METAL JOINING (WELDING)

Introduction:

Welding which is the process of joining two metallic components for the desired purpose, can be defined as the process of joining two similar or dissimilar metallic components with the application of heat, with or without the application of pressure and with or without the use of filler metal. Heat may be obtained by chemical reaction, electric arc, electrical resistance, frictional heat, sound and light energy. If no filter metal is used during welding then it is termed as 'Autogenous Welding Process'.

Welding is a materials joining process in which two or more parts are coalesced at their contacting surfaces by a suitable application of heat and/or pressure. Many welding processes are accomplished by heat alone, with no pressure applied; others by a combination of heat and pressure; and still others by pressure alone, with no external heat supplied.

In some welding processes a filler material is added to facilitate coalescence. The assemblage of parts that are joined by welding is called a weldment. Welding is most commonly associated with metal parts, but the process is also used for joining plastics. Our discussion of welding will focus on metals.

Welding is a relatively new process. Its commercial and technological importance derives from the following:

- Welding provides a permanent joint. The welded parts become a single entity.
- The welded joint can be stronger than the parent materials if a filler metal is used that has strength properties superior to those of the parents, and if proper welding techniques are used.
- Welding is usually the most economical way to join components in terms of material usage and fabrication costs. Alternative mechanical methods of assembly require more complex shape alterations (e.g., drilling of holes) and addition of fasteners (e.g., rivets or bolts). The resulting mechanical assembly is usually heavier than a corresponding weldment.
- Welding is not restricted to the factory environment. It can be accomplished ''in the field.''

Although welding has the advantages indicated above, it also has certain limitations and **drawbacks** (or potential drawbacks):

- Most welding operations are performed manually and are expensive in terms of labour cost. Many welding operations are considered ''skilled trades,'' and the labour to perform these operations may be scarce.
- Most welding processes are inherently dangerous because they involve the use of high energy.
- Since welding accomplishes a permanent bond between the components, it does not allow for convenient disassembly. If the product must occasionally be disassembled (e.g., for repair or maintenance), then welding should not be used as the assembly method.
- The welded joint can suffer from certain quality defects that are difficult to detect. The defects can reduce the strength of the joint.

APPLICATIONS:

Although most of the welding processes at the time of their developments could not get their place in the production except for repair welding, however, at the later stage these found proper place in manufacturing/production. Presently welding is widely being used in fabrication of pressure vessels, bridges, building structures, aircraft and space crafts, railway coaches and general applications. It is also being used in shipbuilding, automobile, electrical, electronic and defense industries, laying of pipe lines and railway tracks and nuclear installations etc.

General Applications:

Welding is vastly being used for construction of transport tankers for transporting oil, water, milk and fabrication of welded tubes and pipes, chains, LPG cylinders and other items. Steel furniture, gates, doors and door frames, body and other parts of white goods items such as refrigerators, washing machines, microwave ovens and many other items of general applications are fabricated by welding.

Pressure Vessels:

One of the first major use of welding was in the fabrication of pressure vessels. Welding made considerable increases in the operating temperatures and pressures possible as compared to riveted pressure vessels.

Bridges:
Early use of welding in bridge construction took place in Australia . This was due to problems in transporting complete riveted spans or heavy riveting machines necessary for fabrication on site to remote areas. The first all welded bridge was erected in UK in 1934. Since then all welded bridges are erected very commonly and successfully.

Ship Building:
Ships were produced earlier by riveting. Over ten million rivets were used in 'Queen Mary' ship which required skills and massive organization for riveting but welding would have allowed the semiskilled/ unskilled labour and the principle of pre-fabrication. Welding found its place in ship building around 1920 and presently all welded ships are widely used. Similarly submarines are also produced by welding.

Building Structures:
Arc welding is used for construction of steel building leading to considerable savings in steel and money. In addition to building, huge structures such as steel towers etc also require welding for fabrication.

Aircraft and Spacecraft:
Similar to ships, aircrafts were produced by riveting in early days but with the introduction of jet engines welding is widely used for aircraft structure and for joining of skin sheet to body.
Space vehicles which have to encounter frictional heat as well as low temperatures require outer skin and other parts of special materials. These materials are welded with full success achieving safety and reliability.

Railways:
Railways use welding extensively for fabrication of coaches and wagons, wheel tyres laying of new railway tracks by mobile flash butt welding machines and repair of cracked/damaged tracks by thermit welding.

Automobiles:
Production of automobile components like chassis, body and its structure, fuel tanks and joining of door hinges require welding.

Electrical Industry:
Starting from generation to distribution and utilization of electrical energy, welding plays important role. Components of both hydro and steam power generation system, such as penstocks, water control gates, condensers, electrical transmission towers and distribution system equipment are fabricated by welding. Turbine blades and cooling fins are also joined by welding.

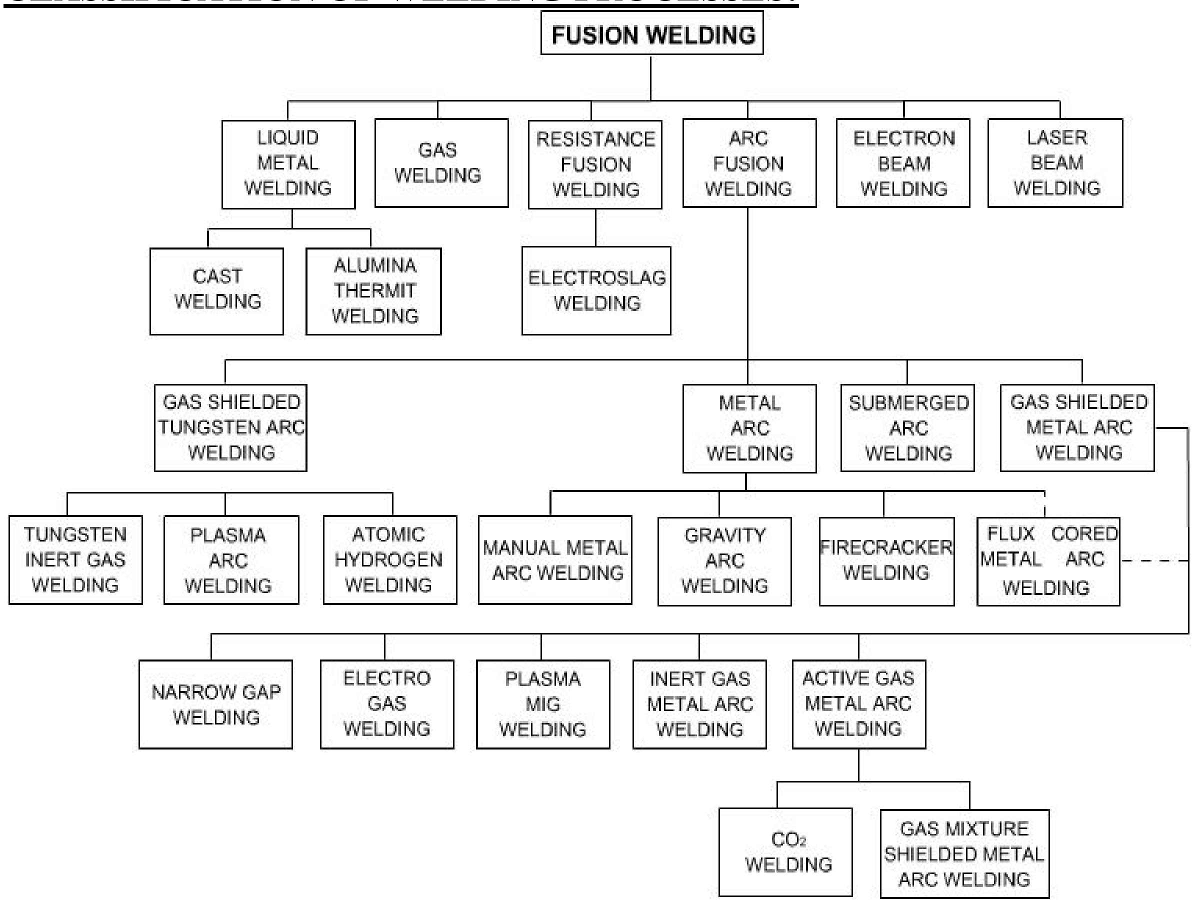
Electronic Industry:
Electronic industry uses welding to limited extent such as for joining leads of special transistors but other joining processes such as brazing and soldering are widely being used. Soldering is used for joining electronic components to printed circuit boards. Robotic soldering is very common for joining of parts to printed circuit boards of computers, television, communication equipment and other control equipment etc.

Nuclear Installations:
Spheres for nuclear reactor, pipe line bends joining two pipes carrying heavy water and other components require welding for safe and reliable operations.

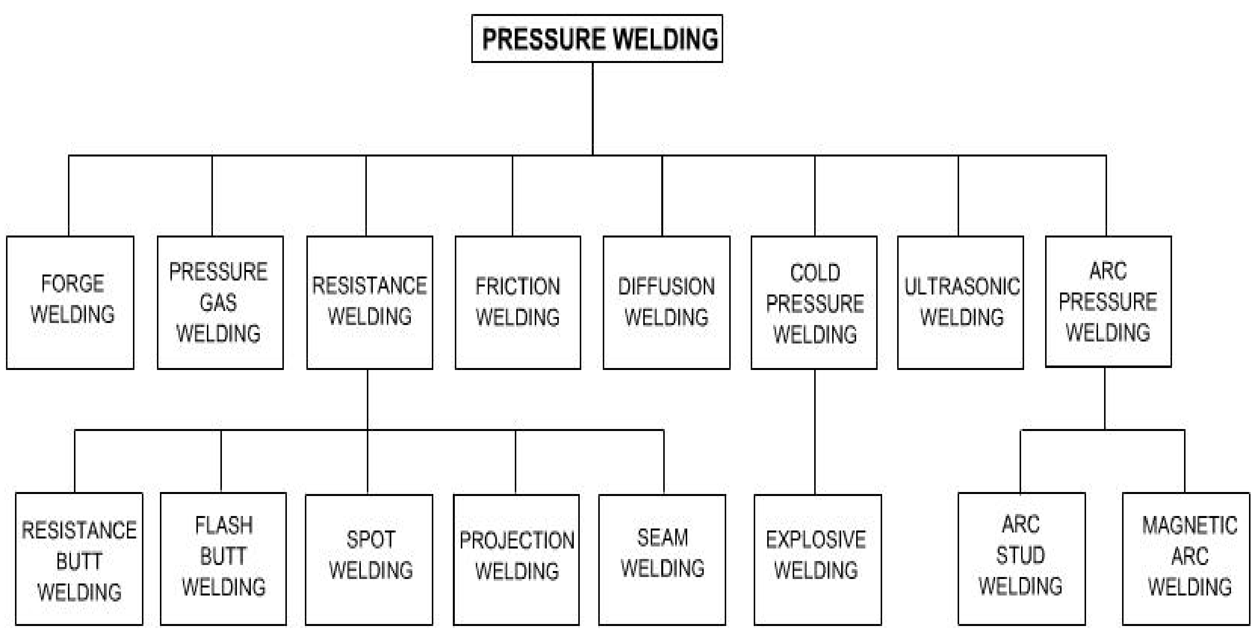
Defence Industry:
Defence industry requires welding for joining of many components of war equipment. Tank bodies fabrication, joining of turret mounting to main body of tanks are typical examples of applications of welding.

Micro-Joining:
It employs the processes such as micro-plasma, ultrasonic, laser and electron beam welding, for joining of thin wire to wire, foil to foil and foil to wire, such as producing junctions of thermocouples, strain gauges to wire leads etc.
Apart from above applications welding are also used for joining of pipes, during laying of crude oil and gas pipelines, construction of tankers for their storage and transportation. Offshore structures, dockyards, loading and unloading cranes are also produced by welding.

CLASSIFICATION OF WELDING PROCESSES:



Classification of Fusion Welding Processes



OXYFUEL-GAS WELDING / OXY ACETYLENE WELDING

Oxyfuel-gas welding (OFW) is a general term used to describe any welding process that uses a fuel gas combined with oxygen to produce a flame. The flame is the source of the heat that is used to melt the metals at the joint. The most common gas welding process uses acetylene; the process is known as oxyacetylene-gas welding (OAW) and is typically used for structural metal fabrication and repair work.
Developed in the early 1900s, OAW utilizes the heat generated by the combustion of acetylene gas (C_2H_2) in a mixture with oxygen. The heat is generated in accordance with a pair of chemical reactions. The primary combustion process, which occurs in the inner core of the flame (Fig. 4.3), involves the following reaction:

$$C_2H_2 + O_2 \longrightarrow 2CO + H_2 + \text{Heat.} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

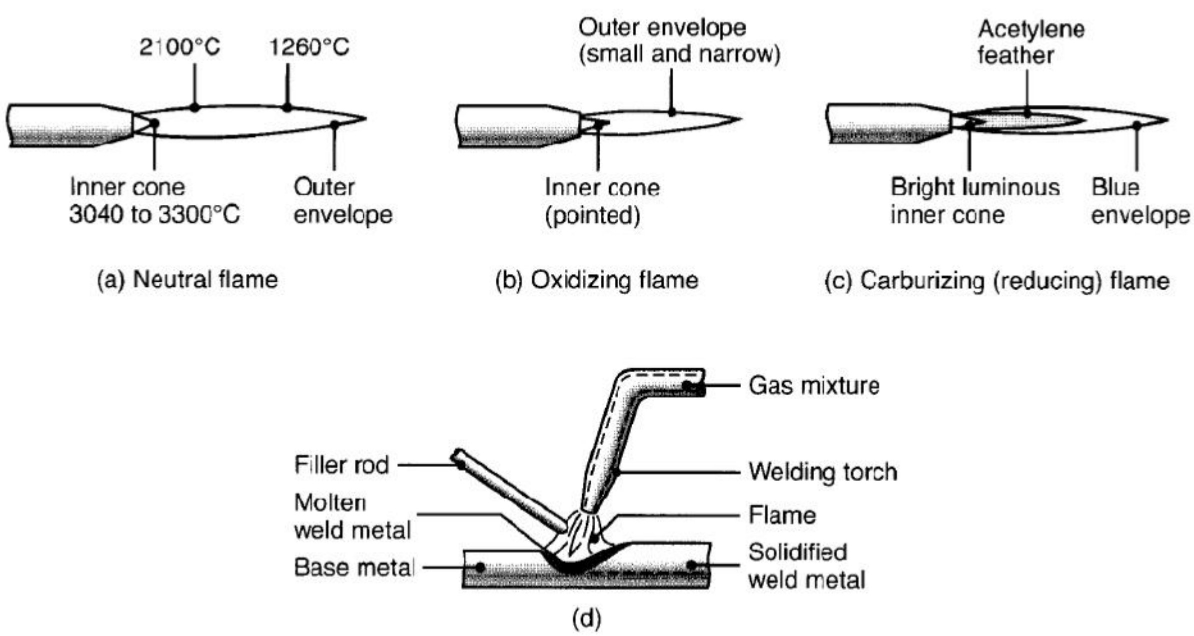
This reaction dissociates the acetylene into carbon monoxide and hydrogen and produces about one-third of the total heat generated in the flame. The secondary combustion process is

$$2CO + H_2 + 1.5O_2 \longrightarrow 2CO_2 + H_2O + \text{Heat.} \quad \ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

This reaction consists of the further burning of both the hydrogen and the carbon monoxide and produces about two-thirds of the total heat. Note that the reaction also produces water vapor. The temperatures developed in the flame can reach 3300°C.

FLAME TYPES

The proportion of acetylene and oxygen in the gas mixture is an important factor in oxyfuel-gas welding. At a ratio of 1:1 (i.e., when there is no excess oxygen), the flame is considered to be neutral (Fig. 4.3a). With a greater oxygen supply, the flame can be harmful (especially for steels), because it oxidizes the metal. For this reason, a flame with excess oxygen is known as an oxidizing flame (Fig. 4.3 b). Only in the welding of copper and copper-based alloys is an oxidizing flame desirable, because in those cases, a thin protective layer of slag
(compounds of oxides) forms over the molten metal. If the oxygen is insufficient for full combustion, the flame is known as a reducing, or carburizing, flame (a flame having excess acetylene; Fig. 4.3c). The temperature of a reducing flame is lower; hence, such a flame is suitable for applications requiring low heat, such as brazing, soldering, and flame-hardening operations.



Three basic types of oxyacetylene flames used in oxyfuel-gas welding and cutting operations: (a) neutral flame; (b) oxidizing flame; (c) carburizing, or reducing, flame. The gas mixture in (a) is basically equal volumes of oxygen and acetylene. (d) The principle of the oxyfuel-gas welding process.

Other fuel gases (such as hydrogen and methyl acetylene propadiene) also can be used in oxyfuel-gas welding. However, the temperatures developed by these gases are lower than those produced by acetylene. Hence, they are used for welding (a) metals with low melting points (such as lead) and (b) parts that are thin and small. The flame with pure hydrogen gas is colourless; therefore, it is difficult to adjust the flame by eyesight.

FILLER METALS

Filler metals are used to supply additional metal to the weld zone during welding. They are available as filler rods or wire and may be bare or coated with flux. The purpose of the flux is to retard oxidation of the surfaces of the parts being welded by generating a gaseous shield around the weld zone.

The flux also helps to dissolve and remove oxides and other substances from the weld zone, thus contributing to the formation of a stronger joint. The slag developed (compounds of oxides, fluxes, and electrode-coating materials) protects the molten puddle of metal against oxidation as it cools.

OXYFUEL-GAS CUTTING.

Oxy fuel-gas cutting (OFC) is similar to oxyfuel welding, but the heat source is now used to remove a narrow zone from a metal plate or sheet (Fig. 4.4 a). This process is suitable particularly for steels. The basic reactions with steel are

$$Fe + O \longrightarrow FeO + Heat, \quad \ldots\ldots 1$$

$$3Fe + 2O_2 \longrightarrow Fe_3O_4 + Heat, \quad \ldots\ldots 2$$

$$4Fe + 3O_2 \longrightarrow 2\,Fe_2O_3 + Heat. \quad \ldots\ldots 3$$

The greatest heat is generated by the second reaction, and it can produce a temperature rise to about 870°C. However, this temperature is not sufficiently high to cut steels; therefore, the work piece is preheated with fuel gas, and oxygen is introduced later (see the nozzle cross section in Fig. 4.4 a). The higher the carbon content of the steel, the higher is the preheating temperature required. Cutting takes place mainly by the oxidation (burning) of the steel; some melting also takes place. Cast irons and steel castings also can be cut by this method. The process generates a kerf similar to that produced by sawing with a saw blade or by wire electrical discharge machining.

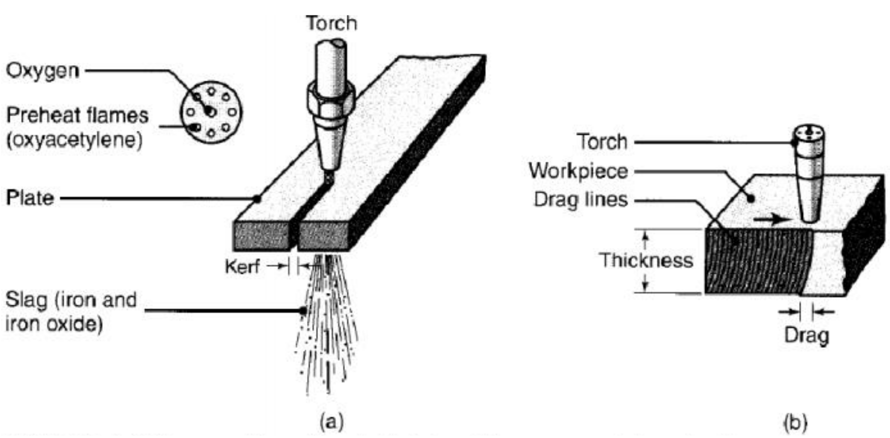


FIGURE (a) Flame cutting of a steel plate with an oxyacetylene torch, and a cross section of the torch nozzle. (b) Cross section of a flame-cut plate, showing drag lines.

The maximum thickness that can be cut by OFC depends mainly on the gases used. With oxyacetylene gas, the maximum thickness is about 300 mm; with oxy hydrogen, it is about 600 mm. Kerf widths range from about 1.5 to 10 mm, with reasonably good control of tolerances. The flame leaves drag lines on the cut surface (Fig. 4.4 b), resulting in a rougher surface than that produced by processes such as sawing, blanking, or other operations that use mechanical cutting tools. Distortion caused by uneven temperature distribution can be a problem in OFC.

Although long used for salvage and repair work, OFC can be used in manufacturing as well. Torches may be guided along specified paths either manually, mechanically, or automatically by machines using programmable controllers and robots.

Underwater cutting is done with specially designed torches that produce a blanket of compressed air between the flame and the surrounding water.

Welding Practice and Equipment.

Oxy fuel-gas welding can be used with most ferrous and nonferrous metals for almost any work piece thickness, but the relatively low heat input limits the process to thicknesses of less than 6 mm. Small joints made by this process may consist of a single-weld bead. Deep-V groove joints are made in multiple passes. Cleaning the surface of each weld bead prior to depositing a second layer is important for joint strength and in avoiding defects. Wire brushes (hand or power) may be used for this purpose.

The equipment for oxy fuel-gas welding consists basically of a welding torch connected by hoses to high-pressure gas cylinders and equipped with pressure gages and regulators . The use of safety equipment (such as goggles with shaded lenses, face shields, gloves, and protective clothing) is essential. Proper connection of the hoses to the cylinders is an important factor in safety. Oxygen and acetylene cylinders have different threads, so the hoses cannot be connected to the wrong cylinders. The low equipment cost is an attractive feature of oxy fuel-gas welding.

Although it can be mechanized, this operation is essentially manual and, hence slow. However, it has the advantages of being portable, versatile, and economical for simple and low-quantity work.

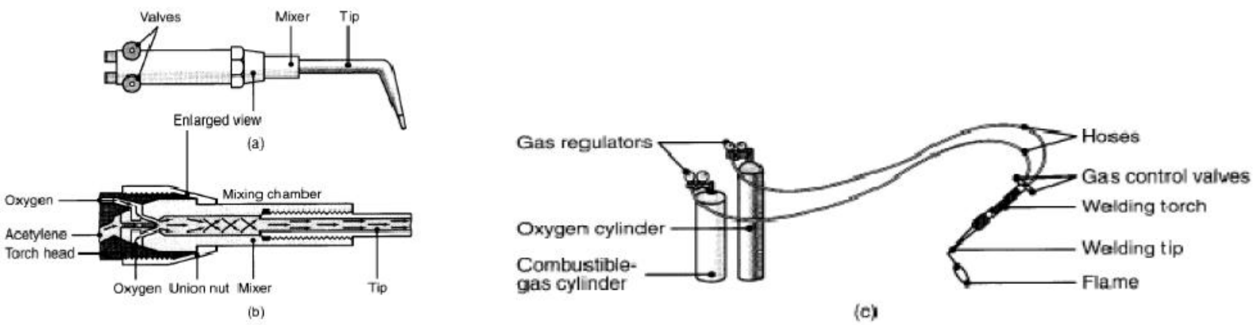


FIGURE (a) General view of, and (b) cross section of, a torch used in oxyacetylene welding. The acetylene valve is opened first. The gas is lit with a spark lighter or a pilot light. Then the oxygen valve is opened and the flame adjusted. (c) Basic equipment used in oxyfuel-gas welding. To ensure correct connections, all threads on acetylene fittings are left handed, whereas those for oxygen are right handed. Oxygen regulators usually are painted green and acetylene regulators red.

ARC WELDING POWER SOURCES:

The main requirement of a power source is to deliver controllable current at a voltage according to the demands of the welding process being used. Each welding process has distinct differences from one another, both in the form of process controls required to accomplish a given operating condition and the consequent demands on the power source. Therefore, arc welding power sources are playing very important role in welding. The conventional welding power sources are:

Power Source Supply

Power Source	Supply
(i) Welding Transformer	AC
(ii) Welding Rectifier	DC
(iii) Welding Generators	AC or DC (Depending on generator)

Welding transformers, rectifiers and DC generators are being used in shop while engine coupled AC generators as well as sometimes DC generators are used at site where line supply is not available. Normally rectifiers and transformers are preferred because of low noise, higher efficiency and lower maintenance as compared to generators. Selection of power source is mainly dependent on welding process and consumable. The open circuit voltage normally ranges between 70-90 V in case of welding transformers while in case of rectifiers it is 50-80 V. However, welding voltages are lower as compared to open circuit voltage of the power source.

Based on the static characteristics power sources can be classified in two categories

- Constant current or drooping or falling characteristic power source.
- Constant potential or constant voltage or flat characteristic power source.

Constant voltage power source does not have true constant voltage output. It has a slightly downward or negative slope because of sufficient internal electrical resistance and inductance in the welding circuit to cause a minor droop in the output volt ampere characteristics.

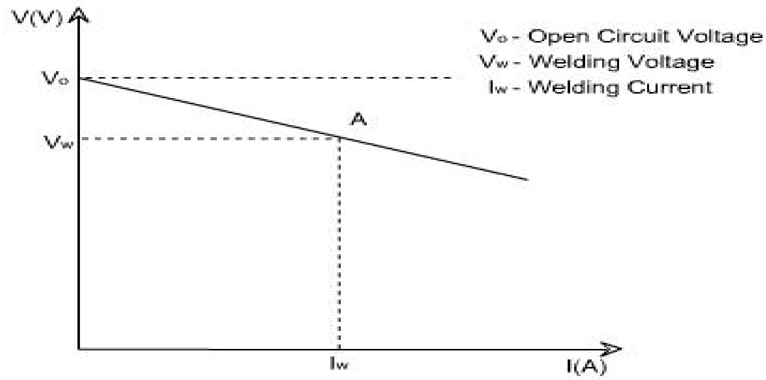


FIGURE Constant Potential or Constant Voltage or Flat Characteristic.

With constant voltage power supply the arc voltage is established by setting the output voltage on the source. The power source shall supply necessary current to melt the electrode at the rate required to maintain the preset voltage or relative arc length. The speed of electrode drive is used to control the average welding current. The use of such power source in conjunction with a constant electrode wire feed results in a self regulating or self adjusting arc length system. Due to some internal or external fluctuation if the change in welding current occurs, it will automatically increase or decrease the electrode melting rate to regain the desired arc length.

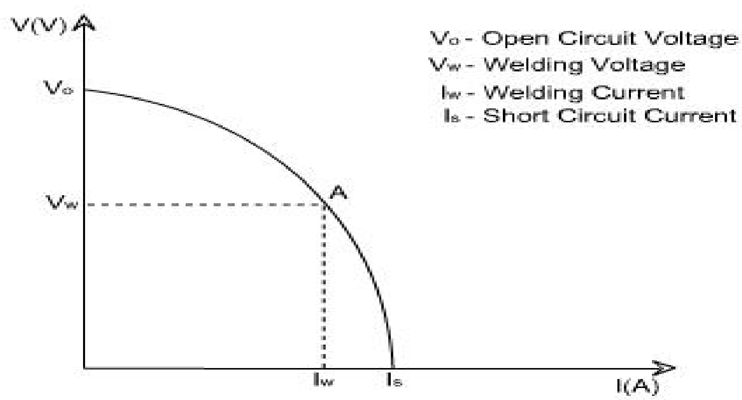


FIGURE- Drooping or Constant current or Falling Characteristic.

The volt ampere output curves for constant current power source are called ‘drooper' because of substantial downward or negative slope of the curves. The power source may have open circuit voltage adjustment in addition to output current control. A change in either control will change the slope of the volt ampere curve. With a change in arc voltage, the change in current is small and, therefore, with a consumable electrode welding process, electrode melting rate would remain fairly constant with a change in arc length. These power sources are required for processes using relatively thicker consumable electrodes which may sometimes get stubbed to work piece or with non consumable tungsten electrode where during touching of electrode for starting of arc may lead to damage of electrode if current is unlimited. Under these conditions the short circuiting current shall be limited leading to safety of power source and the electrode.

Some power sources need high frequency unit to start the arc, which may be requirement of processes like TIG and plasma arc. High frequency unit is introduced in the welding circuit but in between the control circuit and HF unit, filters are required so that high frequency may not flow through control circuit and damage it. High frequency unit is a device which supplies high voltage of the order of few KV along with high frequency of few KHz with low current. This high voltage ionizes the medium between electrode and work piece/nozzle starting pilot arc which ultimately leads to the start of main arc. Although high voltage may be fatal for the operator but when it is associated with high frequencies then current does not enter body but it causes only skin effect i.e. current passes through the skin of operator causing no damage to the operator.

Duty Cycle:

Duty cycle is the ratio of arcing time to the weld cycle time multiplied by 100. Welding cycle time is either 5 minutes as per European standards or 10 minutes as per American standard and accordingly power sources are designed. It arcing time is continuously 5 minutes then as per European standard it is 100% duty cycle and 50% as per American standard. At 100% duty cycle minimum current is to be drawn i.e. with the reduction of duty cycle current drawn can be of higher level. The welding current which can be drawn at a duty cycle can be evaluated from the following equation;

$$D_R \times I_R^2 = I^2 \times D_{100}$$

Where I - is current at 100% duty cycle

D_{100} - 100% duty cycle

I_R - Current at required duty cycle

D_R - Required duty cycle

Duty cycle and associated currents are important as it ensures that power source remains safe and its windings are not getting damaged due to increase in temperature beyond specified limit. The maximum current which can be drawn from a power source depends upon its size of winding wire, type of insulation and cooling system of the power source.

Table : Welding Processes, Type of Current and Static Characteristic

Welding Process	**Type of Current**	**Static Characteristic of The Power Source**
Manual Metal Arc Welding	DC AC	Constant Current
Tungsten Inert Gas Welding	DC AC[Al]	Constant Current
Plasma Arc Welding	DC	Constant Current
Submerged Arc Welding	DC AC	Constant Current (if electrode □ = 2.4 mm)
	DC	Constant Potential (if electrode □ = 2.4 mm)
Gas Metal Arc Welding / Metal Inert Gas Welding / Metal Active Gas Welding	DC	Constant Potential

Arc-welding Processes: Non consumable Electrode:

In arc welding, developed in the mid-1800, the heat required is obtained from electrical energy. The process involves either a consumable or a non consumable electrode. An AC or a DC power supply produces an arc between the tip of the electrode and the work piece to be welded. The arc generates temperatures of about 30,000 °C, which are much higher than those developed in oxy fuel-gas welding.

In non consurnable-electrode welding processes, the electrode is typically a tungsten electrode (Fig. 4.9). Because of the high temperatures involved, an externally supplied shielding gas is necessary to prevent oxidation of the weld zone. Typically, direct current is used, and its polarity (the direction of current flow) is important. The selection of current levels depends on such factors as the type of electrode, metals to be welded, and depth and width of the weld zone.

In straight polarity-also known as direct-current electrode negative (DCEN)- the work piece is positive (anode), and the electrode is negative (cathode). DCEN generally produces welds that are narrow and deep. .

In reverse polarity-also known as direct-current electrode positive (DCEP)-the work piece is negative and the electrode is positive.

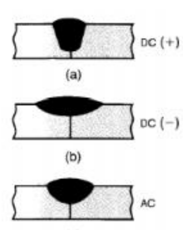


FIGURE : The effect of polarity and current type on weld beads: (a) DC current with straight polarity; (b) DC current with reverse polarity; (c) AC current

Weld penetration is less, and the weld zone is shallower and wider . Hence, DCEP is preferred for sheet metals and for joints with very wide gaps. ln the AC current method, the arc pulsates rapidly. This method is suitable for welding thick sections and for using large-diameter electrodes at maximum currents (Fig. 4.8c).

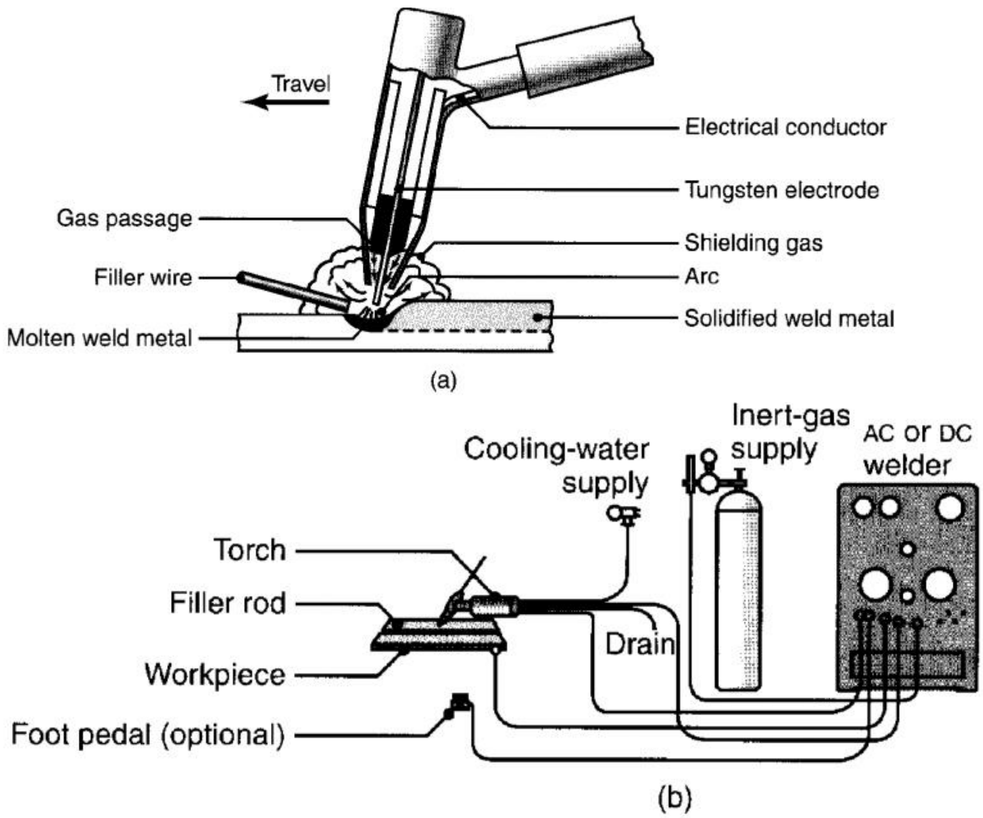


FIGURE (a) The gas tungsten-arc welding process, formerly known as TIG (for tungsten-inert-gas) welding. (b) Equipment for gas tungsten-arc welding operations.

Heat Transfer in Arc Welding

The heat input in arc Welding is given by the equation

$$\frac{H}{l} = e\frac{VI}{v}, \quad \text{……………………………………………1}$$

Where H is the heat input (] or BTU), I is the Weld length, V is the voltage applied, I is the current (amperes), and υ is the welding speed. The term e is the efficiency of the process and varies from around 75% for shielded metal-arc welding to 90% for gas metal-arc welding and submerged-arc Welding. The efficiency is an indication that not all of the available energy is beneficially used to melt material, because the heat is conducted through the workpiece, some is lost by radiation, and still more is lost by convection to the surrounding environment.

The heat input given by Eq. (1) melts a certain volume of material, usually the electrode or filler metal, and can also be expressed as

$$H = uV_m = uAl, \quad \text{……………………………………..2}$$

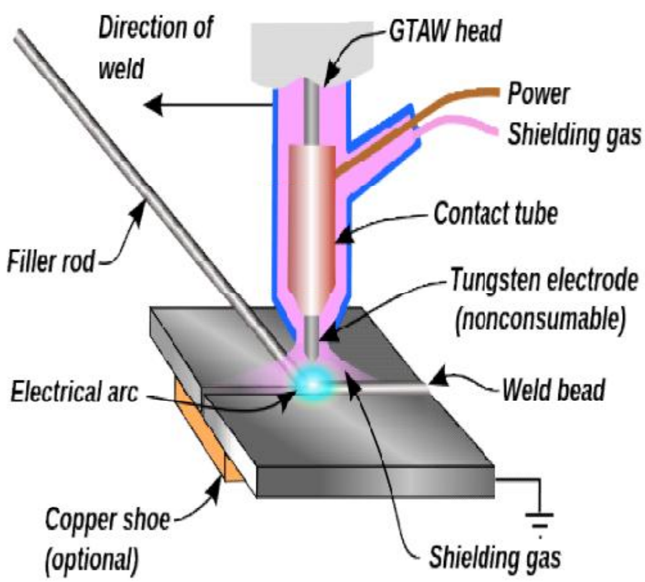
where u is the specific energy required for melting, V," is the volume of material melted, and A is the cross section of the Weld. Some typical values of u are given in Table . Equations (1) and (2) allow an expression of the welding speed:

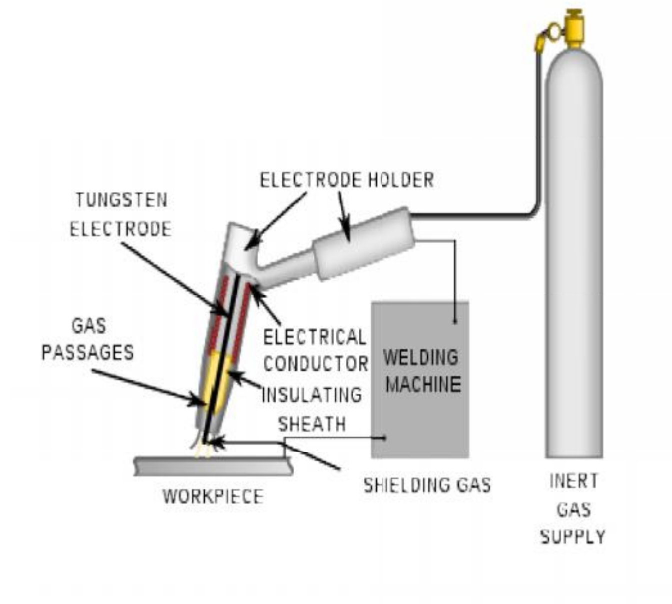
$$v = e\frac{VI}{uA}. \quad \text{…………………………………………..3}$$

Although these equations have been developed for arc Welding, similar ones can be obtained for other fusion-welding operations as Well, taking into account differences in Weld geometry and process efficiency.

TIG WELDING/ GAS TUNGSTEN-ARC WELDING (GTAW)

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is an arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by an inert shielding gas (argon or helium), and a filler metal is normally used.





Principle of operations-

- Welding current, inert gas supply and water are turn on.
- Electric arc is struck between non consumable electrode and work piece by touching on work using a high frequency unit.
- A high frequency current is super imposed on the welding current, welding torch is brought near to the job (2-3 mm), a spark jumps across the air gap b/w the electrode and job
- Air path gets ionized and arc is established.
- **TIG also known as GTAW uses AC and DC power source, DC is preferred over AC for welding of SS, NI, Cu and its alloys. Gives the higher quality weld among common arc wildings.**
- AC is used for welding of MS, Al, Mg and their alloys.
- **Inert gas-** Ar, He, Ar and He, Ar and O_2 mixture.
- **Advantages-** Suitable for high quality of thin materials, No danger of flux entrapments.
  Operator can have a better control with the help og goggles, Welding of nonferrous metals, suitable in all position welding.
- **Limitations-** Slower than MIG, Tungsten inclusion is hard and brittle, more Costly, Skill and trained operator.

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PLASMA-ARC WELDING

In plasma-arc welding (PAW), developed in the 1960s, a concentrated plasma arc is produced and directed towards the weld area. The arc is stable and reaches temperatures as high as 33,000°C. A plasma is an ionized hot gas composed of nearly equal numbers of electrons and ions. The plasma is initiated between the tungsten electrode and the orifice by a low-current pilot arc. What makes plasma-arc welding unlike other processes is that the plasma arc is concentrated because it is forced through a relatively small orifice. Operating currents usually are below 100 A, but they can be higher for special applications. When a filler metal is used, it is fed into the arc, as is done in GTAW. Arc and weld-zone shielding is supplied by means of an outer-shielding ring and the use of gases such as argon, helium, or mixtures.

There are two methods of plasma-arc welding:

- In the transferred-arc method (Fig. a), the work piece being welded is part of the electrical circuit. The arc transfers from the electrode to the work piece hence the term transferred.
- In the nontransferred method (Fig. b), the arc occurs between the electrode and the nozzle, and the heat is carried to the work piece by the plasma gas. This thermal-transfer mechanism is similar to that for an oxy fuel flame.

Compared with other arc-welding processes, plasma-arc welding has better arc stability, less thermal distortion, and higher energy concentration, thus permitting deeper and narrower welds. In addition, higher welding speeds, from 120 to 1000 mm/min, can be achieved. A variety of metals can be welded with part thicknesses generally less than 6 mm.

The high heat concentration can penetrate completely through the joint (known as the keyhole technique), with thicknesses as much as 20 mm for some titanium and aluminium alloys. In the keyhole technique, the force of the plasma arc displaces the molten metal and produces a hole at the leading edge of the weld pool.

Plasma-arc welding (rather than the GTAW process) often is used for butt and lap joints because of its higher energy concentration, better arc stability, and higher welding speeds. Proper training and skill are essential for operators who use this equipment. Safety considerations include protection against glare, spatter, and noise from the plasma arc.

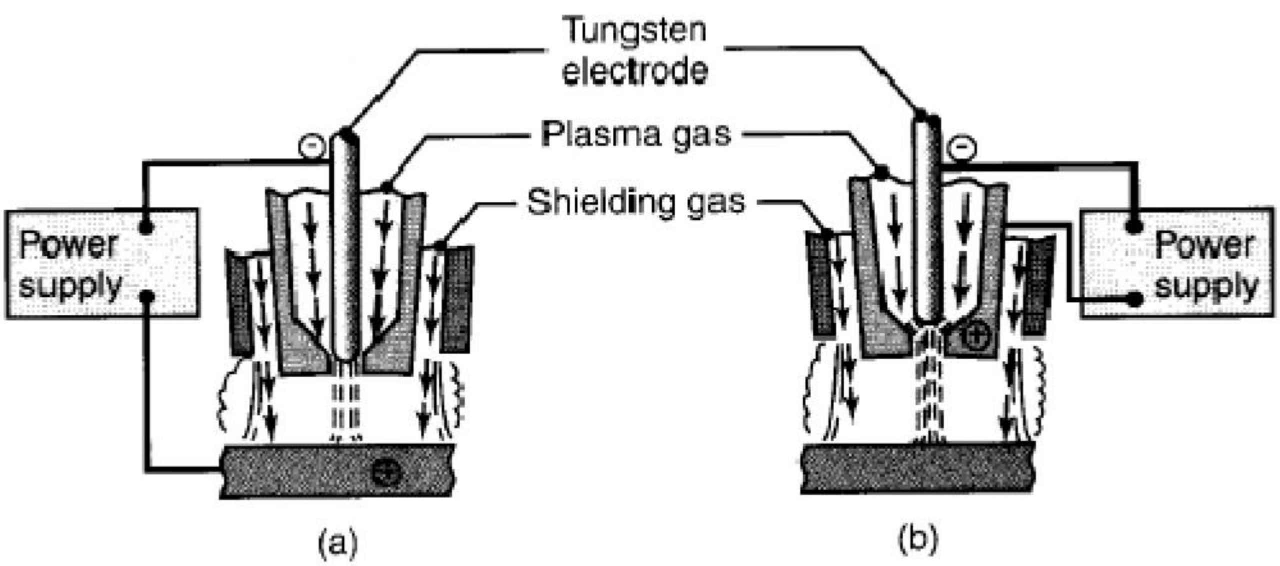


FIGURE Two types of plasma-arc welding processes: (a) transferred and (b) non transferred. Deep and narrow welds can be made by these processes at high welding speeds.

Atomic-hydrogen Welding

In atomic-hydrogen welding (AHW), an arc is generated between two tungsten electrodes in a shielding atmosphere of hydrogen gas. The arc is maintained independently of the work piece or parts being welded. The hydrogen gas normally is diatomic (HZ), but where the temperatures are over 6,000°C near the arc, the hydrogen breaks down into its atomic form, simultaneously absorbing a large amount of heat from the arc. When the hydrogen strikes the cold surface of the Work pieces to be joined, it recombines into its diatomic form and rapidly releases the stored heat. The energy in AHW can be varied easily by changing the distance between the arc stream and the work piece surface. This process is being replaced by shielded metal-arc welding, mainly because of the availability of inexpensive inert gases.

ARC-WELDING PROCESSES: CONSUMABLE ELECTRODE

There are several consumable-electrode arc-welding processes.

SHIELDED METAL-ARC WELDING

Shielded metal-arc welding (SMAW) is one of the oldest, simplest, and most versatile joining processes. About 50% of all industrial and maintenance welding currently is performed by this process. The electric arc is generated by touching the tip of a coated electrode against the work piece and withdrawing it quickly to a distance sufficient to maintain the arc (Fig. a). The electrodes are in the shapes of thin, long rods (hence, this process also is known as stick welding) that are held manually.

The heat generated melts a portion of the electrode tip, its coating, and the base metal in the immediate arc area. The molten metal consists of a mixture of the base metal (the work piece), the electrode metal, and substances from the coating on the electrode; this mixture forms the weld when it solidifies. The electrode coating deoxidizes the weld area and provides a shielding gas to protect it from oxygen in the environment.

A bare section at the end of the electrode is clamped to one terminal of the power source, while the other terminal is connected to the work piece being welded (Fig. b). The current, which may be DC or AC, usually ranges from 50 to 300 A. For sheet-metal welding, DC is preferred because of the steady arc it produces. Power requirements generally are less than 10 kW.

The SMAW process has the advantages of being relatively simple, versatile, and requiring a smaller variety of electrodes. The equipment consists of a power supply, cables, and an electrode holder. The SMAW process commonly is used in general construction, shipbuilding, pipelines, and maintenance work. It is especially useful for work in remote areas where a portable fuel-powered generator can be used as the power supply. SMAW is best suited for workpiece thicknesses of 3 to 19 mm, although this range can be extended easily by skilled operators using multiple- pass techniques (Fig. 4.12).

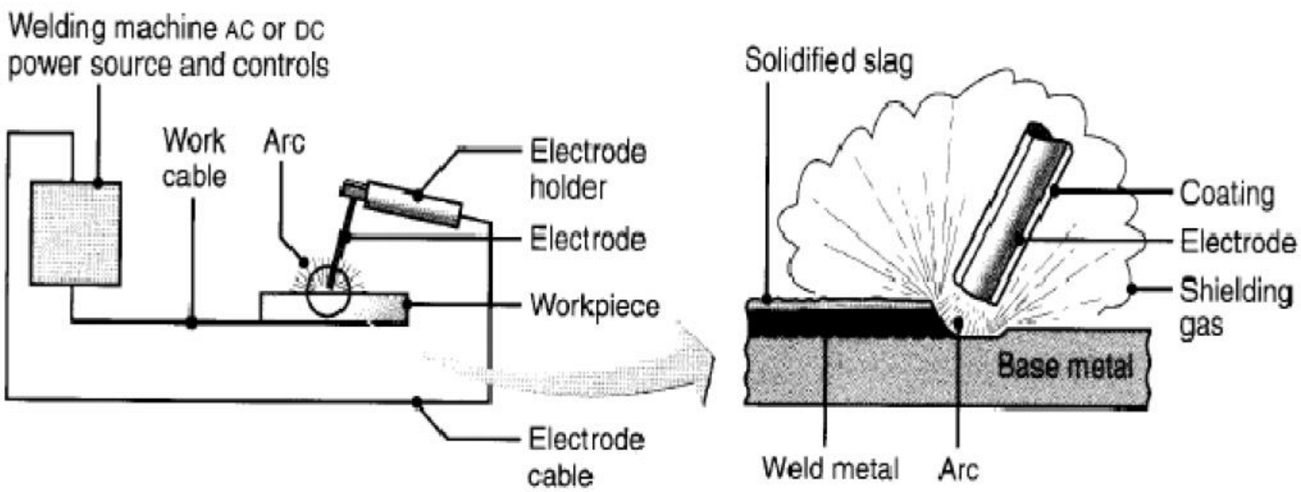


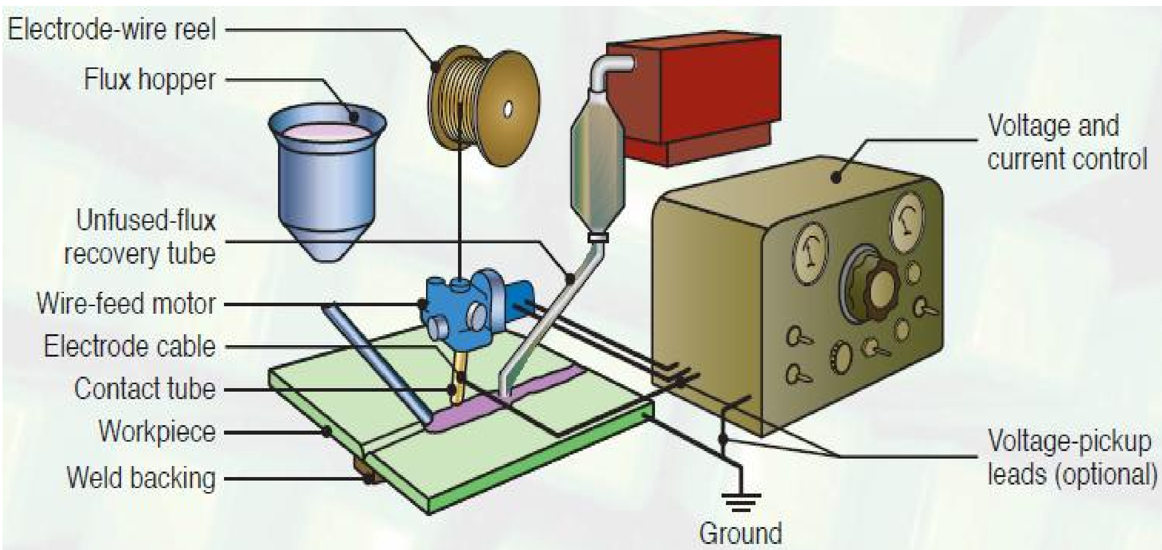
FIGURE Schematic illustration of the shielded metal-arc welding process. About 50% of all large-scale industrial-welding operations use this process.

FIGURE A deep weld showing the build up sequence of eight individual weld beads.

The multiple-pass approach requires that the slag be removed after each weld bead. Unless removed completely, the solidified slag can cause severe corrosion of the weld area and lead to failure of the weld, but it also prevents the fusion of weld layers and, therefore, compromises the weld strength. Before another weld is applied, the slag should be removed completely-for example, by wire brushing or weld chipping. Consequently, both labour costs and material costs are high

Submerged-arc Welding (SAW):

In **Submerged-arc Welding (SAW)**, the weld arc is shielded by a granular flux consisting of lime, silica, manganese oxide, calcium fluoride and other compounds. The flux is fed into the weld zone from a hopper by gravity flow through a nozzle. The thick layer of flux completely covers the molten metal. Covered flux prevents spatter and sparks and suppresses the intense ultraviolet radiation and fumes characteristic of the shielded metal-arc welding (SMAW) process. The flux acts as a thermal insulator by promoting deep penetration of heat into the work piece.
The consumable electrode is a coil of bare round wire 1.5 to 10 mm in diameter, consumable electrode is fed automatically through a tube. Electric currents typically range from 300 to 2000A. The power supplies usually are connected to standard single-phase or three-phase power lines with a primary rating up to 440V.



Schematic illustration of the submerged-arc welding equipment.

The flux is gravity fed, the Submerged-arc welding process is limited largely to welds in a flat or horizontal position having a backup piece. As image shows, the unfused flux is recovered, treated and reused. Submerged-arc welding is automated and is used to weld a variety of carbon and alloy steel and stainless-steel sheets or plates at speeds as high as 5 m/min. The quality of the Weld is very high with good toughness, ductility and uniformity of properties. The Submerged-arc welding process provides very high welding productivity, depositing 4 to 10 times the amount of weld metal per hour as the shielded metal-arc welding process.

Advantages:

- Smooth welds of high strength and ductility with low H_2 and N_2 content.
- Because of high current, high metal deposition, high welding speeds and good penetration are achieved.
- Due to high speeds less distortion will occur, Elimination of fumes and spatter.
- Absence of visible arc and ease of penetration.

Limitations:

- During welding process arc is not visible, judging the welding progress is difficult and so tools like jigs, fixtures and guides are required.
- Pre-placing of flux may not always possible.
- This welding process is limited to flat position.
- Flux is subjected to contamination that may cause weld porosity.
- Chlorine, Aluminium, Magnesium, Lead, Zinc can not be welded.

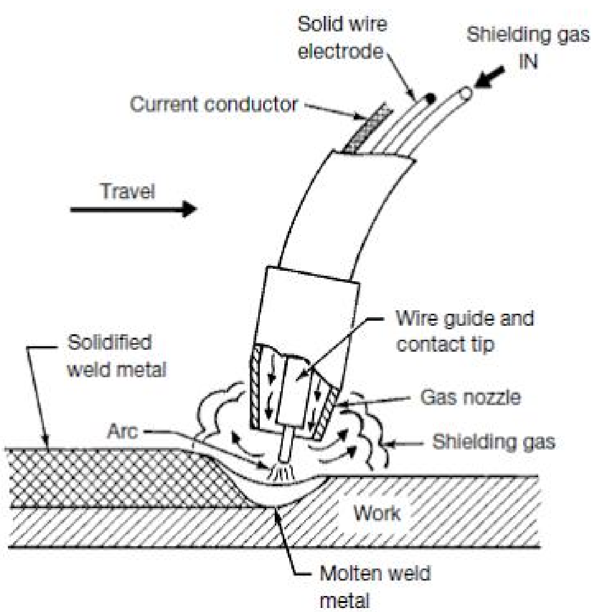
- **Applications:**

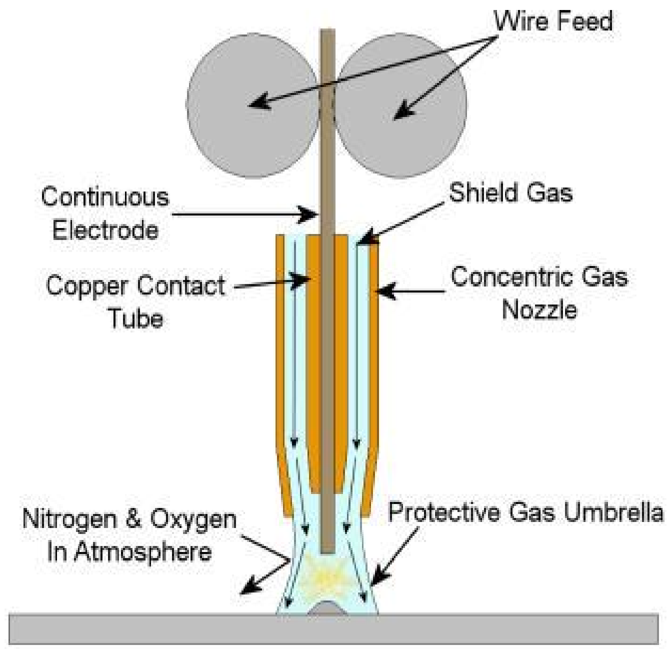
The weld made by Submerged-arc welding have high strength and ductility with low Hydrogen and Nitrogen content. It is suitable for welding low alloy steel, high tensile steel, LC and MC steels, high resisting steel, corrosion resistant steel, high strength steel and many of non-ferrous alloys.

GAS METAL-ARC WELDING

Metal inert gas (MIG) welding:

In the metal inert gas (**MIG**) **welding** process, an electric arc is struck between the filler wire and the **work** piece, while a shroud of inert gas shields the electrode and protects the molten pool against oxidation. Generally, a smoothed direct current power source is used.





Process characteristics

MIG/MAG welding is a versatile technique suitable for both thin sheet and thick section components. An arc is struck between the end of a wire electrode and the work piece, melting both of them to form a weld pool. The wire serves as both heat source (via the arc at the wire tip) and filler metal for the joint. The wire is fed through a copper contact tube (contact tip) which conducts welding current into the wire. The weld pool is protected from the surrounding atmosphere by a shielding gas fed through a nozzle surrounding the wire. Shielding gas selection depends on the material being welded and the application. The wire is fed from a reel by a motor drive, and the welder moves the welding torch along the joint line. Wires may be solid (simple drawn wires), or cored (composites formed from a metal sheath with a powdered flux or metal filling). Consumables are generally competitively priced compared with those for other processes. The process offers high productivity, as the wire is continuously fed.

Manual MIG/MAG welding is often referred as a semi-automatic process, as the wire feed rate and arc length are controlled by the power source, but the travel speed and wire position are under manual control. The process can also be mechanized when all the process parameters are not directly controlled by a welder, but might still require manual adjustment during welding. When no manual intervention is needed during welding, the process can be referred to as automatic.

The process usually operates with the wire positively charged and connected to a power source delivering a **constant voltage**.

Metal transfer mode- The manner, or mode, in which the metal transfers from the electrode to the weld pool largely, determines the operating features of the process-

Short circuiting/ Dip- Short-circuiting and pulsed metal transfer are used for low current operation while currents. In short-circuiting or 'dip' transfer, the molten metal forming on the tip of the wire is transferred by the wire dipping into the weld pool. This is achieved by setting a low voltage; for a 1.2mm diameter wire, arc voltage varies from about 17V (100A) to 22V (200A). Care in setting the voltage and the inductance in relation to the wire feed speed is essential to minimize spatter.

- **Droplet / spray-** Spray transfer- a much higher voltage is necessary to ensure that the wire does not make contact i.e. short-circuit, with the weld pool; for a 1.2mm diameter wire, the arc voltage varies from approximately 27V (250A) to 35V (400A).The molten metal at the tip of the wire transfers to the weld pool in the form of a spray of small droplets (about the diameter of the wire and smaller). However, there is a minimum current level, threshold, below which droplets are not forcibly projected across the arc. If an open arc technique is attempted much below the threshold current level, the low arc forces would be insufficient to prevent large droplets forming at the tip of the wire. These droplets would transfer erratically across the arc under normal gravitational forces.
- **Pulsed-** The pulsed mode was developed as a means of stabilizing the open arc at low current levels i.e. below the threshold level, to avoid short-circuiting and spatter. Metal transfer is achieved by applying pulses of current, each pulse having sufficient force to detach a droplet. Synergic pulsed MIG refers to a special type of controller which enables the power source to be tuned (pulse parameters) for the wire composition and diameter, and the pulse frequency to be set according to the wire feed speed.
- **Globular-** Globular transfer means the weld metal transfers across the arc in large droplets, usually larger than the diameter of the electrode being used. This mode of transfer generally is used on carbon steel only and uses 100 percent CO_2shielding gas. The method typically is used to weld in the flat and horizontal positions because the droplet size is large and would be more difficult to control if used in the vertical and overhead positions compared to the short-circuit arc transfer

Shielding gas

In addition to general shielding of the arc and the weld pool, the shielding gas performs a number of important functions:

- forms the arc plasma, stabilizes the arc roots on the material surface
- ensures smooth transfer of molten droplets from the wire to the weld pool

Thus, the shielding gas will have a substantial effect on the stability of the arc and metal transfer and the behaviour of the weld pool, in particular, its penetration. General purpose shielding gases for MIG welding are mixtures of argon, oxygen and CO_2, and special gas mixtures may contain helium. The gases which are normally used for the various materials are:

- **For steels- CO_2, argon +2 to 5% oxygen, argon +5 to 25% CO_2**
- **For non-ferrous (e.g. Aluminum, copper or nickel alloys)- argon, argon / helium**
  Argon based gases, compared with CO_2 , are generally more tolerant to parameter settings and generate lower spatter levels with the dip transfer mode. However, there is a greater risk of lack of fusion defects because these gases are colder. As CO_2 cannot be used in the open arc (pulsed or spray transfer) modes due to high back-plasma forces, argon based gases containing oxygen or CO_2 are normally employed.

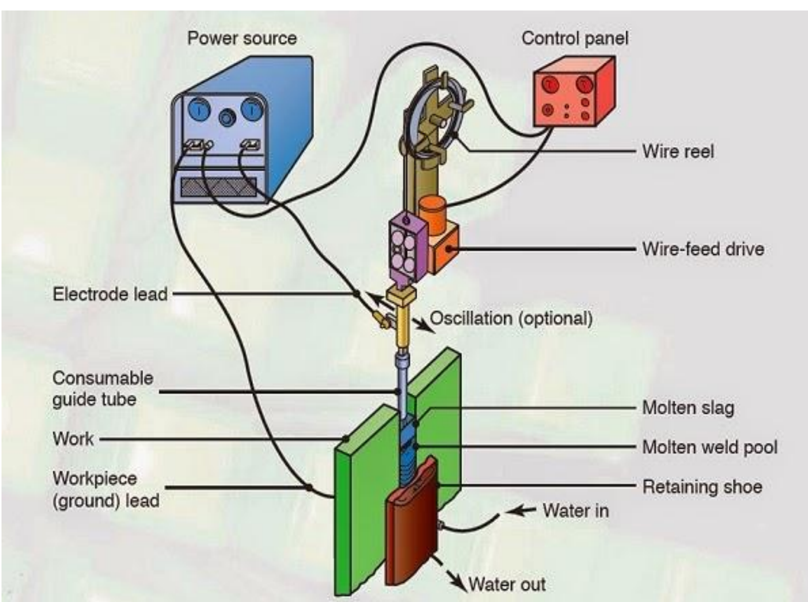
Applications- MIG/MAG is widely used in most industry sectors and accounts for more than 50% of all weld metal deposited. Compared to MMA, MIG/MAG has the advantage in terms of flexibility, deposition rates and suitability for mechanization. However, it should be noted that while MIG/MAG is ideal for 'squirting' metal, a high degree of manipulative skill is demanded of the welder.

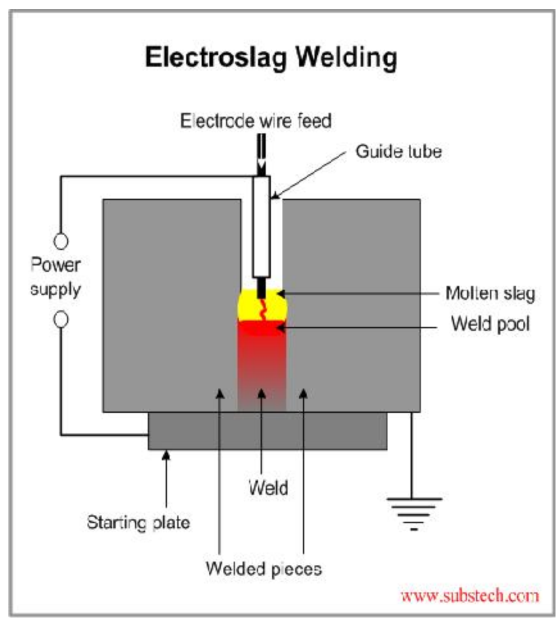
9.5.6 Comparision Between TIG (GTAW) and MIG (GMAW) Welding

Tungsten inert gas welding (GTAW)	Metal inert gas welding (GMAW)
1. In TIG welding a non-consumable (permanent) tungsten electrode is used.	1. MIG uses a copper coated wire of same chemical composition as the parent metal being welded.
2. TIG welding electrode, servers the purpose of producing the arc only filler rod needed if any.	2. MIG welding wire servers both the purpose of producing the arc as well as of filler metal.
3. TIG welding process is not so faster as MIG welding process as separately a filler rod is added.	3. MIG is faster process as compared to TIG because no filler rod is added separately.
4. TIG welding requires a skill operator.	4. Not so much skill operator is needed.
5. TIG welding torch may be watercool.	5. MIG welding torch are not water cooled.
6. Penetration is not so much deeper as compared to MIG.	6. Deeper penetration can be achieved very easily.
7. TIG welding is not recommended for greater than 6 mm thickness of sheet.	7. No such condition applicable in MIG welding.
8. If filler rod is added, operators both hands are engaged. So work must be held in position with clamps or fixture.	8. In MIG welding, wire electrode and gases come from same run and thus can be made easily automatic.

Electroslag welding (ESW)

Electroslag welding (ESW) applications are similar to electrogas welding. The main difference is that the arc is started between the electrode tip and the bottom of the part to be welded. Flux is added, which then melts by the heat of the arc. After the molten slag reaches the tip of the electrode, the arc is extinguished. Heat is produced continuously by the electrical resistance of the molten slag. Because the arc is extinguished, Electroslag welding is not strictly an arc-welding process. Single or multiple solid as well as flux-cored electrodes may be used.





Electroslag welding is capable of welding plates with thicknesses ranging from 50 mm to more than 900 mm and welding is done in one pass. The current required is about 600 A at 40 to 50 Volts although higher currents are used for thick plates. The travel speed of the weld is in the range from 12 to 36 mm/min. Weld quality is high. This process is used for large structural-steel sections, such as heavy machinery, bridges, ships and nuclear-reactor vessels.

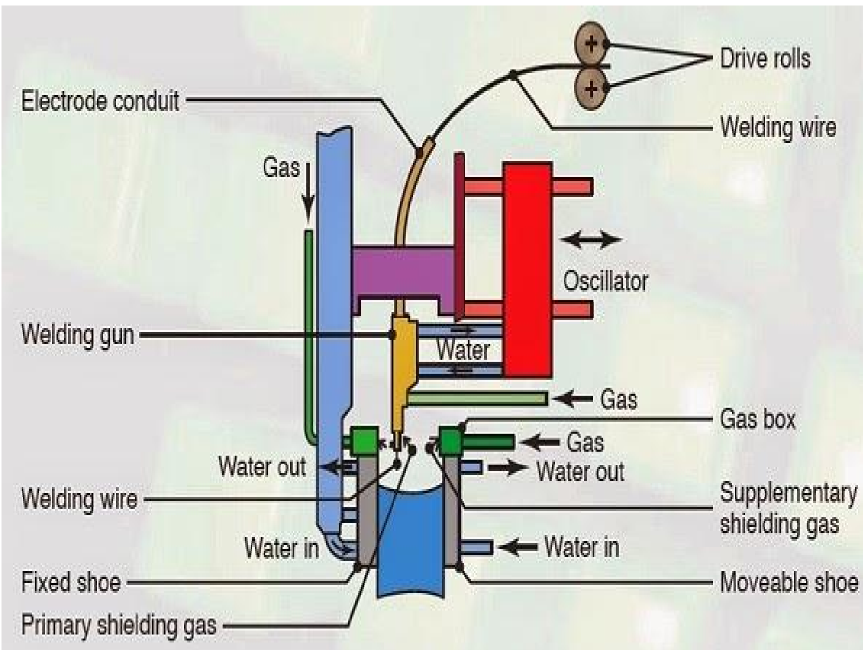
Electroslag welding depends on….

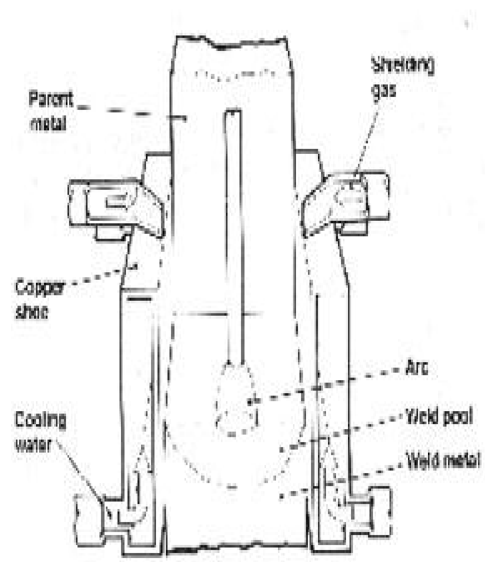
- The ratio of width of the weld pool and its maximum depth known as Form Factor.
- Weld current and voltage.
- Slag depth.
- Number of electrodes and their spacing etc.

Advantages-
Disadvantages-
Applications-

Electrogas welding (EGW)

Electrogas welding (EGW) is an vertical positioned arc welding process, is used for welding the edges of sections vertically and in one pass with the pieces placed edge to edge (butt joint). It is classified as a machine-welding process, because for its operation requires special equipment. The weld metal is deposited into a weld cavity between the two pieces to be joined. The space is covered by two water-cooled copper dams(shoes) to prevent the molten slag from running off; mechanical drives move the shoes upward.





One or more electrodes are fed through a conduit and a continuous arc is maintained by flux-cored electrodes at up to 750 A or solid electrodes at 400 A. Power requirements is 20 kW. Shielding is done by means of an inert gas, such as argon or helium depending on the type of material being welded. The gas may be provided either from an external source, from a flux-cored electrode or from both the sources. The equipment of electro gas welding is reliable and training an operator is easy. Weld thickness is between 12 mm to 75 mm on steels, titanium and aluminum alloys.
Electrogas welding process is used in the construction of bridges, pressure vessels, thick-walled and large-diameter pipes, storage tanks, submarines and ships.

ELECTRODES FOR ARC WELDING:

Electrodes for consumable arc-welding processes are classified according to the following properties:

- ❖ Strength of the deposited weld metal
- ❖ Current (Ac or Dc)
- ❖ Type of coating.

Electrodes are identified by numbers and letters or by colour code if the numbers and letters are too small to imprint. Typical coated-electrode dimensions are in the range from 150 to 460 mm in length and 1.5 to 8 mm in diameter.
Specifications for electrodes and filler metals (including dimensional tolerances, quality control procedures, and processes) are published by the American Welding Society (AWS) and the American National Standards Institute (ANSI).
Some specifications appear in the Aerospace Materials Specifications (AMS) by the Society of Automotive Engineers (SAE). Electrodes are sold by weight and are available in a wide variety of sizes and specifications.

Electrode Coatings

Electrodes are coated with claylike materials that include silicate binders and powdered materials, such as oxides, carbonates, fluorides, metal alloys, cotton cellulose, and wood flour. The coating, which is brittle and takes part in complex interactions during welding, has the following basic functions:

- Stabilize the arc.
- Generate gases to act as a shield against the surrounding atmosphere; the gases produced are carbon dioxide, water vapour, and small amounts of carbon monoxide and hydrogen.
- Control the rate at which the electrode melts.
- Act as a flux to protect the weld against the formation of oxides, nitrides, and other inclusions and, with the resulting slag, to protect the molten-weld pool.
- Add alloying elements to the weld zone to enhance the properties of the joint among these elements are deoxidizers to prevent the weld from becoming brittle.

The deposited electrode coating or slag must be removed after each pass in order to ensure a good weld; a wire brush (manual or power) can be used for this purpose. Bare electrodes and wires made of stainless steels and aluminium alloys also are available. They are used as filler metals in various welding operations.

RESISTANCE WELDING:

Resistance welding processes are pressure welding processes in which heavy current is passed for short time through the area of interface of metals to be joined. These processes differ from other welding processes in the respect that no fluxes are used, and filler metal rarely used. All resistance welding operations are automatic and, therefore, all process variables are preset and maintained constant. Heat is generated in localized area which is enough to heat the metal to sufficient temperature, so that the parts can be joined with the application of pressure. Pressure is applied through the electrodes.

The heat generated during resistance welding is given by following expression:

$$H = I^2 R T$$

Where, **H** is heat generated

I is current in amperes

R is resistance of area being welded

T is time for the flow of current.

The process employs currents of the order of few KA, voltages range from 2 to 12 volts and times vary from few ms to few seconds. Force is normally applied before, during and after the flow of current to avoid arcing between the surfaces and to forge the weld metal during post heating. The necessary pressure shall vary from 30 to 60 N mm^{-2} depending upon material to be welded and other welding conditions. For good quality welds these parameters may be properly selected which shall depend mainly on material of components, their thicknesses, type and size of electrodes.

Apart from proper setting of welding parameters, component should be properly cleaned so that surfaces to be welded are free from rust, dust, oil and grease. For this purpose components may be given pickling treatment i.e. dipping in diluted acid bath and then washing in hot water bath and then in the cold water bath. After that components may be dried through the jet of compressed air. If surfaces are rust free then pickling is not required but surface cleaning can be done through some solvent such as acetone to remove oil and grease.

The current may be obtained from a single phase step down transformer supplying alternating current. However, when high amperage is required then three phase rectifier may be used to obtain DC supply and to balance the load on three phase power lines.

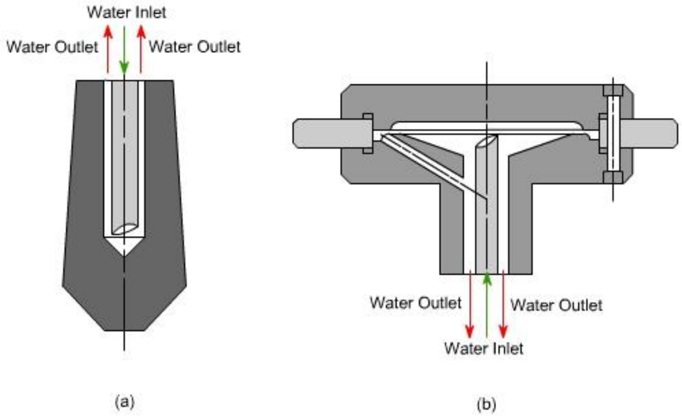


FIGURE Water Cooling of Electrodes (a) Spot Welding (b) Seam Welding

The material of electrode should have higher electrical and thermal conductivities with sufficient strength to sustain high pressure at elevated temperatures. Commonly used electrode materials are pure copper and copper base alloys. Copper base alloys may consist of copper as base and alloying elements such as cadmium or silver or chromium or nickel or beryllium or cobalt or zirconium or tungsten. Pure tungsten or tungsten-silver or tungsten-copper or pure molybdenum may also be used as electrode material. To reduce wear, tear and deformation of electrodes, cooling through water circulation is required. Figure 4.16 shows the water cooling system of electrodes.
Commonly used resistance welding processes are spot, seam and projection welding which produce lap joints except in case of production of welded tubes by seam welding where edges are in butting position. In butt and flash welding, components are in butting position and butt joints are produced.

1. Spot Welding

In resistance spot welding, two or more sheets of metal are held between electrodes through which welding current is supplied for a definite time and also force is exerted on work pieces. The principle is illustrated in Figure 4.17.

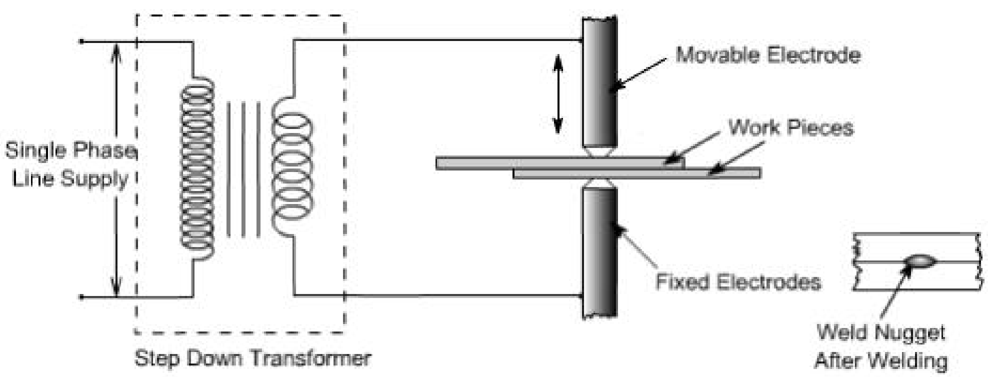


FIGURE: Principle of Resistance spot Welding

The welding cycle starts with the upper electrode moving and contacting the work pieces resting on lower electrode which is stationary. The work pieces are held under pressure and only then heavy current is passed between the electrodes for preset time. The area of metals in contact shall be rapidly raised to welding temperature, due to the flow of current through the contacting surfaces of work pieces. The pressure between electrodes, squeezes the hot metal together thus completing the weld. The weld nugget formed is allowed to cool under pressure and then pressure is released. This total cycle is known as resistance spot welding cycle and illustrated in Figure 4.18.

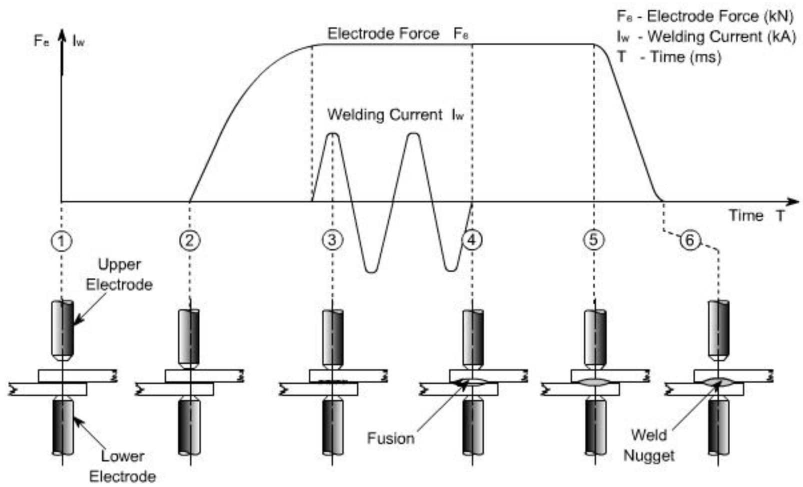
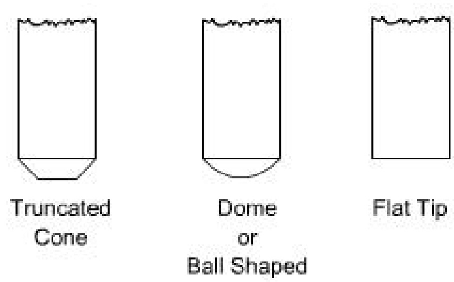


Fig : Resistance Spot Welding Cycle

Spot welding electrodes of different shapes are used. Pointed tip or truncated cones with an angle of 120° - 140° are used for ferrous metal but with continuous use they may wear at the tip. Domed electrodes are capable of withstanding heavier loads and severe heating without damage and are normally useful for welding of nonferrous metals. The radius of dome generally varies from 50-100 mm. A flat tip electrode is used where minimum indentation or invisible welds are desired.



Most of the industrial metal can be welded by spot welding, however, it is applicable only for limited thickness of components. Ease of mechanism, high speed of operation and dissimilar metal combination welding, has made is widely applicable and acceptable process. It is widely being used in electronic, electrical, aircraft, automobile and home appliances industries.

2. Seam Welding:

In seam welding overlapping sheets are gripped between two wheels or roller disc electrodes and current is passed to obtain either the continuous seam i.e. overlapping weld nuggets or intermittent seam i.e. weld nuggets are equally spaced. Welding current may be continuous or in pulses. The process of welding is illustrated in Figure .

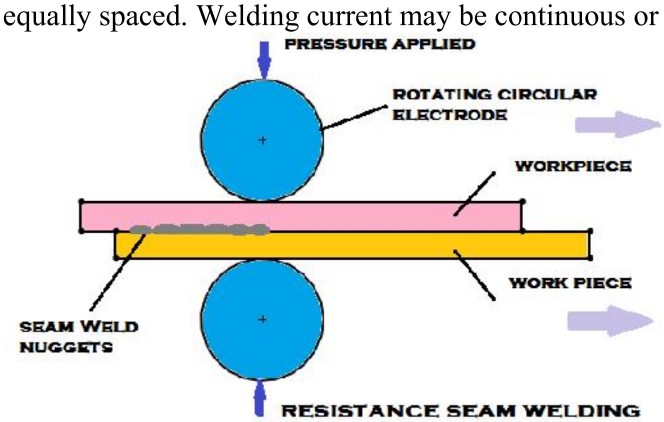
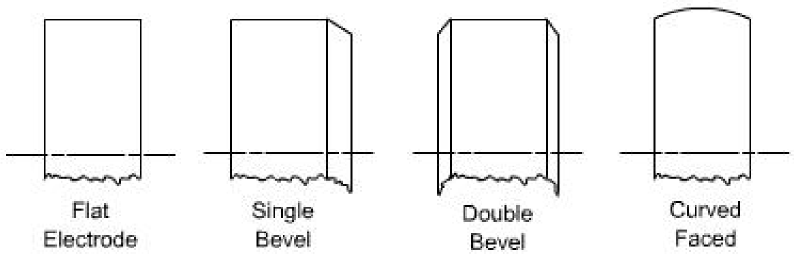


FIGURE Process of Seam welding



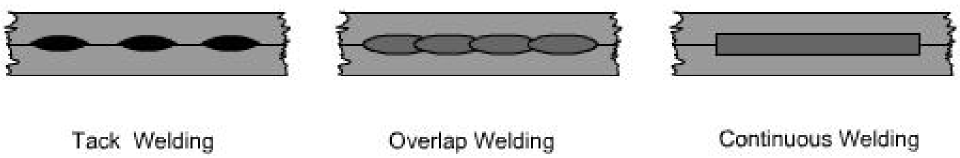


FIGURE Type of Seam Welds

FIGURE Electrode Shapes of Seam Welding

Overlapping of weld nuggets may vary from 10 to 50 %. When it is approaching around 50 % then it is termed as continuous weld. Overlap welds are used for air or water tightness.
It is the method of welding which is completely mechanized and used for making petrol tanks for automobiles, seam welded tubes, drums and other components of domestic applications.
Seam welding is relatively fast method of welding producing quality welds. However, equipment is costly and maintenance is expensive. Further, the process is limited to components of thickness less than 3 mm.

3. <u>Projection Welding:</u>

Projections are little projected raised points which offer resistance during passage of current and thus generating heat at those points. These projections collapse under heated conditions and pressure leading to the welding of two parts on cooling. The operation is performed on a press welding machine and components are put between water cooled copper platens under pressure. Figures 4.22 and 4.23 illustrate the principle of resistance projection welding.

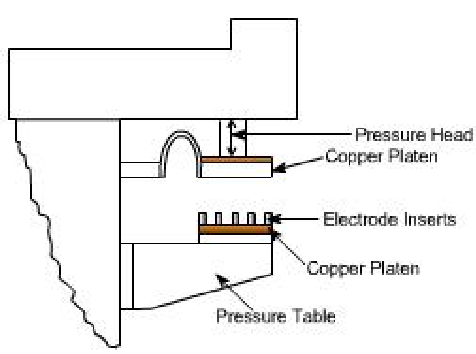


FIGURE Resistance Projection Welding Machine

These projections can be generated by press working or machining on one part or by putting some external member between two parts. Members such as wire, wire ring, washer or nut can be put between two parts to generate natural projection.

Insert electrodes are used on copper platen so that with continuous use only insert electrodes are damaged and copper platen is safe. Relatively cheaper electrode inserts can be easily replaced whenever these are damaged.

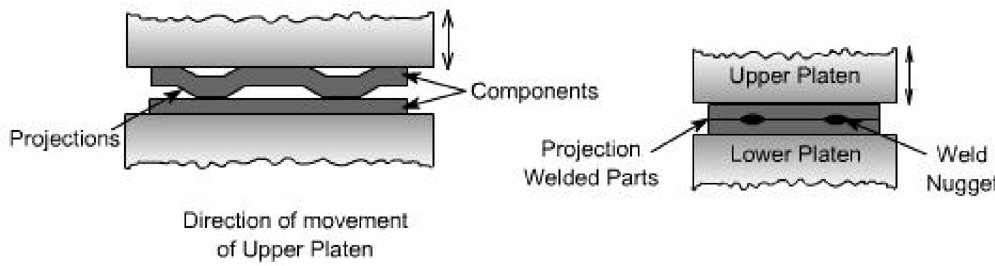


FIGURE Formation of Welds from Projections on Components

Projection welding may be carried out with one projection or more than one projections simultaneously.
No consumables are required in projection welding. It is widely being used for fastening attachments like brackets and nuts etc to sheet metal which may be required in electronic, electrical and domestic equipment.

BRAZING

Brazing is a joining process in which a filler metal is placed between the faying surfaces to be joined (or at their periphery) and the temperature is raised sufficiently to melt the filler metal, but not the components (the base metal)-as would be the case in fusion welding. Thus, brazing is a liquid-solid-state bonding process. Upon cooling and solidification of the filler metal, a strong joint is obtained. Filler metals used for brazing typically melt above 450°C, which is below the melting point (solidus temperature) of the metals to be joined. Brazing is derived from the word brass, an archaic word meaning "to harden," and the process was first used as far back as 3000 to 2000 B.C.
In a typical brazing operation, a filler (braze) metal wire is placed along the periphery of the components to be joined, as shown in Fig. 4.23a. Heat is then applied by various external means, melting the braze metal and, by capillary action, filling the closely fitting space (joint clearance) at the interfaces (Fig. 4.23b).

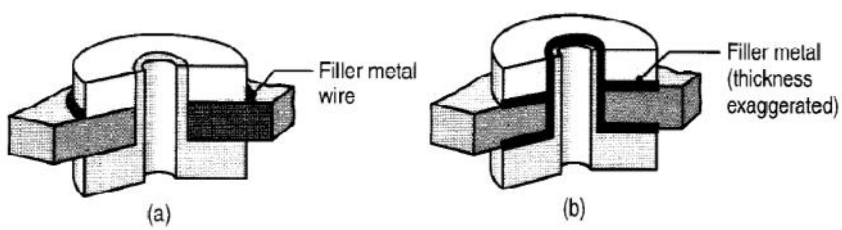


FIGURE An example of furnace brazing (a) before and (b) after brazing. The filler metal is a shaped wire and moves into the interfaces by capillary action with the application of heat.

In braze welding, filler metal (typically brass) is deposited at the joint by a technique similar to oxyfuel-gas welding (see Fig. d); the major difference is that the base metal does not melt. The main application of braze welding is in repair work, typically on parts made of cast steels and irons. Because of the wider gaps between the components being welded (as in oxyfuel-gas welding), more braze metal is used than in conventional brazing.

FILLER METALS

Several filler metals (braze metals) are available with a range of brazing temperatures. Note that, unlike those for other welding operations, filler metals for brazing generally have a composition that is significantly different from those of the metals to be joined. They are available in a variety of shapes, such as wire, rod, ring, shim stock, and filings. The selection of the type of filler metal and its composition are important in order to avoid embrittlement of the joint by (a) grain-boundary penetration of liquid metal; (b) the formation of brittle interinetallic compounds at the joint; and (c) galvanic corrosion in the joint.
Because of diffusion between the filler metal and the base metal, the mechanical and metallurgical properties of a joint can change as a result of subsequent processing or during the service life of a brazed part. For example, when titanium is brazed with pure tin as the filler metal, it is possible for the tin to diffuse completely into the titanium base metal when it is subjected to subsequent aging or to heat treatment. Consequently, the joint no longer exists.

FLUXES

The use of a flux is essential in brazing; a flux prevents oxidation and removes oxide films. Brazing fluxes generally are made of borax, boric acid, borates, fluorides, and chlorides. Wetting agents may be added to improve both the wetting characteristics of the molten filler metal and the capillary action.
It is essential that the surfaces to be brazed be clean and free from rust, oil, and other contaminants in order (a) for proper wetting and spreading of the molten filler metal in the joint and (b) to develop maximum bond strength.

Sand blasting also may be used to improve the surface finish of the faying surfaces for brazing. Because they are corrosive, fluxes must be removed after brazing, usually by washing with hot water.

SOLDERING:

In soldering, the filler metal (called solder) melts at a relatively low temperature. As in brazing, the solder fills the joint by capillary action between closely fitting or closely placed components. Two important characteristics of solders are low surface tension and high wetting capability. Heat sources for soldering are usually soldering irons, torches, or ovens. The word "solder" is derived from the Latin solid are, meaning "to make solid." Soldering with copper-gold and tin-lead alloys was first practiced as far back as 4000 to 3000 B.C.

TYPES OF SOLDERS AND FLUXES

Solders melt at a temperature that is the eutectic point of the solder alloy. Solders traditionally have been tin-lead alloys in various proportions. For example, a solder of 61.9% Sn-38.1% Pb composition melts at 188°C, whereas tin melts at 232°C and lead at 327°C. For special applications and higher joint strength (especially at elevated temperatures), other solder compositions are tin-zinc, lead-silver, cadmium-silver, and zinc-aluminium alloys.
Because of the toxicity of lead and its adverse effects on the environment, lead free solders are being developed continuously and are coming into wider use. Among the various candidate materials are silver, indium, and bismuth eutectic alloys in combination with tin. Three typical compositions are 96.5% Sn-3.5% Ag, 42% Sn-58% Bi, and 48% Sn-52% In However, none of these combinations are suitable for every soldering application. Fluxes are used in soldering and for the same purposes as they are in welding and brazing. Fluxes for soldering are generally of two types:

1. Inorganic acids or salts, such as zinc-ammonium-chloride solutions, which clean the surface rapidly. To avoid corrosion, the flux residues should be removed after soldering by washing the joint thoroughly with water.
2. Noncorrosive resin-based fluxes, used typically in electrical applications.

"FRICTION WELDING"

Friction welding is a widely used commercial process, amenable to automated production methods. The process was developed in the (former) Soviet Union and introduced into the United States around 1960. Friction welding (FRW) is a solid state welding process in which coalescence is achieved by frictional heat combined with pressure. The friction is induced by mechanical rubbing between the two surfaces, usually by rotation of one part relative to the other, to raise the temperature at the joint interface to the hot working range for the metals involved. Then the parts are driven toward each other with sufficient force to form a metallurgical bond. The sequence is portrayed in Figure for welding two cylindrical parts, the typical application. The axial compression force upsets the parts, and a flash is produced by the material displaced. Any surface films that may have been on the contacting surfaces are expunged during the process. The flash must be subsequently trimmed (e.g., by turning) to provide a smooth surface in the weld region. When properly carried out, no melting occurs at the faying surfaces. No filler metal, flux, or shielding gases are normally used.
Nearly all FRW operations use rotation to develop the frictional heat for welding. There are two principal drive systems, distinguishing two types of FRW: (1) continuous drive friction welding, and (2) inertia friction welding. In continuous-drive friction welding, one part is driven at a constant rotational speed and forced into contact with the stationary part at a certain force level so that friction heat is generated at the interface.

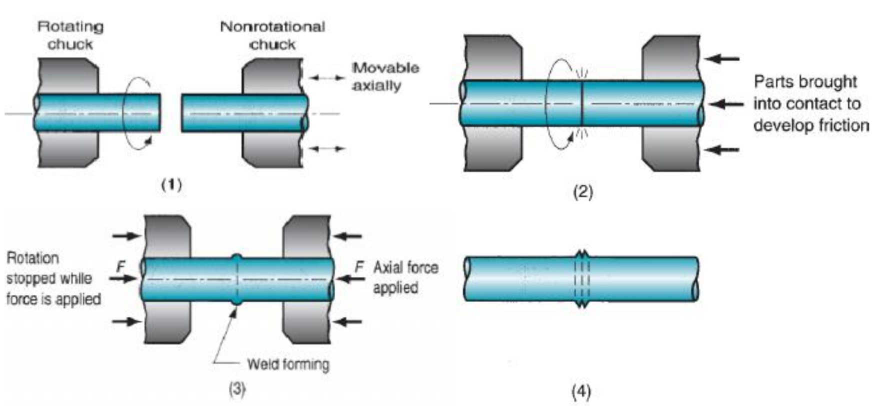


FIGURE Friction welding (FRW): (1) rotating part, no contact; (2) parts brought into contact to generate friction heat; (3) rotation stopped and axial pressure applied; and (4) weld created.

When the proper hot working temperature has been reached, braking is applied to stop the rotation abruptly, and simultaneously the pieces are forced together at forging pressures. In inertia friction welding, the rotating part is connected to a flywheel, which is brought up to a predetermined speed. Then the flywheel is disengaged from the drive motor, and the parts are forced together. The kinetic energy stored in the flywheel is dissipated in the form of friction heat to cause coalescence at the abutting surfaces. The total cycle for these operations is about 20 seconds.
Machines used for friction welding have the appearance of an engine lathe. They require a powered spindle to turn one part at high speed, and a means of applying an axial force between the rotating part and the non rotating part. With its short cycle times, the process lends itself to mass production. It is applied in the welding of various shafts and tubular parts in industries such as automotive, aircraft, farm equipment, petroleum, and natural gas. The process yields a narrow heat-affected zone and can be used to join dissimilar metals. However, at least one of the parts must be rotational, flash must usually be removed, and upsetting reduces the part lengths (which must be taken into consideration in product design).
The conventional friction welding operations discussed above utilize a rotary motion to develop the required friction between faying surfaces. A more recent version of the process is linear friction welding, in which a linear reciprocating motion is used to generate friction heat between the parts. This eliminates the requirement for at least one of the parts to be rotational (e.g., cylindrical, tubular).

SOLIDIFICATION OF THE WELD METAL

After the application of heat and the introduction of the filler metal (if any) into the weld zone, the weld joint is allowed to cool to ambient temperature. The solidification process is similar to that in casting and begins with the formation of columnar (dendritic) grains. These grains are relatively long and form parallel to the heat flow. Because metals are much better heat conductors than the surrounding air, the grains lie parallel to the plane of the two components being welded (Fig.). In contrast, the grains in a shallow weld are shown in Figs. 4.25b and c.
Grain structure and grain size depend on the specific metal alloy, the particular welding process employed, and the type of filler metal. Because it began in a molten state, the weld metal basically has a cast structure, and since it has cooled slowly, it has coarse grains. Consequently, this structure generally has low strength, toughness, and ductility. However, the proper selection of filler-metal composition or of heat treatments following welding can improve the mechanical properties of the joint.
The resulting structure depends on the particular alloy, its composition, and the thermal cycling to which the joint is subjected. For example, cooling rates may be controlled and reduced by pre/venting the general weld area prior to welding.
Preheating is important, particularly for metals having high thermal conductivity, such as aluminium and copper. Without preheating, the heat produced during welding dissipates rapidly through the rest of the parts being joined.

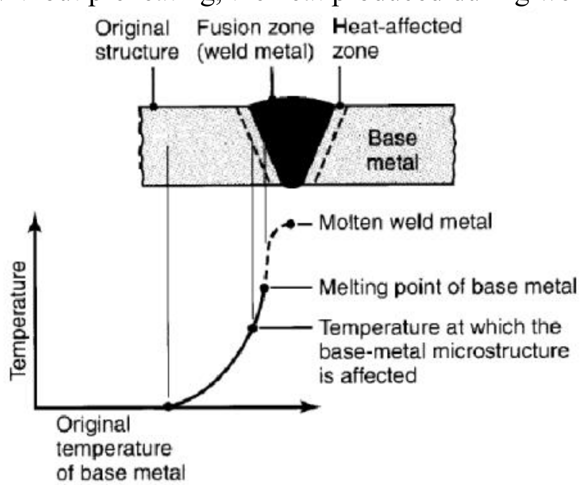


FIGURE Characteristics of a typical welded zone in oxy fuel gas and arc welding

Heat-affected Zone (HAZ):

The heat-affected zone (HAZ) is within the base metal itself. It has a microstructure different from that of the base metal prior to welding, because it has been temporarily subjected to elevated temperatures during welding. The portions of the base metal that are far enough away from the heat source do not undergo any micro structural changes during welding because of the far lower temperature to which they are subjected.

The properties and microstructure of the HAZ depend on (a) the rate of heat input and cooling and (b) the temperature to which this zone was raised. In addition to metallurgical factors (such as the original grain size, grain orientation, and degree of prior cold work), physical properties (such as the specific heat and thermal conductivity of the metals) influence the size and characteristics of the HAZ.

The strength and hardness of the HAZ (Fig. 4.3 d) depend partly on how the original strength and hardness of the base metal was developed prior to the welding.

The heat applied during welding recrystallizes the elongated grains of the cold worked base metal. On the one hand, grains that are away from the weld metal will recrystallize into fine, equiaxed grains. On the other hand, grains close to the weld metal have been subjected to elevated temperatures for a longer time. Consequently, the grains will grow in size (grain growth), and this region will be softer and have lower strength. Such a joint will be weakest at its HAZ.

The effects of heat on the HAZ for joints made from dissimilar metals and for alloys strengthened by other methods are so complex as to be beyond the scope of this book. Details can be found in the more advanced references listed in the bibliography at the end of this chapter.

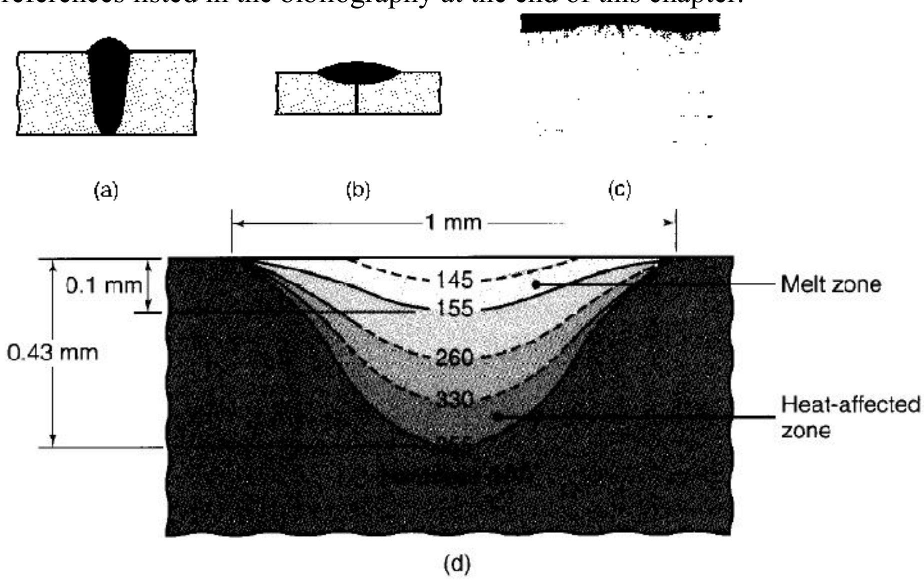


FIGURE Grain structure in (a) a deep weld and (b) a shallow weld. Note that the grains in the solidified weld metal are perpendicular to their interface with the base metal. (c) Weld bead on a cold-rolled nickel strip produced by a laser beam. (d) Micro hardness (HV) profile across a weld bead.

WELDABILITY:

The weldability of a metal is usually defined as its capacity to be Welded into a specific structure that has certain properties and characteristics and will satisfactorily meet service requirements. Weldability involves a large number of variables; hence, generalizations are difficult. As noted previously, the material characteristics (such as alloying elements, impurities, inclusions, grain structure, and processing history) of both the base metal and the filler metal are important. For example, the Weldability of steels decreases with increasing carbon content because of martensite formation (which is hard and brittle) and thus reduces the strength of the Weld. Coated steel sheets present various challenges in welding, depending on the type and thickness of the coating.

Because of the effects of melting and solidification and of the associated micro structural changes, a thorough knowledge of the phase diagram and the response of the metal or alloy to sustained elevated temperatures is essential. Also influencing Weldability are mechanical and physical properties: strength, toughness, ductility, notch sensitivity, elastic modulus, specific heat, melting point, thermal expansion, surface-tension characteristics of the molten metal, and corrosion resistance.

The preparation of surfaces for Welding is important, as are the nature and properties of surface-oxide films and of adsorbed gases. The particular Welding process employed significantly affects the temperatures developed and their distribution in the Weld zone. Other factors that affect Weldability are shielding gases, fluxes, moisture content of the coatings on electrodes, Welding speed, Welding position, cooling rate, and level of preheating, as Well as such post welding techniques as stress relieving and heat treating.

Weldability of Ferrous Materials:

- ❖ Plain-carbon steels: Weldability is excellent for low-carbon steels, fair to good for medium-carbon steels, poor for high-carbon steels.
- ❖ Low-alloy steels: Weldability is similar to that of medium-carbon steels.
- ❖ High-alloy steels: Weldability generally is good under well-controlled conditions.
- ❖ Stainless steels: These generally are weldable by various processes.
- ❖ Cast irons: These generally are weldable, although their weldability varies greatly.

Weldability of Nonferrous Materials:

- ❖ Aluminum alloys: These are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important. Aluminum alloys containing zinc or copper generally are considered unvveldable.
- ❖ Copper alloys: Depending on composition, these generally are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important.
- ❖ Magnesium alloys: These are weldable With the use of a protective shielding gas and fluxes.
- ❖ Nickel alloys: Weldability is similar to that of stainless steels. The lack of sulphur is undesirable.
- ❖ Titanium alloys: These are weldable with the proper use of shielding gases.
- ❖ Tantalum: Weldability is similar to that of titanium.
- ❖ Tungsten: Weldable under well-controlled conditions.
- ❖ Molybdenum: Weldability is similar to that of tungsten.
- ❖ Niobium (colurnbiufn): Possesses good Weldability.

WELD QUALITY

The purpose of any welding process is to join two or more components into a single structure. The physical integrity of the structure thus formed depends on the quality of the weld. Our discussion of weld quality deals primarily with arc welding, the most widely used welding process and the one for which the quality issue is the most critical and complex.

Residual Stresses and Distortion The rapid heating and cooling in localized regions of the work during fusion welding, especially arc welding, result in thermal expansion and contraction that cause residual stresses in the weldment.

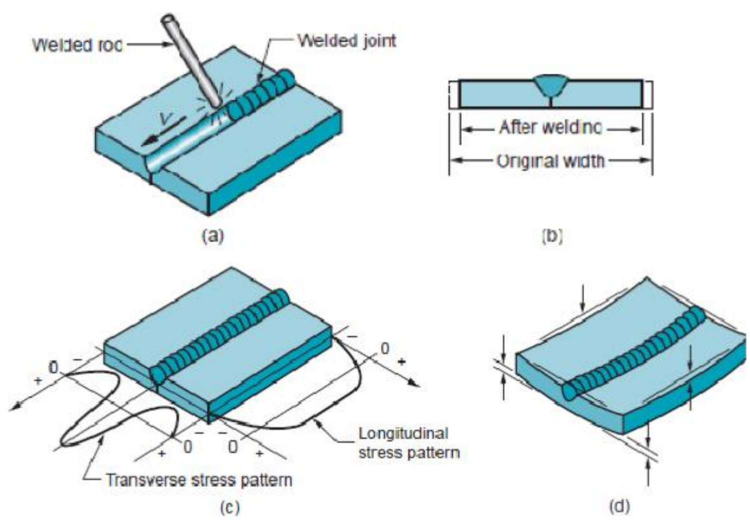


FIGURE (a) Butt welding two plates; (b) shrinkage across the width of the welded assembly;
(c) Transverse and longitudinal residual stress pattern; and (d) likely warping in the welded assembly.

These stresses, in turn, can cause distortion and warping of the welded assembly. The situation in welding is complicated because (1) heating is very localized, (2) melting of the base metals occurs in these local regions, and (3) the location of heating and melting is in motion (at least in arc welding). Consider, for example, butt welding of two plates by arc-welding as shown in Figure(a).

The operation begins at one end and travels to the opposite end. As it proceeds, a molten pool is formed from the base metal (and filler metal, if used) that quickly solidifies behind the moving arc. The portions of the work immediately adjacent to the weld bead become extremely hot and expand, while portions removed from the weld remain relatively cool. The weld pool quickly solidifies in the cavity between the two parts, and as it and the surrounding metal cool and contract, shrinkage occurs across the width of the weldment, as seen in Figure (b).

The weld seam is left in residual tension, and reactionary compressive stresses are set up in regions of the parts away from the weld. Residual stresses and shrinkage also occurs along the length of the weld bead. Since the outer regions of the base parts have remained relatively cool and dimensionally unchanged, while the weld bead has solidified from very high temperatures and then contracted, residual tensile stresses remain longitudinally in the weld bead. These transverse and longitudinal stress patterns are depicted in Figure (c). The net result of these residual stresses, transversely and longitudinally, is likely to cause warping in the welded assembly as shown in Figure (d).

The arc-welded butt joint in our example is only one of a variety of joint types and welding operations. Thermally induced residual stresses and the accompanying distortion are a potential problem in nearly all fusion-welding processes and in certain solid-state welding operations in which significant heating takes place. Following are some techniques to minimize warping in a weldment: (1) Welding fixtures can be used to physically restrain movement of the parts during welding. (2) Heat sinks can be used to rapidly remove heat from sections of the welded parts to reduce distortion. (3) Tack welding at multiple points along the joint can create a rigid structure prior to continuous seam welding. (4) Welding conditions (speed, amount of filler metal used, etc.) can be selected to reduce warping. (5) The base parts can be preheated to reduce the level of thermal stresses experienced by the parts. (6) Stress relief heat treatment can be performed on the welded assembly, either in a furnace for small weldments, or using methods that can be used in the field for large structures. (7) Proper design of the weldment itself can reduce the degree of warping.

WELDING DEFECTS:

In addition to residual stresses and distortion in the final assembly, other defects can occur in welding. Following is a brief description of each of the major categories, based on a classification:

- **Cracks.** Cracks are fracture-type interruptions either in the weld itself or in the base metal adjacent to the weld. This is perhaps the most serious welding defect because it constitutes a discontinuity in the metal that significant reduces weld strength. Several forms are defined in Figure 4.28.Welding cracks are caused by embrittlement or low ductility of the weld and/or base metal combined with high restraint during contraction. Generally, this defect must be repaired.
- **Cavities.** These include various porosity and shrinkage voids. Porosity consists of small voids in the weld metal formed by gases entrapped during solidification. The shapes of the voids vary between spherical (blow holes) to elongated (worm holes). Porosity usually results from inclusion of atmospheric gases, sulfur in the weld metal, or contaminants on the surfaces. Shrinkage voids are cavities formed by shrinkage during solidification. Both of these cavity-type defects are similar to defects found in castings and emphasize the close kinship between casting and welding.
- **Solid inclusions**. These are nonmetallic solid materials trapped inside the weld metal. The most common form is slag inclusions generated during arc-welding processes that use flux. Instead of floating to the top of the weld pool, globules of slag become encased during solidification of the metal. Another form of inclusion is metallic oxides that form during the welding of metals such as aluminum, which normally has a surface coating of Al_2O_3.
- **Incomplete fusion**. Several forms of this defect are illustrated in Figure 4.27. Also known as lack of fusion, it is simply a weld bead in which fusion has not occurred throughout the entire cross section of the joint.Arelated defect is lack of penetration which means that fusion has not penetrated deeply enough into the root of the joint.
- **Imperfect shape or unacceptable contour. T**he weld should have a certain desired profile for maximum strength, as indicated in Figure (a) for a single V-groove weld. This weld profile maximizes the strength of the welded joint and avoids incomplete fusion and lack of penetration. Some of the common defects in weld shape and contour are illustrated in Figure .

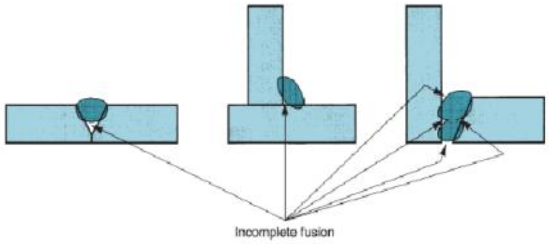


FIGURE 4.27 Several forms of incomplete fusion.

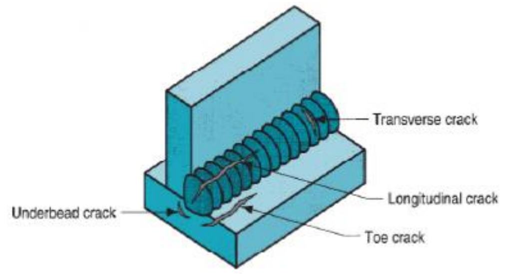


FIGURE 4.28 Several forms of incomplete fusion.

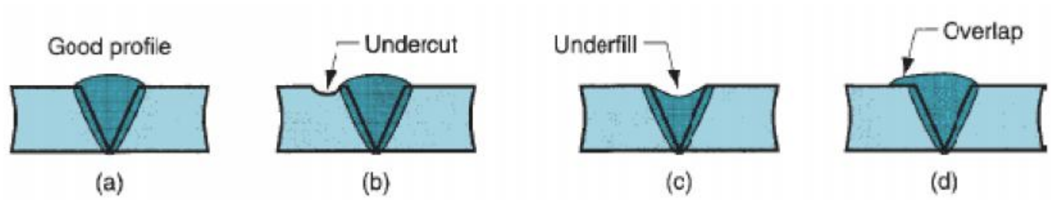


FIGURE 4.29 (a) Desired weld profile for single V-groove weld joint. Same joint but with several weld defects: (b) undercut, in which a portion of the base metal part is melted away; (c) underfill, a depression in the weld below the level of the adjacent base metal surface; and (d) overlap, In which the weld metals pills beyond the joint on to the surface of the base part but no fusion occurs.

- **Weld Profile.** Weld profile is important not only because of its effects on the strength and appearance of the Weld, but also because it can indicate incomplete fusion or the presence of slag inclusions in multiple-layer welds.
  - Under filling results when the joint is not filled with the proper amount of weld metal. Fig. 4.29c
  - Undercutting results from the melting away of the base metal and the consequent generation of a groove in the shape of a sharp recess or notch .Fig. 4.29b.If it is deep or sharp, an undercut can act as a stress raiser and can reduce the fatigue strength of the joint; in such cases, it may lead to premature failure.
  - Overlap is a surface discontinuity. Usually caused by poor Welding practice or by the selection of improper materials. A good Weld is shown in Fig. 4.29c.

- **Miscellaneous defects.** This category includes arc strikes, in which the welder accidentally allows the electrode to touch the base metal next to the joint, leaving a scar on the surface; and excessive spatter, in which drops of molten weld metal splash onto the surface of the base parts.