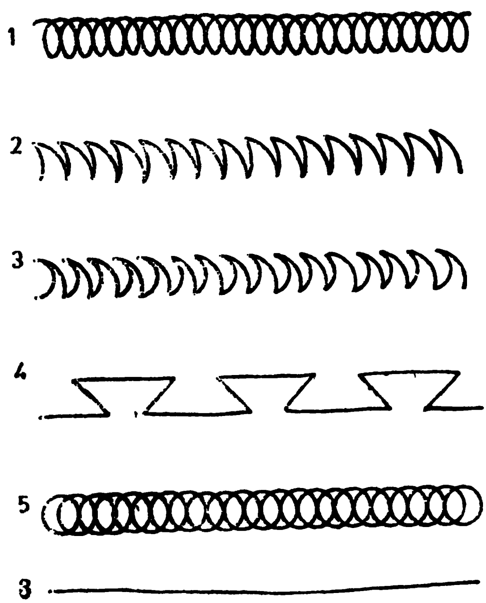


Fig. 2·9. Weld movement.

The limitations are as follows :

1. It takes longer time to weld that in the case of arc welding.
2. The heat-affected zone and distortion are larger than in arc welding.
3. Oxygen and acetylene gases are expensive.
4. There are safety problems in handling and storage of the gases.
5. The use of flux in preventing contamination may not be satisfactory in many cases.

2·7. Oxyacetylene Cutting

In this process, an oxyacetylene flame is used to heat ferrous metals. An oxygen jet is used to perform the cutting operation. (The process is also called 'flame cutting').

Principle. The basic principle is as follows : When iron is heated to a temperature of 760—870°C, it reacts rapidly with oxygen to form iron oxides. The melting point of the oxide is somewhat lower than that of steel. The heat generated by the burning iron in oxygen is sufficient to melt iron oxides (and some free iron) which run off as molten slag. Further areas of metal are then exposed to the oxygen jet.

Theoretically 1 cu-metre of oxygen is required to oxidize about 3/4 cu metre of iron. Actually, the *kerf* or cut, is not entirely oxidised, but 30 to 40% of the metal is washed out as metallic iron. (Fig. 2·10).

Although acetylene is used for the preheating flame, other gases such as hydrogen, natural gas and propane can also be used at considerable savings.

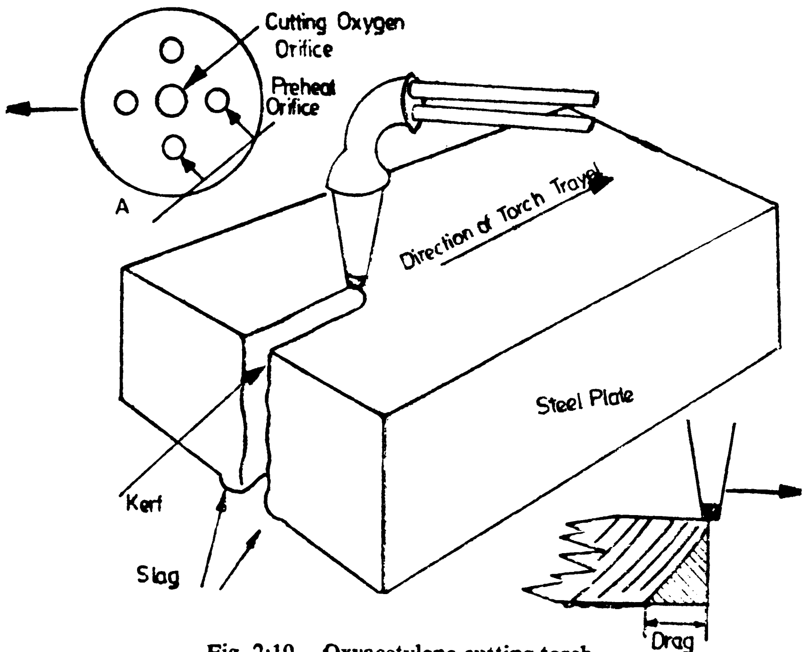


Fig. 2·10. Oxyacetylene cutting torch.

Cutting torch. Oxyacetylene cutting torch is different in construction from the welding torch. The cutting torch has a central orifice for oxygen jet and several orifices at the periphery for oxygen-acetylene mixture to produce preheating flames. Therefore, the oxygen jet is surrounded by several oxy-acetylene flames during cutting operation. (See Table 2·1).

Flame cutting machines. Simple guide rail attachments can be used for moving the torch for straight cuts. For circular cuts, the torch is fixed in a radial arm with pivoted centre.

Apart from these, special machines are available for moving the torch in an angular position for bevel cutting. Further machines that are motorised and follow a tracer as in the case of copying milling machines, are also made. Several automatically controlled machines are employed in large fabrication works.

It is possible to cut at the same time several plates placed one above the other. This is called "stack cutting". As an example twelve steel plates, each of 18 mm thickness, can be clamped together and cut by oxyacetylene cutting torch.

Large flame cutting machines carry more than one cutting head and each head can be fitted with two or three nozzles. Some-

Table 2·1. Data for Oxy-acetylene Cutting of Mild Steel Plate by Hand

Plate Thickness (mm)	*Nozzle size (mm)*	*Oxygen Pressure at Regulator (N)*	*Cutting Speed (m/hour)*	*Gas Consumption (Cu. m/hour)*	
				Oxygen	*Acetylene*
6	1·2	111—133	30—45	1·35—2·7	0·43
12	1·2	133—155	30—37	2·7 —4·5	0·49
18	1·2	155—180	25—30	2·7 —5·0	0·54
25	1·5	155—220	20—27	4·5 —5·9	0·60
37	1·5	178—270	18—24	4·9 —6·8	0·68
50	1·5	200—290	12—18	5·4 —7·2	0·76
75	1·5	220—333	7·5—1·5	5·8 —8·1	0·76
100	2·0	244—333	5·4—7·5	8·8 —11·6	0·76
125	2·0	290—378	4·8—6·6	10·3 —13·2	0·95
150	2·0	311—400	3·6—5·4	15·3 —19·5	0·95

times they are used to cut double bevel-edge preparation for thick plates.

Metallurgical aspects. While cutting steels of medium or high carbon content, the edges may get hardened due to quenching effect (or fact cooling) of the adjacent metal. This may cause cracking of metal near the edges later. (This is not a problem for mild steel upto about 25 mm thickness). The best method of avoiding this condition of hard edges is to preheat the plates.

If flame cutting is employed for stainless steels, chromium oxide forms along with iron oxides. The slag containing chromium oxide interferes with cutting. In such cases flux-injection cutting and power cutting are employed.

Cast iron is also difficult to cut because of higher melting point of the slag produced. For cutting cast iron, a higher preheat temperature and an oxygen pressure from 25 to 100% greater than that for steel are employed. A carburising flame may be used. Often the entire casting is preheated to facilitate cutting and to avoid cracking.

Flux-injection cutting. This process involves feeding a flux powder into the hose carrying oxygen. The powder removes the viscous chromiumoxide—containing slag while cutting stainless steel.

Powder cutting. In this method, iron-rich powder is fed through a tube attached to the cutting torch. The powder may be forced under pressure of compressed air or nitrogen. The powder burns with considerable generation of heat and accelerates the cutting process. Further the process can be extended to cut stainless steel and certain non-ferrous metals.

Ferrous metals upto 1·5 metre thickness and even concrete upto 0·5 metre thickness can be cut by the powder process.

Both flux-injection and powder methods of oxy-acetylene cutting are being replaced by plasma arc cutting methods.

Oxygen lance cutting. This process is very simple in equipment. A preheating flame is separately held and a stream of oxygen is used to cut the metal from a metallic pipe or 'lance'. The methods can be used to cut steel to a depth of 2·5 metres. It is especially suited for

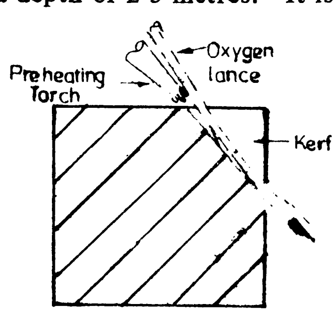


Fig. 2·11. Oxygen lance cutting.

piercing holes in steel, for example a hole of 65 mm diameter can be drilled in a plate of 300 mm thickness in about 2 minutes.

Oxygen lancing is used to cut risers from large steel castings, for tapping blast furnace and for piercing holes in large shafts.

Oxyfuel gas underwater cutting. There are occasions when metals held under water should be cut. For this purpose, oxy-acetylene method of cutting can be used with an important variation. A compressed air jet is used to keep the water away from the torch.

A special torch is needed which has a slotted cylinder surrounding the cutting tip and an additional connection for compressed air.

Gouging. A cutting torch can be used for making a curved groove on the edge or surface of a plate. This is called 'gouging'. For this, instead of using a high velocity oxygen jet, a large orifice low velocity jet is employed. Gouging is often done to prepare the metal for welding or during repair work.

2·8. Gas Welding of Aluminium

Aluminium and its alloys can be easily welded by oxy-acetylene torch using a suitable flux. The process is usually limited to a thickness of 6 mm. The groove angle for a V-joint is between 90—120°. When welding thin sheets, they should be clamped rigidly on both sides to reduce distortion. Further, to reduce heat losses, asbestos plates can be kept on the sheets. After completing the joint, the flux should be thoroughly removed since it can corrode the metal.

Table 2·2. Type of Flame for Non-ferrous Metals

Metal/alloy	*Flame*
Aluminium	Slightly carburising
Brass	Slightly oxidising
Bronze	Slightly oxidising or neutral
Copper	Slightly oxidising or neutral
Nickel	Slightly carburising
Monel	Slightly carburising
Inconel	Slightly carburising
Lead	Neutral

3

Arc Welding-General

3·1. Introduction

This chapter discusses several aspects common to all arc welding processes *viz.*, shielded metal arc, carbon-arc, gas tungsten arc and gas metal arc. Firstly the arc welding power sources and their characteristics are discussed. Then matters relating to heat input, deposition rate, and use of positioners and fixtures are explained. Thus this chapter provides a basic preparation for the following chapters.

3·2. Arc Welding Power Sources

Electrical power sources for arc welding are derived from either line supply or diesel generator sets. For arc welding both alternating current (AC) and direct current (DC) can be employed. In both cases, the open circuit voltage is in the range 50—80 V while during the actual welding operation, arc voltage is around 25 V. The current required can vary over a large range—from 50 amperes (for thin sheet metal welding) to 1000 or more amperes for high rate of deposition in submerged-arc welding (SAW) and other processes. For normal work by manual welding, portable welding machines provide maximum currents in the range 150 to 400 amperes (at 60% duty cycle). (The term 'duty cycle' is defined later).

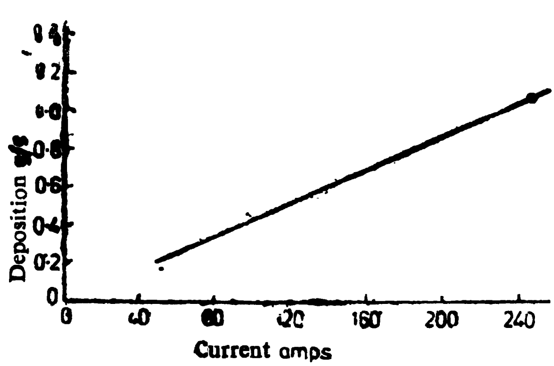


Fig. 3·1. Deposition rate *vs* arc current.

Since the current drawn and melting rate of the electrode in arc welding depend on the diameter of the electrode rod, welding sets of higher current ratings are required for welding with thicker electrodes, *i.e.* for higher deposition rate. A typical relationship between deposition rate and arc current is shown in Fig. 3·1 for SMAW.

In general welding units are one of the following types :

1. Transformer (only AC welding is possible),
2. Transformer and rectifier unit (both AC and DC welding are possible) and
3. Motor-generator sets (AC or DC types).

Welding Transformer

Since transformers are least expensive and are widely employed, we shall discuss the features of welding transformers in considerable detail.

The internal arrangement of a typical welding transformer is shown in Fig. 3·2. The output voltage-current characteristic will

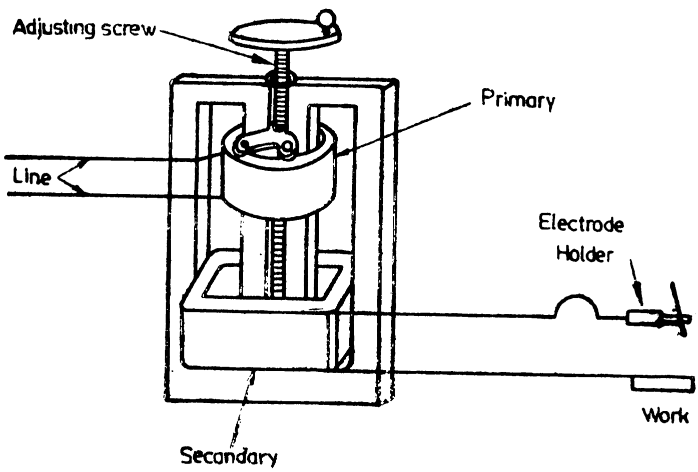


Fig. 3·2. Welding transformer.

depend on the inductive coupling between primary and secondary coils. The distance between the two coils can be varied by a lead screw ; the maximum current setting will correspond to the position of coils being closest to each other (Fig. 3·3).

Transformers with rectifiers (full-wave, bridge type), are available for providing a D.C. source. In such equipments both AC and DC welding are possible.

Arc Voltage-Arc Current Characteristics

The arc welding power sources are best understood in terms of arc voltage—arc current characteristics. The nature of the characteris-

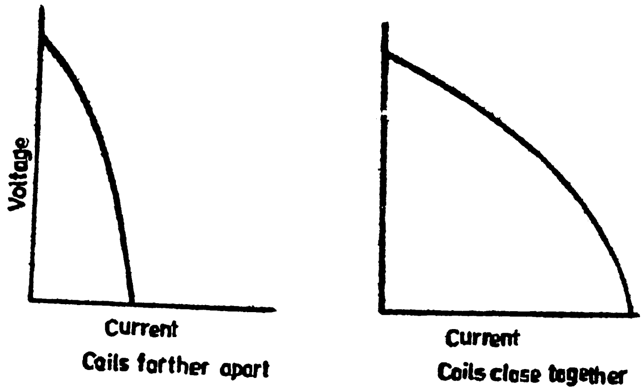


Fig. 3·3 Voltage-current characteristics for coil positions.

tic determines the suitability of the source for specific welding processes. There are mainly three types :

1. Drooping Arc Voltage characteristic (DAV),
2. Constant Arc Voltage characteristic (CAV),
3. Rising Arc Voltage characteristic (RAV).

(In older literature the classification was restricted to two categories *viz.*, constant voltage and constant current characteristics).

These characteristics are schematically shown in Fig. 3·4. The DAV characteristic is obtained in transformer operation.

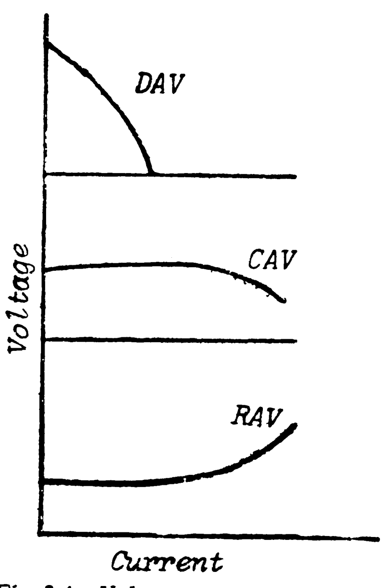


Fig. 3·4. Voltage-current characteristics.

DAV characteristic is well suited for manual operation and is widely used for manual arc or shielding metal arc welding (SMAW).

The basic reason for this application is based on the fact that arc voltage depends on arc gap or arc length. Since in manual operation it is extremely difficult to maintain a constant arc gap, the arc voltage may vary over a wide range-typically if the arc voltage is 25 V, it may range 25±5 V. In such a case, the variation in current is rather small, because of the steep fall of the voltage-current

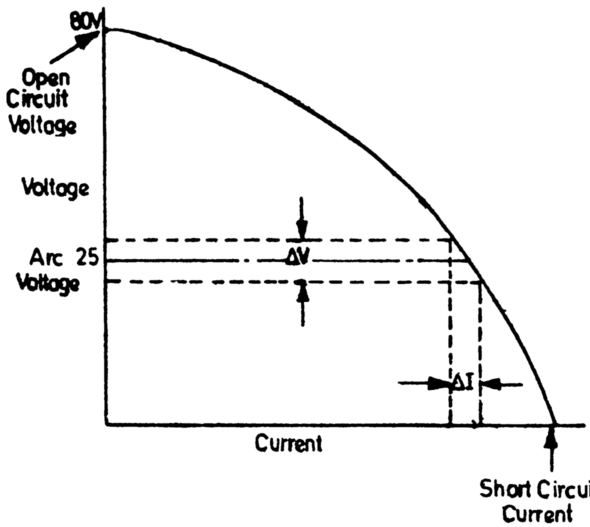


Fig. 3·5. DAV Characteristic.

relationship. (Fig. 3·5). This means that the arc current remains fairly steady and consequently the deposition rate is nearly constant. Therefore, a smooth, uniform deposition of weld metal is possible in manual operation.

CAV Characteristic shows that the arc voltage is maintained constant. This is possible in automatic welding machines employing continuous feeding of wire for melting. In this case the arc gap is maintained accurately by adjusting the wire feed rate. The wire feed will also depend on the arc current employed, *i.e.* the melting rate of the wire. In such systems discussed under GMAW, it is a great advantage that deposition rates can be varied to suit the particular job by changing the arc current. Note that the arc current, deposition rate, welding speed and wire feed rate are related parameters. Higher the arc current, greater the other parameters.

RAV Characteristic implies that with increasing arc current, arc voltage is also increased. This is advantageous for large arc currents. The CAV and RAV characteristics are most sulted for semiautomatic or automatic machines while operating in the mode of spray transfer (see chapter 7).

Duty Cycle

Apart from ampere-volt ratings, duty cycle is specified for a welding machine. Duty cycle is defined as *the percentage of a 10 minute period that an equipment can be operated at a rated power output without overheating or suffering other damage.* (Occasionally instead of a 10 minutes period, other durations may be specified).

Suppose a welding machine is rated at 300 amps, 40 volts at 60% duty cycle, it means that it can supply at 300 amps-40 volts output only for 6 minutes out of every 10 minutes. A 100% duty cycle power supply is meant for continuous use. Normally a 60% duty cycle is specified. (Light duty power supplies are usually 20% duty cycle machines).

An important point is that the duty cycle of a power supply is based on the output current and not on the V-I or kilowatt rating.

The current rating at other than specified duty cycle is calculated using the formula :

$$T_a = \left(\frac{I}{I_a}\right)^2 T$$

where T is the rated duty cycle in %, T_a is the required duty cycle, I, the rated current, I_a is the maximum current at required duty cycle.

Example 1. *At what duty cycle can a 200 amps power supply rated at 60% duty cycle be operated at 250 amps. output ?*

Solution. $$T_a = \left(\frac{200}{250}\right)^2 \times 60 = \mathbf{38\%}$$

i.e. if the power supply is operated at 250 amps, it should be used only for 3·8 minutes out of every 10 minutes.

Example 2. *If the same power supply is to be operated continuously, what could be maximum output current ?*

Solution. $$I_a = 200\left(\frac{60}{100}\right)^{1/2} = \mathbf{155\ amps.}$$

3·3. Heat Input

Three important variables in arc welding are arc voltage (V), arc current (I) and welding speed (S). As explained in chapter 1, they can be considered together in one parameter—*Heat Input* :

$$\text{Heat Input } H = \frac{VI}{S}$$

Another related quantity is *net heat input*

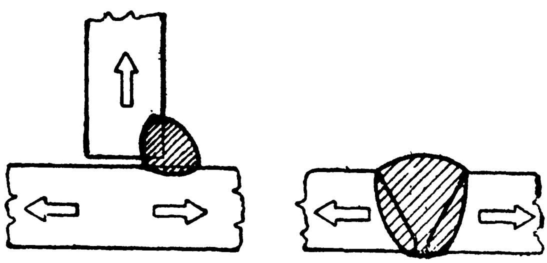
$$H_{net} = f_1 H$$

where f_1 is heat transfer coefficient, (f_1 is approximately equal to 0·9.)

It is important that heat input is kept as low as possible to prevent cracking and reduce distortion, at the same time maintaining a fast welding speed. Higher rate of deposition (and, therefore, more rapid welding) is possible with higher current, but then the heat input may be increased unless there is a proportional increase in welding speed.

It is commonly found that when number of passes is increased for a particular welding job, cracking and other problems are reduced because heat input during each pass is reduced. There is, however, an upper limit. Very large number of passes will not only be uneconomical, but also increases the cooling rate of the weld since the amount of heating between the passes is small. Therefore an optimum level of heat input and number of passes in multipass welding are suggested.

Considering fillet welding, heat can be conducted away by three paths or sections during welding (Fig. 3·6). Therefore, for fillet welds,



Fillet weld Butt weld

Fig. 3·6. Heat paths in fillet and butt welds.

the actual heat input going into the weld region is only 2/3 of net heat input.

$$\therefore \quad H_{net} = \tfrac{2}{3} f_1 H.$$

Example 3. *Calculate the net heat input for a butt welding job performed at an arc voltage of 30 volts and a current of 150 amps at a welding speed of 300 mm/min. Assume that the heat transfer efficiency is 0·9.*

Solution. Heat input $H = \frac{V \times I}{S}$

$$= \frac{30 \times 150}{300/60}$$

$$= 900 \text{ Joules/mm.}$$

Net heat input $= H_{net} = 0{\cdot}9 \times 900$

$$= 810 \text{ Joules/mm.}$$

Considerable heat losses occur during welding due to conduction through the base metal, convection and radiation. The conduction losses are greater for metals of higher thermal conductivity.

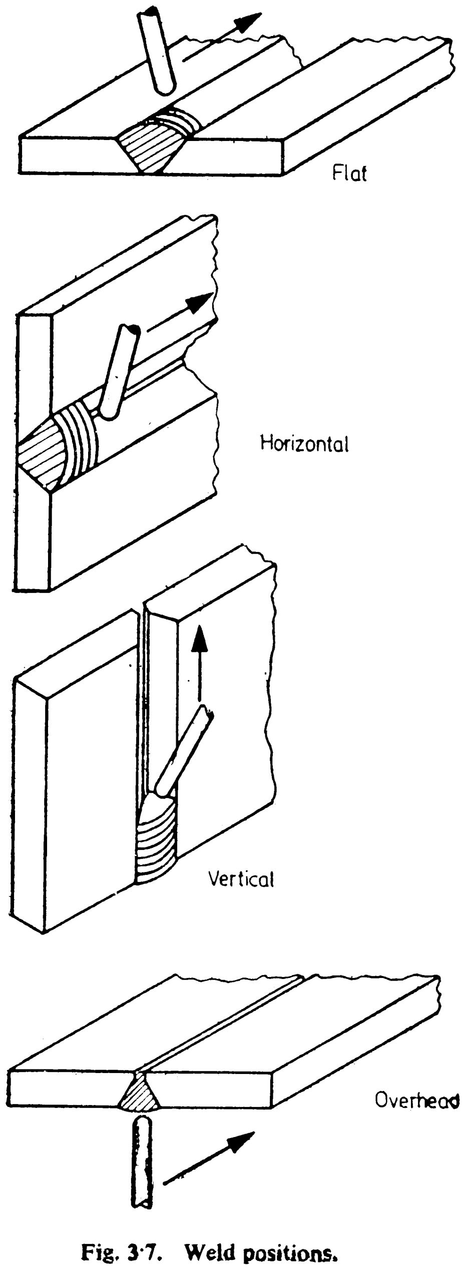


Fig. 3·7. Weld positions.

Thus, other factors being the same, more heat input is required to weld mild steel than stainless steel because the thermal conductivity of stainless steel is much lower than of mild steel. It requires more heat energy or intense source of heat to weld copper as copper can conduct large quantities of heat away from the weld zone.

3·4. Deposition Rate

Deposition rate (expressed in kg/hour) depends on melting rate of the electrode and the deposition efficiency. Melting rate is related to the arc current and is not affected by arc voltage. This increases almost linearly with arc current.

With increasing current deposition efficiency is slightly reduced, due to higher losses of metal by weld spatter. As a general rule, higher deposition rate is obtained with higher arc current, *i.e.* with greater electrode diameter. To increase productivity, therefore, larger diameter wires are preferred while avoiding an excessive heat input.

It can be noted that

$$\text{Deposition rate} = \text{melting rate} \times \text{deposition rate.}$$

3·5. Weld Positions

There are basically four positions in which welding can be done —Flat (*F*), Horizontal (*H*), Vertical (*V*) and Overhead (*O*) (Fig. 3·7). Often from the flat position, a tilt of 15 degrees can be employed. Vertical position has two variations – vertical up and vertical down. Usually the *H*, *V* and *O* positions are called 'out-of-position' welding.

It is important to note that the highest speed of welding is possible in flat or flat with a slight tilt, position. As a typical example consider fillet welding of a 9 mm plate. The welding speeds for different positions are as follows :

Position	*Welding speed*
Vertical (up)	12 (mm/min)
Flat	30
Flat, tilted	47·5

Note that for flat (tilted) position, the speed is nearly four times that of the vertical position.

3·6. Jigs, Fixtures and Positioners

The use of jigs, fixtures and positioners is usually desirable for atleast four reasons : (1) to minimise distortion caused by the heat of welding, (2) to permit welding in a more convenient position, (3) to increase welding efficiency and (4) to minimise fit-up problem.

With a welding jig or fixture, the components of the weldments can be assembled and held securely in proper relationship and with correct fit-up during positioning and during welding. The time required to assemble parts to be welded (set-up and fit-up time) often is a large percentage of total fabrication time. If assembly follows a predetermined sequence of controlled fit-up and alignment conditions, welding efficiency will be increased.

For fabricating a single weldment or a few weldment of the same size and shape, temporary tooling can be used. For quantity production, it is economical to design and construct accurate, durable jigs or fixtures.

Welding Fixtures

Several types of fixtures and clamping devices can be used for welding. Simple ones are clamps and cam-operated clamps.

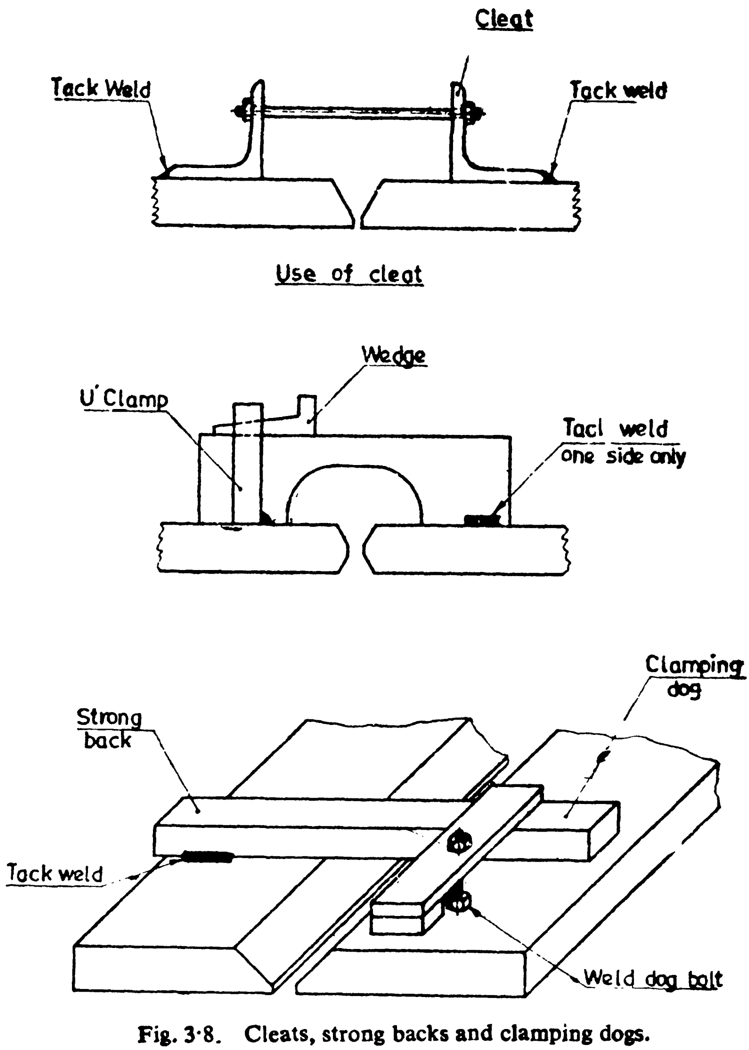


Fig. 3·8. Cleats, strong backs and clamping dogs.

In addition cleats, strong-backs and clamping dogs are used particularly for large plates and angles to be welded (Fig. 3·8).

Cleats. By using cleats with a bolt and nut, accurate spacing or gap between the plates can be maintained. The cleat is tack welded. After finishing the welding job, the cleats are removed. They can be reused.

Strong backs. Strong-backs help to align the plates with correct root gap and with parallel root faces. A strong-back is a piece of plate or angle section that is tack welded in position and used with a clamp and a wedge.

Clamping dogs. First a bolt is tack welded adjacent to the required location of stiffener (an angle section) and then use a clamping dog and wooden blocks. The bolt is tightened. After welding, the bolt is removed and cleaned.

Positioners and Manipulators

The welding positioners and manipulators are tilting tables with provision for rotating the tables as well (Fig. 3·9). Simple trunnion-

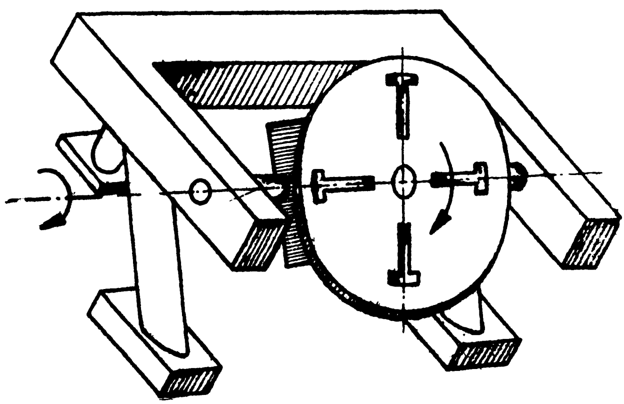


Fig. 3·9. Weld positioner.

mounted rotating fixtures can also be employed. In the case of pipe welding, the pipe can be turned on power-driven rollers so that welding can always be done in the flat position.

The capacity of a manipulator is specified in terms of its loading capacity *e.g.*, 2 tonne manipulator or 10 tonne manipulator and the driving power required to opertae it.

4

Shielded Metal Arc Welding

4·1. Introduction

Shielded metal arc welding (SMAW) is the manual arc welding process using either bare or coated electrodes. It is also called stick welding. The process consists of establishing an electric arc between a metallic electrode and the workpiece to welded. The electrode melts and joins the weld pool. Therefore the process is also classified under consumable arc welding methods. Bare wire electrodes are only rarely used. The coated electrode was invented by Kjellberg, a Swedish engineer.

The coating on the electrode burns, producing a dense smoke which covers or *shields* the metal drops during their transfer from electrode to weld pool. This shielding is important to prevent oxidation and absorption of nitrogen by the metal. At the same

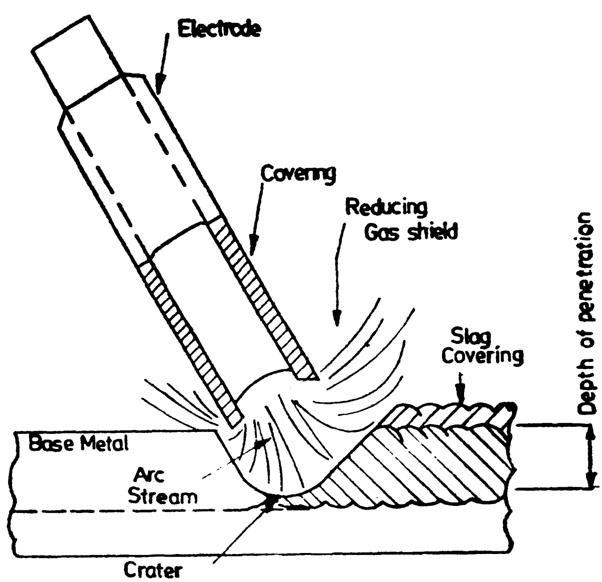


Fig. 4·1. Shielded metal arc welding process.

time the coating melts forming a slag cover on the molten pool. The other functions of the coating are discussed later.

During welding, the parent metal also melts to a particular depth, forming a crater. This depth is called depth of penetration. The weld metal deposited, therefore, is derived partly from parent metal and the rest from the electrode (Fig. 4·1)

The greatest advantage of SMAW is the versatility and flexibility to perform welding in difficult places. Further, the equipment costs are less. SMAW, however, requires considerable skill on the part of the welder. The rate of deposition is rather slow, compared to SAW or GMAW, and therefore SMAW becomes uneconomical for welding thick plates.

This chapter discusses the functions and types of electrode coatings, various welding parameters, common types of electrodes, and weld defects and their remedy, among other matters.

4·2 Power Sources

SMAW can be performed by both AC and DC welding sources. A proper choice of electrode is an important step in correct welding procedure. Much of the practice in SMAW is done with power sources of drooping arc voltage (DAV) characteristics as already explained in chapter 2.

Since the process is manual, the highest current rating can be only about 600 amperes. The weight of the cable and the necessity for cooling the cable restrict the SMAW process to this value. Most portable units are in the current range 50 to 400 amperes.

From the viewpoint of increasing the productivity of a welder, electrodes of largest diameter should be used for a given plate thickness, considering the depth of penetration and heat input. Excessive heat input can lead to cracking problems. Recommendations for electrode diameter and number of passes are given in handbooks.

The recommended relationship between the plate thickness, electrode diameter and arc current settings for mild steel are as follows :

Plate thickness (mm)	*Electrode Diameter (mm)*	*Current (amps)*
1·6	1·6	40-60
2·0	2·4	60-80
2·6	3·2	100
3·2	3·2	125
4·8	4·8	190
5·9	6·4	230
7·0	8·0	275-300
9·0	9·5	400-600

The electrode manufacturers usually provide useful tables for the selection of suitable electrodes and their current ratings.

Direct Current Welding

In general DC welding is easier to perform because the arc is steady and smooth. The polarity connection can be of two kinds :

1. *DC Straight Polarity* (DCSP)—electrode is negative and plate is positive and

2. *DC Reverse Polarity* (DCRP)—electrode is positive and plate is negative.

In most power supplies, a reveısing switch is provided to change from DCSP to DCRP or *vice versa* without making reconnections (Fig. 4·2).

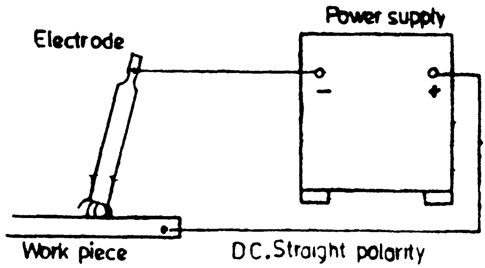


Fig. 4·2. DCSP and DCRP connections.

In DCSP, electrons flow from the electrode to the workpiece and positive ions travel from the workpiece to the electrode. In DCRP the situation is reversed. It is important to note that nearly two-thirds of the heat energy is concentrated around the positive terminal. Melting and deposition rates are higher for DCSP than with reverse polarity. DCSP produces a narrow and shallow penetration.

Straight polarity is used for welding thin sheets and for plates with wide gaps. Reverse polarity produces maximum penetration and, therefore, it is widely used for root passes and for out-of-position welding.

Arc starting is also easier in DC welding. A voltage drop occurs along the cables and, therefore, the cables should be as short as possible. The problem of arc blow is discussed separately.

Alternating Current Welding

Alternating current welding can be considered as DCSP welding in periodic cycles. Since the voltage drops to zero during reversal, the arc is not steady. AC welding requires greater skill on the part of the welding operator.

The penetration characteristic of AC welding is intermediate between those of DCSP and DCRP welding. An advantage of AC welding is that the voltage drop in cables is less compared to DC welding. Further arc blow is not a problem in this method. Arc starting with small diameter electrodes is more difficult than with direct current. Therefore, AC welding is more suited to welding hicker plates.

4·3. Electrode Coatings

Functions of the coatings are as follows :

1. Provides a protective, non oxidising or reducing gas shield around the arc to keep oxygen and nitrogen in the air away from the molten metal ;

2. Facilitates striking the arc and enables it to be stable ;

3. Provides flux for the molten pool of metal ; forms a protective slag which is easily removed ;

4. Gives good penetration ;

5. Increases or decreases fluidity of slag for special purposes, *e.g.*, reduced slag fluidity of electrodes used for overhead position ;

6. We can adjust the composition of weld metal ; add deoxidisers like ferrosilicon and certain alloying elements to the coating.

Ingredients

The coating may consist of several of the ingredients listed here :

1. *Cellulose.* It provides a reducing gas shield, increases arc voltage ;

2. *Potassium aluminium silicate or Kaolin.* Stabilises the arc gives strength to the coating ;

3. *Metal carbonates.* Produces a reducing atmosphere (due to CO_2) ; adjusts the basicity of the slag.

4. *Mineral silicates and asbestos.* Provides slag forming materials, adds strength to the coating ;

5. *Ferromanganese and ferrosilicon.* Used to deoxidise the weld metal ;

6. *Rutile.* Forms a highly fluid and quick freezing slag, adjusts, the basicity of slag.

Additional Ingredients

1. *Clays and gums.* To produce a pasty material for extruding the coating during the manufacturing of electrodes.

2. *Iron power.* (High yielding electrodes ; also called contact or drag electrodes), increases the amount of metal deposited and draws larger current and thereby increases productivity (The deposition efficiency is greater than 100% for high yielding electrodes).

Classification of Coatings

The electrodes are classified into four categories:

1. Cellulose coatings
2. Rutile coatings : (*a*) fairly viscous
   (mineral coating) (*b*) fluid
3. Iron oxide coatings : (*a*) inflated
   (*b*) solid
4. Lime fluorspar (Basic).

Cellulose coating. Provides a gas shield, a deeply penetrating arc and rapid burning rate—easy to use in any welding position—suitable for all types of mild steel welding—mainly used with D.C. supply.

Rutile (T_1O_2) *coating* : (*a*) **Viscous type**. The slag is dense, easily detached and suitable for butt and fillet welds ; suited for A.C. and with D.C. for flat and horizontal position.

(*b*) **Fluid type**. Suited for vertical and overhead position ; suitable for AC and DC (SP or RP).

Iron oxide : (*a*) **inflated type**. Contains oxides and carbonates of iron and manganese ; used for deep groove welding in flat position only—slag freezing with lot of holes ; hence the name inflated slag. The weld profile is very smooth and concave—suitable for DC and AC.

(*b*) **Solid type**. Forms a thick covering, the slag detaches easily—used for single run fillet welds where smooth contour is more important than high strength of the weld metal ; suitable for both AC and DC.

Lime Fluorspar. This class of electrodes is often called *Low-hydrogen* or *basic* electrodes, suitable for welding in all positions. The slag is fairly fluid ; the weld deposit is usually convex to flat in profile ; used for welding heavy sections, highly restrained joints and alloy steels (which are prone to cracking due to hydrogen). It can be used with AC or DCRP only.

Compositions of electrode coatings. Typical compositions of electrode coatings for two types E6010 and E7018 are given here. E6010 is a common, cellulose coated electrode. E7018 is a basic low-hydrogen electrode with iron power.

Ingredients	*E*6010 (%)	*E*7018 (%)
Cellulose	25—40	—
Calcium carbonate	—	15—30
Fluorspar	—	15—30
Titanium dioxide (rutile)	10—20	0—5
Potassium titanate	—	0—5
Feldspar	—	0—5
Asbestos	10—20	—
Iron powder	—	25—40
Ferrosilicon	—	5—10
Ferromanganese	5—10	2—6
Sodium silicate	20—30	0—5
Potassium silicate	—	5—10

Storage of Electrodes

The electrode coating can absorb moisture from the atmosphere. This introduces hydrogen into the weld metal, and hydrogen can also diffuse into the parent metal in the heat affected zone. This can lead to porosity and cracking problems ('fish eye' and underbead cracking). Therefore, electrodes should be stored in any dry place.

Low hydrogen electrodes should be dried in an oven (called *electrode baking oven*) at about 110°C. After removing the electrode from the oven, it should be used with in a few hours (1 to 2 hours). Unused electrodes should be put back into the oven.

Moisture Level. The moisture content may vary from about 0·3 to 4% by weight of coatings. Low hydrogen electrodes have moisture level around 0·3 to 0·5% while cellulose coatings have about 2% moisture.

4·4. Electrode Compositions

Electrodes for Low Carbon Steel

The common electrodes used for welding of low carbon steel (steel with $<$0·2%C) are given by their AWS-ASTM designations (See Appendix 5). The nature of the coating, current and weld positions are also indicated.

Corrosion Resistant Filler Metals

Arc welding electrodes and welding rods which deposit ferrous weld metal with more than 4% chromium and less than 50% Nickel are considered to be corrosion resistant, chromium and chromium-nickel filler metals. They are frequently referred to as the stainless electrode series. The important compositions of this category are given in Table 4·1.

Table 4·1. Corrosion Resistant Electrodes

Series	*Composition* *Chromium* %	*Nickel* %	*Molybdenum* %	*Application*
308	18	8	—	corrosion resistance
309	25	12	—	corrosion resistance
310	25	20	—	hard facing
316	18	12	2	high temp. above 600°C
317	18	12	5	high temp. above 600°C
330	15	35	—	high temp. above 1000°C
347	16	—	—	corrosion resistance
410	12	—	—	abrasion resistance
430	19	9	—	abrasion resistance
502	4—6	—	0·5	abrasion resistance

4·5. Preheating

Preheating is one of the most important methods to avoid cracking in welding of steels with high carbon equivalents. (See chapter 15). Preheating reduces the cooling rate after welding in the heat affected zone thereby avoids the formation of martensite. The reduced cooling rate also decreases the constraction stresses and residual stresses in the weld metal.

4·6. Post Weld Treatments

The common treatments are stress relief treatment (at 650°C, for example for steels) and tempering treatment, if martensite had formed.

Several treatments such as peening (to reduce harmful residual stresses) and vibratory stress relief, may be employed (See chapter 17).

Proper grinding of the welds may be required. For this purpose, portable hand-held grinders and angle grinders are widely used.

4·7. Arc Blow

An electric current flowing through the electrode sets up magnetic field in a continuous series of circles in a plane perpendicular to the axis of the rod. Similarly magnetic lines are also fromed around the workpiece and ground cables. When the fields around the workpiece or around the electrode are unbalanced, the arc bends away from the greater concentration of the magnetic fields. This deflection of the arc from its intended path is called arc blow. Arc blow is encountered particularly when using direct current, because the magnetic field is in a constant direction. This occurs to a minor degree alternating current welding.

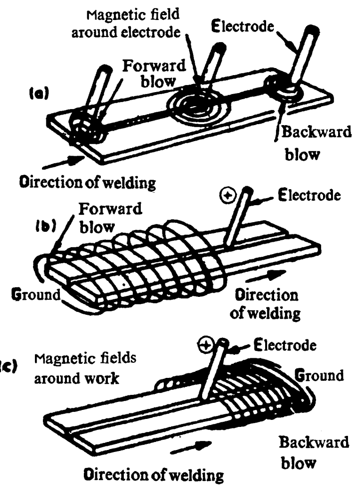


Fig. 4·3. Arc blow.

Fig. 4·3 shows the forward blow, when the arc gets deflected in the direction of travel and the backward blow when the arc is deflected in a direction opposite to welding direction.

Backward blow is encountered when welding towards the ground connection, toward the end of the joint or into a corner. This kind of arc blow can lead to incomplete fusion and excessive weld spatter.

The magnetic field lines surrounding the workpiece are perpendicular to the workpiece. These are present between the electrode and the point at which the ground clamp is fixed. While welding towards the ground connection, backward blow results. Forward blow occurs on welding away from ground connection.

The *corrective methods* for use when severe arc blow occurs are as follows :

1. Change to alternating current ;
2. Reduce welding current and keep arc length at the minimum ;
3. Weld toward a heavy tack weld or toward an existing weld ;
4. On long welds use a back-step sequence ;

5. Place the ground connection (*a*) as far as possible, (*b*) at the start of a weld and then weld toward a veavy tack weld, or (*c*) at the end of the weld ;

6. Wrap the ground cable around the workpiece so that the current flows in a direction that will establish a magnetic field that will neutralize the magnetic field causing arc below.

4·8. Weld Movement

The manipulation of the electrode depends on the thickness of electrode coating. Electrodes with a light coating require more physical manipulation than those with heavy coating. The thick covered electrodes can even touch the base metal and the procedure is called drag technique.

The type of weld movement depends on the operator. The most common types are shown in Fig. 4·4. These movements are

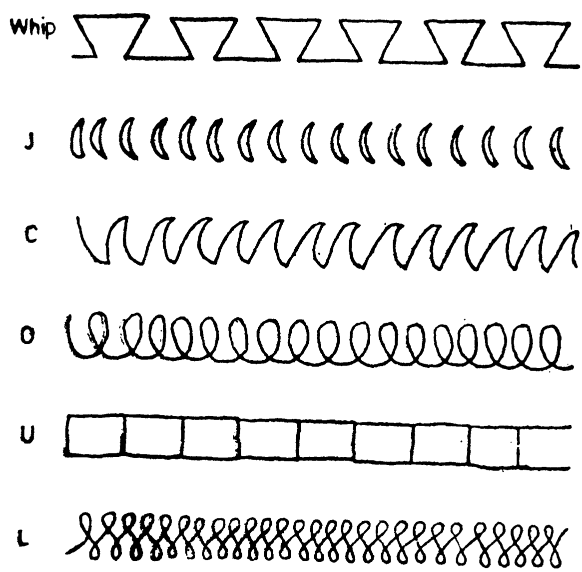


Fig. 4·4. Weld movement.

designed to form a suitable crater of sufficient depth a penetration followed by filling up of the metals and control of welds puddle. Optimum movement allows a hesitation period when the arc is stationary and the crater is filled properly with molten metal. Proper weld movement will avoid the entrapment of slage in the deposition.

For proper operation a constant arc length should be maintained. The arc length is approximately equal to the diameter of the electrode. If the arc length is too long, the shielding effect of the gases is minimised and consequently a weld of poor properties will result.

4·9. Joint Design

The recommended joint profiles are given in Fig. 4·5. A double V joint requires less electrode metal compared to single V joint for

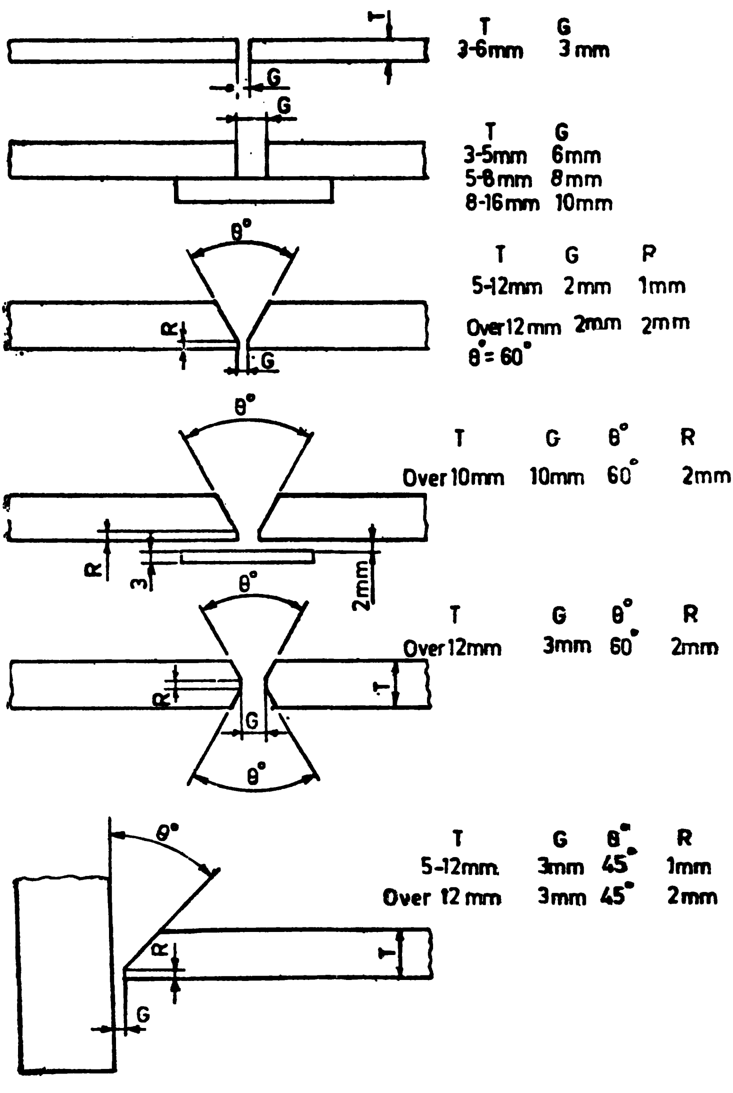


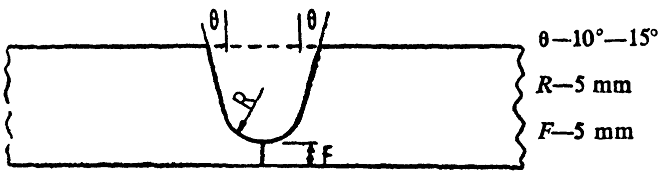
Fig. 4·5. Recommended weld profiles.

the same thickness. Further a double V joint may result in less angular distortion. A V joint with narrow groove angle also requires less electrode metal.

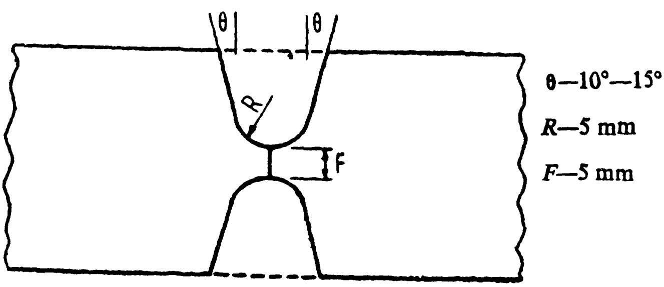
Fit up. Poor fit-up reduces productivity and often is the cause of unsound welds. For butt joints welded in flat position, for a given plate thickness, the speed of welding is greatly reduced with increase in root opening. As an example, for 6 mm thick plate, a joint with a 0·75 mm root opening can be welded nealy three times as fast as the same joint with a 1·5 mm root opening.

For fillet welds, the effect of root opening on welding speed is quite similar.

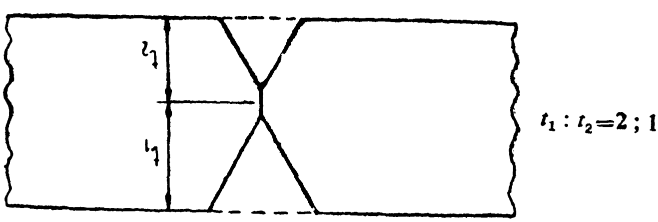
The edge preparation for very thick plates usually involves single U groove or double U groove. U groove results in less angular distortion than V groove. The angle of tilt from the vertical plane is usually 10 to 15°. The recommended root face is 5 mm. [Fig. 4·5 (*a*)]. The cost of edge preparation, however, is higher for U groove.



Single U



Double U



Asymmetric V

Fig. 4·5 (*a*)

The figure also shows asymmetrical double V. This edge geometry results in less distortion for thick plates. The bottom groove is made smaller since more distortion occurs due to earlier passes on the underside.

In summary, the main factors to consider while selecting weld geometry are the cost of edge preparation, shrinkage distortion and volume of deposited weld metal.

Fillet weld design. The largest leg size of single pass fillet weld depends on welding position and is as follows :

flat	......9 mm
horizontal	......7·5 mm
overhead	......7·5 mm
vertical	......12 mm

The fillet leg size is almost always specified on the basis of the required strength. Excessive leg size should be avoided as it increases the cost and the time of welding.

The recommended fillet leg size depends on the plate thickness of the thicker member. For low carbon steels, the recommendations are as follows :

Plate thickness (mm)	*Fillet leg size (mm)*
6	3
6—12	4·5
12—18	6
18—35	8
35—55	10
55—150	12
⊳150	15

To reduce the cost, intermittent fillet welds can be deposited for long welds. For adequate strength, the minimum length of an intermittent weld should be at least four times the leg size, but not less than 35 mm. (Intermittent fillet welds are not recommended when fatigue loads are involved).

4·10. Welding Defects

In the shielded metal-arc welding of steel, slag inclusions and porosity are common weld defects. Other defects that often occur

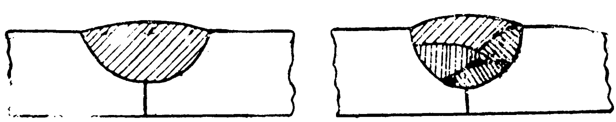


Fig. 4·6. Slag inclusions.

are undercuts, longitudinal (centreline) cracks, underbead cracks and gaps resulting from incomplete fusion. Probable causes of several types of weld defects in steel, together with methods of prevention, are discussed below.

1. *Slag Inclusions* (Fig. 4·6). May be the result of (*a*) incomplete deslagging of a previous pass ; (*b*) wide weaving, which permits slag to solidify at the sides of the bead ; (*c*) erratic progressions of travel ; (*d*) excessive amount of slag ahead of the arc, particularly in deep grooves ; ana (*e*) use of electrodes that are too large. The preventive measures are, respectively : (*i*) to deslag deposit thoroughly before a subsequent weld bead is deposited ; (*ii*) to restrict the width of weaving so that the entire width of slag immediately behind the weld puddle remains molten ; (*iii*) to keep the slag behind the arc by shortening the arc, increasing the electro le angle, or increasing travel speed ; (*iv*) to use a smaller electrode.

2. *Wagon Tracks.* Linear slag inclusions along the axis of the weld arc called "Wagon tracks". They ordinarily result from failure to remove slag remaining from previous passes, or from allowing the slag to run ahead of the weld puddle. Wagon tracks above the root pass have the same effect on weld quality as other inclusions in the weld metal or base metal.

3. *Porosity* (Fig. 4·7). Porosity that is scattered along the entire length of a weld bead can be caused by (*a*) impurities, such as sulphur or phosphorous, in the parent metal ; (*b*) contamination of the surface of the parent metal by rust, grease, moisture or dirt ; (*c*) excessive moisture in electrode coverings ; (*d*) improper arc length ; (*e*) excessive current ; (*f*) welding at a speed too high to permit gases to escape ; and (*g*) freezing of the weld puddle before gases escape. The steps for avoiding the above causes of this type of porosity are, respectively ; (*i*) changing to metal of different composition ; (*ii*) cleaning the work metal, and removing moisture from joint surfaces ;

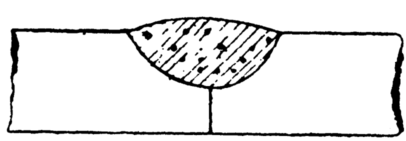


Fig. 4·7. Porosity in weld metal.

(*iii*) redrying electrodes to restore recommended moisture content of covering ; (*iv*) using proper length of arc ; (*v*) reducing welding current ; (*vi*) reducing travel speed to permit gases to escape ; and (*vii*) preheating the work metal or using a different class of electrode or both.

When porosity occurs within the first 6 or 12 mm of bead length, the most likely cause is moisture in the covering of the electrode—particularly if the electrode is of the low hydrogen type.

4. *Wormhole Porosity.* (Fig. 4·8) is usually associated with moisture entrapped in the joint ; when visible at the surface, wormhole porosity is sometimes referred to as 'gas shoots'. Sulphur in the base metal is also a contributing factor. One means of preventing

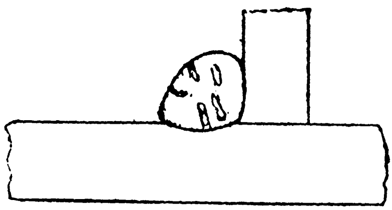


Fig. 4·8. Wormhole porosity.

wormhole porosity is to reduce welding speed to permit gases to escape before the metal freezes.

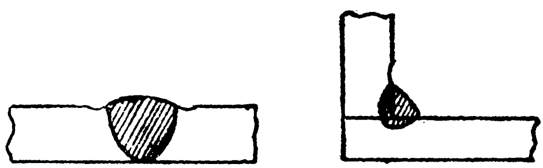


Fig. 4·9. Undercuts.

5. *Undercuts.* (Fig. 4·9) are usually due to excessive weaving speed. In horizontal or vertical welding, additional causes are excessive electrode size and incorrect electrode angles. Travel speed should be such that the deposited weld metal completely fills all melted-out portions of the base metal and when the weaving technique is used, there should be a slight pause at each side of the weld. The arc should be as short as possible without shorting and the current should be appropriate for electrode size and type and for welding position.

6. *Hot Cracking.* Occurs at elevated temperatures, generally just after the weld starts to solidify. Hot cracks, which are for the most part intergranular, can be identified by a coating of oxide on their surfaces. Depending on the magnitude of strain, hot cracks will vary from microfissures to readily visible cracks. (See chapter 15).

Hot cracks are most likely to occur in the root pass weld bead, because of the small cross-section of the bead compared to both the masses of material being welded. Hot cracking often occurs in deep penetrating welds, and in welds of free machining steels. If the initial crack is not repaired it will usually continue through successive layers as they are deposited. Hot cracking of the root bead may be minimized or prevented by preheating to modify strain, by increasing the cross-sectional area of the root bead, by using low hydrogen electrode or by changing the contour or the composition of the weld bead.

7. *Cold Cracking*. Normally occurs in the heat effected zone and near ambient temperature. Its occurrence may be delayed for as long as the stresses within the weldment relieve themselves. Cold cracking is generally recognized as being caused by excessive restraint of the joint, or by martensite formation as a result of rapid cooling. Low hydrogen electrodes are used extensively to overcome cold cracking ; preheating is also helpful. Although a stress-relief heat treatment cannot heal cracks that have already formed, it does reduce the residual stresses, thus reducing susceptibility to fracture.

8. *Centre line Cracks* (Fig. 4·10). Are cold cracks that often occur in single pass concave fillet welds. The usual causes are an incorrect relationship between the size of the weld and the thickness of the parent metal, poor fitup and overly rigid fitup.

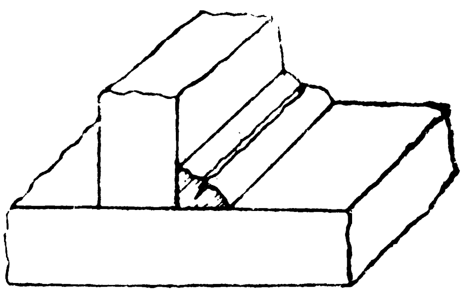


Fig. 4·10. Centreline crack.

The usual ways of preventing centre line cracks are (*a*) positioning the joint slightly uphill so as to produce flat or slightly convex bead contour (*b*) increasing bead size ; (*c*) decreasing gap width or filling one side of the joint before welding the parts together; and (*d*) providing a small gap to allow movement during cooling.

Centre line cracks can occur as extensions of cracks in weld craters or root bead cracks. The first extension of the crack may occur after the weld is completed and is cooling.

9. *Underbead cracks* (Fig. 4·11) are most frequently encountered when welding a hardenable base metal. Excessive joint restraint

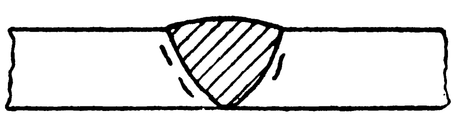


Fig. 4·11. Underbead crack.

and the presence of hydrogen are contributing causes. Underbead cracking can be minimized or prevented by using low hydrogen electrodes or by preheating the plates.

10. *Base Metal Cracking.* Usually originates in the heat effected zone of the base metal as either hot or cold cracks. Cracks often extend into and through the weld metal. A reduction in welding stresses by, for instance, using weld metal with high ductility may alleviate the problem. The presence of a small slag inclusion or large amount of porosity can increase the probability of cracking.

Cold cracks may originate at the toe of the weld and wander off in a random direction. Generally increasing restraint of the base metal, increasing the thickness of the base metal or increasing the length of the weld increase the cold cracking. The probability can be decreased by preheating the base metal, by post heating after welding, by depositing welding in an intermittent pattern or by welding with high current.

11. *Microfissuring* can normally be detected only by the use of a microscope. It is caused by either hot or cold cracking. Extremely small cracks are not detrimental for many applications, but for applications involving fatigue, they make the weldments unacceptable.

12. *Weld Craters* are a recession of the surface and are caused by solidification of molten weld puddle after the arc has been extinguished. Weld crater cracks serve as origins for linear cracking. They are usually removed by chipping or grinding, and the depression is filled with a small deposit of filler metal.

A back step or reverse-travel technique to fill each crater before breaking the arc has been found helpful in preventing crater cracking.

13. *Arc Strikes.* Striking the arc on the base metal outside the weld joint can result in a hardened spot on the surface. Failures can occur due to notch effect. Welders should be cautioned to avoid indiscriminate marking of the base metal surface with arc strikes, as it is unnecessary and may be harmful ; many codes prohibit striking the arc on the workpiece surface.

14. *Gaps from incomplete fusion* (Fig. 4·12). It may occur between the weld metal and the base metal or between the weld beads

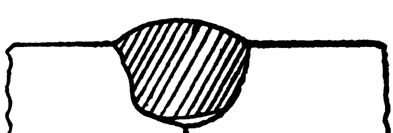


Fig. 4·12. Gaps from incomplete fusion.

of a multiple pass weld. Failure to obtain complete fusion can be caused by excessive travel speed, bridging, excessive electrode size, insufficient current, or poor joint preparation. Gaps usually can be prevented by reducing travel speed, improving joint preparation, or increasing the current.

15. *Oxidation.* Surface oxidation occurs when the base metal or the weld metal has been inadequately protected from the atmosphere. Severe draft which disrupts the protection offered by the gas shield must be avoided, so that the weld metal and adjacent base metal are shielded until they have cooled enough to prevent harmful oxidation.

16. *Sink or Concavity.* It is produced by surface tension on the surface of the weld puddle, which pulls the molten metal up into the joint, or by the effect of gravity when welding in the overhead position. If the condition is severe, root bead cracking can occur.

17. *Weld reinforcement.* The reinforcement left on the weld can have a significant effect on the fatigue strength of the weldment at that point. It is customary on highly stressed weldments to remove the reinforcement by grinding it flat with the level of the adjacent base metal. Use of appropriate welding techniques will result in a weld reinforcement that is smoothly blended into the adjacent surface (See section 15·7).

18. *Over lapping.* Fig. 4·13 (Protrusion of weld metal beyond the toe or root of the weld). It is caused most often by (*a*) insufficient travel speed which permits the weld puddle to get ahead of the electrode and cushion the arc ; (*b*) incorrect electrode angle, which allows the force of the arc to push molten metal over unfused portion of the base metal ; or (*c*) welding away from ground with large electrodes having very fluid weld puddles.

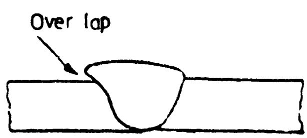


Fig. 4·13. Overlap.

To prevent overlapping the travel speed should be such that the arc leads the weld puddle, and the electrode angle should be such that the force of the arc does not push the molten metal out of the puddle and over the cold base metal. Over lapping is corrected by grinding off the excess weld metal.

19. *Excessive Weld Spatter.* This is caused by an excessive arc length ; if the spatter is fine, excessive current is a likely cause. Weld spatter can be minimized by keeping the arc length at the minimum that will not result in shorting out. A slight drag technique is recommended when using electrodes with iron powder coverings. Current should be kept within the current range recommended for the specific electrode. To improve the surface appearance of the weld, spatter can be removed by grinding.

Effect of Number of Passes. The use of multiple passes is often effective in the prevention of weld cracks. For instance, multiple passes can be effective in fillet welding when cracking has resulted from single pass welding either because the carbon equivalent of the steel was borderline or because attempts to minimize distortion caused severe joint restraint in cooling.

The use of multiple passes (preferably a minimum of three) can sometimes eliminate the need for preheating or post heating when conditions are borderline. In multi-pass welding, the first pass provides some preheating effect for the second pass, and the third pass provides a certain amount of post heating effect for the previous two passes, and so on. Welding should be done quickly, to minimize cooling between passes. Also, the first-pass weld bead must be deep-penetrating, and must be of sufficient size so that it will be strong enough to resist cracking. (If the first-pass bead cracks, the crack will usually propagate through subsequent beads). This technique is particularly adaptable to repair welding in the field, and has proved helpful in shop-welding applications as well. It should not be assumed, however, that the technique can always be considered as a substitute for preheating and post heating.

20. *Lamellar Tearing.* It is the pulling apart of base metal under stresses acting in the thickness direction generated by thermal contraction strains in a welded joint. It is primarily associated with T-type or corner joints that are highly restrained (Fig. 4·14). The

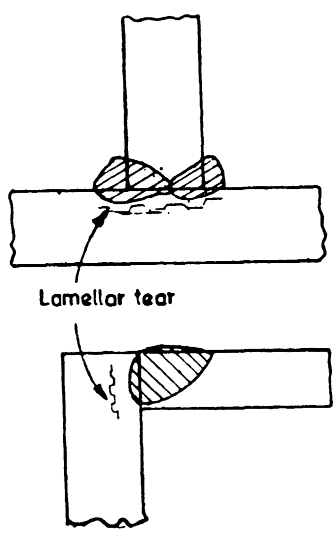


Fig. 4·14. Lamellar tearing.

tearing originates in or just outside the heat affected zone. It is trigged by decohesion of elongated silicate or sulphide inclusions.

Resistance to lamellar tearing is increased by aluminium killing of steels (fully killed) and desulphurisation by rare earth additions or liquid metal treatments at additional cost. The fabrication procedures can be altered to reduce the possibility of lamellar tearing, *e.g.* welding sequence, avoiding oversize welds or overmatching strength electrodes, moisture control of low hydrogen electrodes, intermediate stress relief and controlled peening. An effective technique is to butter the surface of the member adequately either in a pregrooved area or on top, before attaching the leg of the T joint (Fig. 4·15).

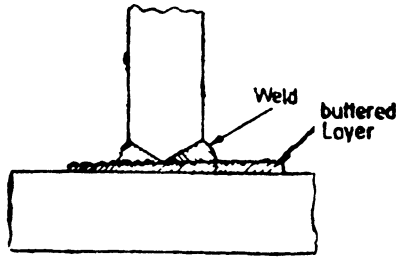


Fig. 4·15. Buttered layer.

4·12. Cost of Welding

Since SMAW is the most widely used method, the cost analysis of welding is explained here.

For SMAW, the elements of cost are as follows :

$$\text{Cost} = C = L_1 + L_2 + O + C_1 + P$$

where L_1—Cost for direct welding labour

L_2—Cost for associated labour

O—Overhead charges

C_1—Cost of consumables (mainly electrodes)

P—Plant and maintenance cost.

The direct labour cost is considerable for SMAW. In can be minimised by controlling the factors affecting the time of welding. The important factors are as follows :

1. Duty cycle
2. Deposition rate
3. Weld geometry.

Duty cycle is defined as the percentage of arcing time to the total time :

$$\text{duty cycle} = \frac{\text{arcing time}}{\text{total time}} \times 100\%$$

The duty cycle should be as high as possible. With the help of associated labour, fit-up time can be reduced and duty cycle can be maintained at a high value.

The deposition rate can be increasing by using the flat position. To achieve this, the work may have to be tilted. Work positioners are, therefore, to be provided to obtain flat position.

The cost of direct labour and cost of electrode can be reduced by suitable weld geometry. The groove angle for butt joint can be reduced to as low a value as 45°, instead of the usually recommended 60°. Further, parallel penetration welds may be adequate in most cases from strength considerations. (Partial penetration should be avoided when fatigue loads are involved). For fillet welds, the leg size can be minimised.

Associated labour cost includes the cost of providing a helper to the welder.

Overhead charges include a part of the centralised expenditure of the works. A common method of computing overhead charge is to add to labour cost a fixed percentage which may vary from 150% to 350% ; but the usual figure is 300%, *i.e.*, the overhead cost is taken as three times the direct labour cost.

The cost of consumables is essentially the cost of electrodes. [See appendix 1]. It depends mainly on electrode efficiency which can vary from 80 to 95%.

Capital cost of the welding equipment is computed from the cost of the welding set divided by expected life. The maintenance cost varies from 5 to 15% of the capital cost.

4·13. Underwater Arc Welding

The underwater arc welding is similar to welding in open air. The following modifications are required :

(*a*) The cables and connections should be well insulated since water, particularly sea-water, can conduct electricity.

(*b*) The electrode coatings should be protected with proper water repellent materials, for example, celluloid varnish.

(*c*) Since the parent metal and weld metal can cool rapidly due to surrounding water, the arc current should be higher, about 10 to 20% greater than the normal arc current is employed.

Since visibility is poor, it is difficult to obtain good quality welds. Further a high degree of skill is needed.

4·14. Oxygen-arc Cutting

In oxy-arc cutting, the steel is preheated by an electric arc. The oxygen jet is used to oxidise iron with the liberation of heat sufficient to melt and to form a cut. The principle is the same as in flame cutting.

A hollow metallic electrode with a flux covering is used. Oxygen is passed through the bore of the electrode (at a pressure of 5 bars). The electrode is consumed during the cutting operation. (Fig. 4·A-1).

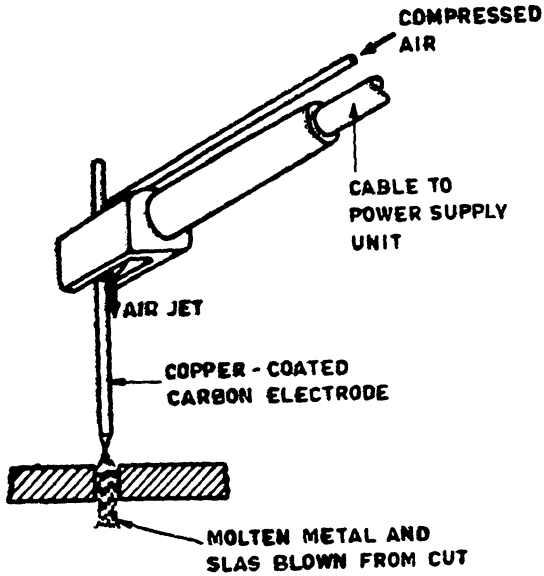


Fig. 4·A-1

The flux coating helps in easy melting of the oxides formed while cutting steels with alloying elements such as chromium and silicon. Oxides of these metals h ve high melting points and result in viscous slag which interfere with cutting.

The diameters of the electrodes are usually 5 mm and 7 mm. The hole diameters are 1·6 and 2·5 mm respectively. The length of the electrode is usually 450 mm. The electrode is connected as DC negative (DCSP).

The data for cutting low carbon steels is as follows :

Electrode dia (mm)	*Thickness range (mm)*	*Current (amps)*	*Cutting speed (m/h)*
5	8—38	120—135	55—25
7	50—100	190—250	25—17

For cutting stainless steel plates of 25 mm thickness, the cutting speed will be lower, about 4 m/h.

A major advantage of oxy-arc cutting is that cutting speeds are 3—4 times higher than that for flame cutting. Compared to flame cutting or plasma cutting, the surface of the cut is rough. This process is mainly used as a manual operation. The maximum thickness that can be cut is about 100 mm for steels.

Oxy-arc cutting is also widely used to cut stainless steels, nickel alloys, copper alloys and cast irons. It is also used for piercing holes in steel plates (upto 150 mm thickness) and for removing rivets. It is a useful process for repairing welds and defects in castings.

4·15. Air-arc Cutting and Gouging

In air-arc cutting, the heat required to melt the steel or non ferrous metal is provided by the arc. There is insufficient oxidation of iron to heat the metal. A compressed air stream is used to blow the metal out of the cut. This method is suitable for plates upto 30 mm thickness.

The electrode material is a combination of carbon and graphite, usually coated with copper. The carbon electrode is held in a holder which has provision for a jet of compressed air (with pressure 0·5 MPa). The air jet is close to the electrode. The electrode is DC positive. The air-arc cutting can also be done with a metallic electrode (Fig. 4·A-2).

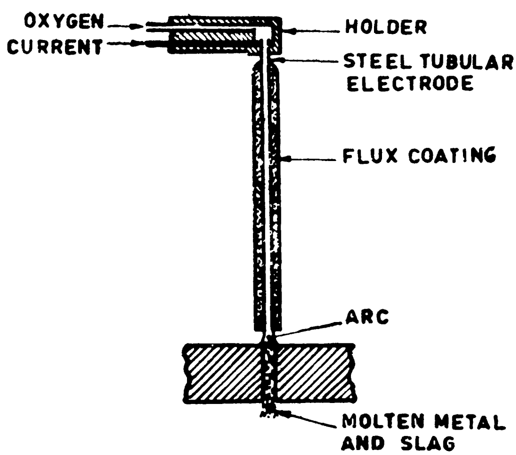


Fig. 4·A-2

The air-arc cutting method is widely used for gouging, particularly in repair work. The root side of a weld may be gouged to form a shallow groove and a sealing run may be deposited. (For preparation of root of welds, the carbon electrodes used may vary from 4 mm dia rods to 12 mm diameter. The current employed is in the range 180—550 amps.)

Further, broken castings can be gouged by air-arc torch before deposition of weld metal.

4·16. Under Water Arc Cutting

Underwater cutting may employ metallic or carbon/graphite electrodes. Metallic electrodes are usually low carbon steel rods (6 mm diameter and 400 mm long) with a thick flux coating. The coating is covered with moisture-proof material. Generally a high current is used since the metal to be cut is quickly cooled by the surrounding water. The typical working data are as follows :

Plate thickness (*mm*)	*Arc current* (*A*)	*Cutting speed* (*m/h*)
5	500	10
10	600	4
20	800	0·7
40	1000	0·2
60	1000	0·12

An important special precaution in underwater cutting is to insulate all the current carrying parts upto the electrode. Sea water has high electrical conductivity and therefore such insulation is required for cutting under sea water.

Underwater cutting is required for repair, salvaging and breaking of ships, and for maintenance of off-shore oil platforms.

4·17. Fillet Weld Design

The largest leg size of single pass fillet weld depends on welding position and is as follows :

flat..................9 mm

horizontal.........7·5 mm

overhead ....7·5 mm

vertical............12 mm

The fillet leg size is almost always specified on the basis of the required strength. Excessive leg size should be avoided as it increases the cost and the time of welding.

The recommended fillet leg size depends on the plate thickness of the thicker member. For low carbon steels, the recommendations are as follows :

Plate thickness (mm)	*Fillet leg size (mm)*
6	3
6—12	4·5
12—18	6
18—35	8
35—55	10
55—150	12
>150	15

To reduce the cost, intermittent fillet welds can be deposited for long welds. For adequate strength, the minimum length of an intermittent weld should be at least four times the leg size, but not less than 35 mm. (Intermittent fillet welds are not recommended when fatigue loads are involved).

5

Submerged Arc Welding

5·1. Introduction

Submerged arc welding is next in importance to shielded metal arc (*i.e.* manual arc) welding. It provides a method of welding thick plates in a few passes because of high rate of deposition and deeper penetration. It is well suited for welding long plates automatically or for pipe welding. It is generally preferred for thicknesses in the range 25—100 mm.

5·2. Description

It is quite similar to SMAW except that, instead of coated electrode, a bare wire electrode in the form of continuous wire can be used and the arc is shielded by a layer of granular and fusible flux which blankets the molten weld metal. The fused flux protects the weld metal from atmospheric contamination.

The essential features of the equipment are shown in Fig. 5·1. There are three components : (1) a hopper for flux ; (2) wire feeding rollers with a contact tube through which the wire passes ; and (3) a suction tube for absorbing unused flux (which can be reused again),

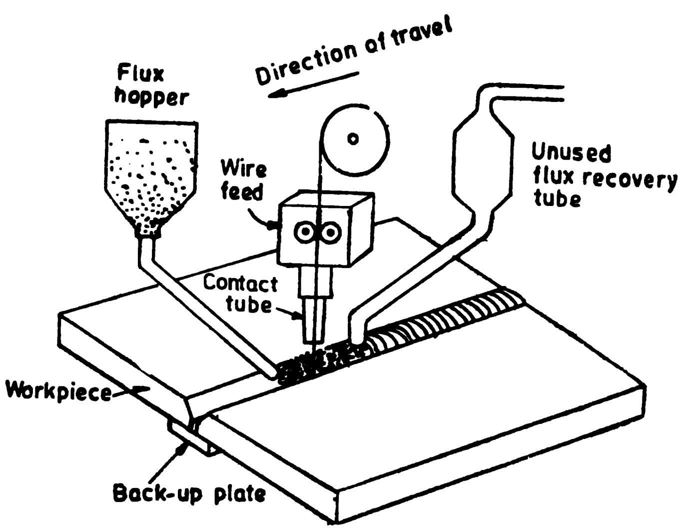


Fig. 5·1. Submerged arc welding unit (Schematic).

The contact tube is connected to one of the leads of the power source. These three components move along the weld groove. A control unit ensures the proper feed rate of wire and power supply for arc.

The plates need a backing to retain the flux and molten metal. This can be in the form of a back-up plate or backing steel strip.

The molten flux is usually highly conducting although cold flux is an insulator. The flux also acts to supply deoxidisers and scavengers that react chemically with the weld metal. Alloying elements can be added to the flux also.

The electrode is a bare wire or coated with copper, fed from a spool through the feed mechanism. In some types of automatic machines, two or more electrodes are fed simultaneously to the same joint. The electrodes can be side by side or one behind the other. The latter method is called *tandem arc welding*, which produces a multiple pass welding in a single traverse of the joint.

(Initially the arc is generated and the flux melted by placing steel wool at the starting end. It may also be started by a high voltage, high frequency current).

5·3. Advantages

1. Joints can be prepared with a shallow V groove, resulting in lesser electrode consumption compared to SMAW. (The groove angle can be 45° instead of 60° as used in SMAW).

2. Weld spatter is eliminated. Deposition efficiency is nearly 100%.

3. The process can be used at high welding speeds and deposition rates, to weld cylindrical or flat plate or pipe sections (Fig. 5·2).

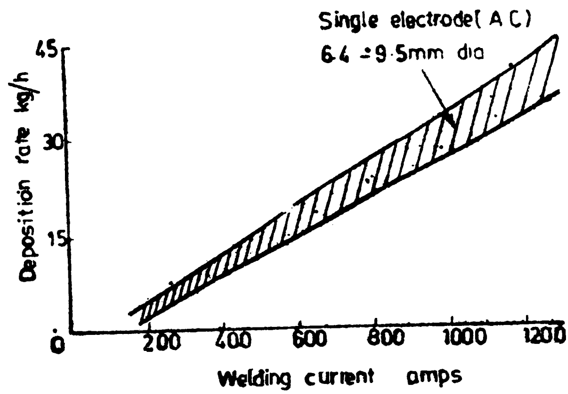


Fig. 5·2. Deposition rate *vs* weldidg current for SAW.

4. For welding unalloyed low carbon inexpensive electrode wires can be used—plain carbon steel wire either bare or flash plated with copper. (Copper plating is done to improve electrical contact and avoid rusting).

5. The entire welding action takes place beneath a bath of molten flux, without sparks, smoke or flash. Protective shields, helmets, smoke collectors or ventillating systems are not needed. (Operator may, however, wear welding goggles).

5·4. Limitations

1. The process is not flexible. Flux, flux handling equipment, backing plates etc. are required.

2. Flux is subject to contamination and absorption of moisture that may lead to weld porosity.

3. Slag (after flux has melted and solidified) must be removed after each pass to avoid entrapment of slag between the passes.

4. The process is not suitable for plate thicknesses less than 5 mm.

5. Generally the process is limited to flat and horizontal positions only.

While SAW can be used for many steels and other metals, it is not suitable for cast iron because cast iron cannot withstand the thermal stresses resulting from high heat input.

5·5. Joint Design

Because of high heat input, the penetration is very deep in SAW. It is possible to obtain full penetration in a 15 mm thick plate.

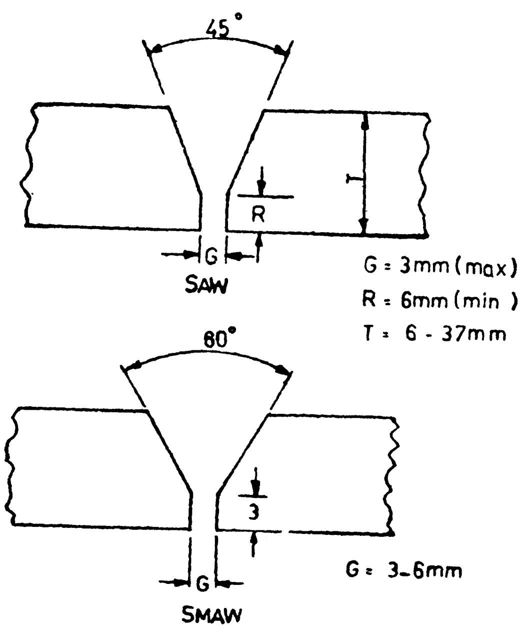


Fig. 5·3. Weld geometry.

Therefore, the grooves can be narrow in SAW compared to SMAW. Further in SAW, upto 15 mm thick plates, welding can be done without edge preparation for butt welds. Because of deeper penetration a 'U' groove with 15 degrees is possible. The bottom groove can be a smaller one and can be first welded manually, *i.e.* by SMAW. When done this way, backing is not needed (Fig. 5·4).

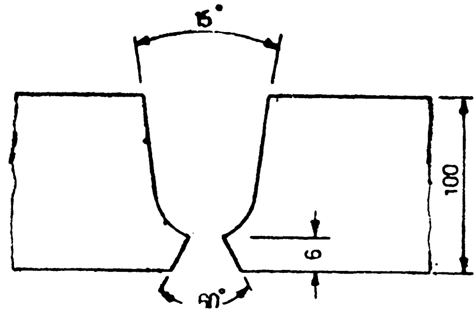


Fig. 5·4. U groove geometry for SAW. Bottom groove welded by SMAW.

5·6. Structure of the Weld

Normally the cast dendritic or columnar structure in single pass SAW is not undesirable. But normalising heat treatment may be given, if necessary. Such a heat treatment is not required for multi-pass weld as the next pass normalizes the structure of the weld metal deposited in the previous pass.

5·7. Weld Geometry

The deep penetration in SAW enables a weld geometry with narrow grooves. The narrow groove requires less electrode metal and reduces the welding time. The problem of slag removal is, however, greater for narrow groove.

It is possible to try different weld geometries in SAW to obtain the most economical solution.

5·8. Applications

The major applications of submerged arc welding are in the fields of ship building and power plant construction. The pressure vessels are often fabricated by SAW. SAW is also widely used for pipe welding, including oil pipe lines.

As mentioned in the introduction, SAW is most economical for plate thicknesses above 25 mm. A great advantage of applying SAW is the reduction in fabrication time when compared to SMAW.

Weldments made by SAW can replace large castings with simple shapes. Typical applications include large brake shoes (200 mm width) and gear blanks (400 mm diameter).

APPENDIX 5·1

Process Parameters

The important process parameters (for a specified flux composition) are : wire dia, welding current, welding speed and electrode stickout, affecting the electrode melting rate and deposition rate.

As an example, for 3mm wire dia, the following equations were obtained for deposition rate for low carbon steel and for stainless steel (308) welding for DCRP connection :

Low carbon steel : $y=-1{\cdot}0+0{\cdot}02\,x+0{\cdot}000016\,x^*x$

Stainless steel : $y=1{\cdot}5+0{\cdot}017\,x+0{\cdot}000028\,x^*x$

where y=deposition rate (lb/hour)

x=welding current (amps)

for the range $x=250$ amps to $x=750$ amps.

[**Note**. For DCRP supply, the deposition rate will be increased by 30 to 50%.]

The important weld parameters to be considered are : electrode melting rate, area of weld bead, arc penetration and weld dilution. The empirical relations (given by C E Jackson and others) based on industrial trials, are given here.

Weld dilution is the ratio of base metal melted to the weld metal deposited. (See section 15·4) and affects the mechanical properties of the weld metal. Weld metal cracking increases as the dilution is increased. Dilution depends on melting rate, welding current and speed. An empirical formula is given later.

The relationship between welding current and welding voltage (for several commercial fluxes) is found to be as follows :

$$V=17{\cdot}34+0{\cdot}023\,I-6{\cdot}3x10^{-6}\,I^*I$$

where I=welding current (amps)

V=welding voltage (volt)

Electrode wire diameter affects in several ways. With increasing diameter, the melting rate is increased and is proportional to (diameter). Decreasing the wire diameter, however, increases arc penetration and depth/width ratio.

Welding speed influences the producuon rate and weld quality. With greater speed, the heat input is decreased. Higher speed can result in undercutting and weld porosity.

The use of correct (maximum) welding speed for given welding current to avoid undercutting is found from the realtion :

Speed $S=1{\cdot}6\times10^{+6}\,I^{-1{\cdot}638}$

where s (in/minute) and I (amps).

Empirical Formulae for process parameters

Electrode Melting Rate

$$MR=\frac{I}{1000}\left[0{\cdot}35+d^2+2{\cdot}08\times10^{-7}\left(\frac{IL}{d^2}\right)^{1{\cdot}22}\right]$$

Weld Bead Area (Sq. in.)

$$A=\frac{I^{0\cdot55}}{10^{3\cdot95}\,S^{0\cdot903}}$$

and

$$\text{dilution}=100-\frac{353\times MR}{A\times S}$$

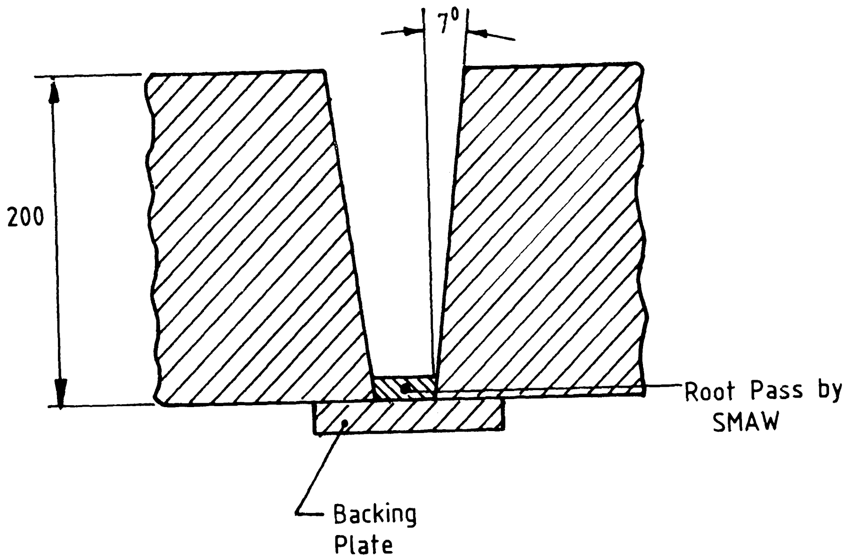


Fig. 5·5 Typical Weld Geometry for Pressure Vessel Welding with Automatic SAW.

$$\text{Arc Penetration (in)}=k\left(\frac{I^4}{SE^2}\right)^{\frac{1}{3}}$$

where *MR—Electrode melting rate (lb. per minute)*

I—Welding current (amps)

d—Electrode diameter (in.)

L—Electrode stickout (in.)

A—Area of weld bead (sq. inches)

S—Speed of travel (in. per minute)

P—Arc penetration (in.)

E—Welding voltage (volts)

K—Process penetration constant (0·0012 for calcium silicate flux).