Introduction To Welding And Allied Processes

WELDING is recognised all over the world, today, as a remarkably versatile means of metal fabrication. Welding, in combination with allied processes like thermal cutting, brazing, brazewelding and metal spraying has provided ample freedom to the modern designer to develop metallic products in which optimum mechanical properties, lightness and aesthetics are harmoniously blended.

A large number of welding and allied processes have come into industrial use in the last 30 years. Variations and extensions of these processes are being developed and put to practical use from time to time. Thus the metal-joining technology is in a constant state of flux. The wide range and variety of these processes enables the modern engineer to join almost all commercial metals and alloys in many different shapes and sizes and in thicknesses ranging from a fraction of a millimetre to over 500 mm.

Plain carbon steels, low-alloy steels, stainless and heat-resisting steels, and many non-ferrous metals and their alloys (such as of aluminium, nickel and copper) and metals such as titanium, columbium, molybdenum and zirconium are welded extensively. Modern industrial products such as automobiles, railway rolling stock, transmission pipelines, pressure vessels, storage tanks, machinery, power generation equipment, offshore platforms, oil refineries and fertiliser plants, which have contributed to the material prosperity of mankind, owe their development and efficient performance to welding.

In the last few years, many of the new high-temperature metals and superalloys have been fabricated by welding into critical components required for guided missiles, jet aircraft and nuclear power plants. These and other similar recent spectacular developments

would not have been possible without the use of welding.

The technique of joining metal pieces by welding apparently originated more than 1,500 years ago, when man learnt the art of manufacturing wrought iron, heating iron pieces to dull red and then hammering them together. This became the traditional hammer-and-tong process of the village blacksmith, which today is known as forge-welding. The 1,500-year-old Iron Pillar at the Qutab Minar in Delhi is made of pure iron ingots forgewelded together.

An amazing piece of early welding can be seen in the 13th century temple at Konarak in Orissa. The flat stone roof of the Black Pagoda there is supported on welded beams; each beam is 25 cm^2 and nearly 6 metres long, and is fabricated from 75 mm blocks of iron by welding.

The well-known Damascus swords and many other specimens of ancient and medieval swords that are seen in museums today were produced by hammer welding strips of high carbon steel to low carbon steel, forging the composite metal, doubling it upon itself, again welding and forging, and repeating these steps until a finely laminated strip was obtained, from which the blade was forged and ground. Such a weapon could be hardened and given a sharp cutting edge, but at the same time it was ductile enough to resist brittle fracture in combat.

In the western countries, especially in the U.S.A., the U.K. and West Germany, the application of welding to the mass production of industrial items and war equipment dates only from the second decade of the present century. Welding received special impetus during World War II, when the urgency of providing

large fleets of ships, tanks, trucks and aircraft at a short notice led to the large-scale replacement of riveting by welding. During the following decades, the use of welding multiplied with amazing swiftness and today this method of joining metals has a dominant place in modern life.

Having briefly touched upon the history of welding, let us revert to the present-day welding and allied processes. These can be conveniently grouped under seven main headings as follows, each suggesting the technological principle on which they are based:

- Fusion welding
- Electric resistance welding
- Solid phase welding
- Braze welding
- Brazing
- Thermal cutting and
- Thermal spraying

Each of these can be further divided into sub-groups and their variations and extensions. All of them have been presented at a glance in the Ador Welding Limited process chart (Table 1.1).

Before starting to introduce this process chart, it is necessary to explain the terms weld and welding. The American Welding Society (AWS) defines weld as a localised coalescence of metals or non-metals produced either by heating the materials to suitable temperatures, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler material. Indian Standard IS: 812–1957 defines the weld as "a union between two pieces of a metal at faces rendered plastic or liquid by heat or by pressure, or both.

Filler metal may be used to effect the union." International Organisation for Standardisation (ISO) has defined welding as "an operation by which two or more parts are united, by means of heat or pressure, or both, in such a way that there is continuity of the nature of the material between these parts. A filler material, the melting temperature of which is of the same order as that of the parent material, may or may not be used." Welding is defined by the AWS, simply as a materials joining process used in making a weld.

To elaborate, a weld is a localised coalescence or union of metals. The word coalescence comes from the verb to coalesce, whose dictionary meaning is, to grow together or unite into one body. This implies that in the

formation of a weld, the abutting surfaces grow together into a common mass, so that the joint has metallic continuity. The ideal weld is one in which there is perfect continuity between the parts joined, such that every part of the joint is indistinguishable from the metal in which the joint is made.

This ideal is never achieved in practice, because the microstructure and mechanical properties are not identical over the entire joint and the original metal. Yet, welds which give satisfactory service can, and are being made, using the proper welding process to suit each metal, type of joint and application. The skill of the welding engineer consists in the recognition of the essential requirements which a particular weld must satisfy and the choice of appropriate welding process, and procedure which will meet them.

FUSION WELDING PROCESSES

These processes involve fusion of the base metal to complete the weld. Fusion welds ordinarily do not require the application of pressure, and they may be completed with or without the addition of filler metal. A fusion weld made without the addition of filler metal is called autogenous weld. In most cases, fusion welding involves the use of filler metal.

In the process chart (Table 1.1), fusion welding processes and, among them, electric arc processes have been given the first place. This is justified by the fact that they are used to the largest extent in industry today.

Metal-Arc Welding

This is a group of processes in which the heat required for fusion is generated by the electric arc formed between a *metallic* electrode and the base metal. The electrode is consumed in the arc and provides the filler metal for the joint.

The electric arc is an ideal source of welding heat. The extremely high arc temperature of over 5000°C permits it to supply a large amount of heat to a small area. Hence the welding speed is very high, and any metallurgical disturbance in the base metal is restricted to a narrow zone.

Among the arc processes, manual metal-arc welding is the most common, versatile and inexpensive one and accounts for over 50% of the total welding in advanced countries and over 80% of the total welding in India. It is a manual process, and hence depends on the skill and experience of the welder. It makes use of a flux-coated electrode having a core of solid metallic wire (diameter

ador WELDING

Table 1.1

PROCESS CHART

By S. V. Nadkarni

WELDING, CUTTING, AND ALLIED PROCESSES

FUSION WELDING
- ARC
  - METAL ARC
    - MANUAL METAL ARC
    - SUBMERGED ARC
    - MIG
      - SYNERGIC MIG
      - PLASMA MIG
    - MAG (CO$_2$)
    - FLUX CORED
      - GAS SHIELDED
      - SELF SHIELDING
    - GRAVITY
    - FIRECRACKER
      - AUTO CONTACTOR
  - CARBON ARC
  - TIG
  - ARC SPOT
  - ARC STUD
  - ATOMIC HYDROGEN
  - ELECTROGAS
  - PLASMA ARC
    - MICRO PLASMA
- GAS
- THERMIT
- ELECTRON BEAM
- ELECTROSLAG
  - CONSUMABLE GUIDE
- LASER

ELECTRIC RESISTANCE
- RESISTANCE
  - RESISTANCE BUTT
  - FLASH
  - SPOT
    - STITCH
    - MULTIPLE SPOT
    - SERIES SPOT
    - ROLLER SPOT
  - PROJECTION
  - SEAM
    - BUTT SEAM
    - FOIL BUTT SEAM
- PERCUSSION
- HIGH FREQUENCY RESISTANCE

SOLID PHASE
- FORGE
  - BLACKSMITH
  - HAMMER
  - ROLL
- GAS PRESSURE
- HIGH FREQUENCY PRESSURE
- COLD
- DIFFUSION BONDING
- EXPLOSIVE
- FRICTION
- FRICTION STIR
- ULTRASONIC
- MAGNETIC PULSE

BRAZEWELDING

BRAZING
- DIP
- FLAME
- FURNACE
- INDUCTION
- SALTBATH
- DIFFUSION
- MIG

THERMAL CUTTING
- OXYGEN
  - OXYGEN
  - OXYGEN ARC
  - POWDER LANCING
    - FLAME
  - ARC
    - CARBON ARC
    - METAL ARC
    - AIR ARC
    - PLASMA ARC
- SPARK EROSION
- ELECTRON BEAM
- LASER

THERMAL SPRAYING
- FLAME
- ELECTRIC ARC
- PLASMA ARC

6.3-1.6 mm, length 450-250 mm). It needs a power source, either a transformer supplying A.. or a generator/rectifier/inverter supplying DC (see Fig. 1.1).

The process is extremely flexible and suitable for the entire range of plate thicknesses, and for almost all commercial metals and alloys. It is used for joining as well as for surfacing (rebuilding). It can be used in all welding positions. It is well-suited for site welding.

Submerged-Arc Welding

This is mostly used as a fully-automatic process, and sometimes as a semi-automatic process.

The electrode is a continuous metallic wire (solid or flux-cored) in the form of a spool or a coil. It is fed automatically into the arc at a constant speed. The arc is covered with a layer of dry granular flux which performs the same functions as the coating of a manual electrode. The arc length is automatically controlled. The power source can be a transformer (AC) or a generator/rectifier (DC). It is generally of very high capacity, say 750 or even up to 3,000 amps (see Fig. 1.2).

In semi-automatic welding, the operator guides the flexible welding head along the seam. In doing so he controls the speed of travel and the line of travel. Controlling the line is difficult, because the joint is submerged by flux. Hence this version is usually restricted to fillet welds and grooved butt welds.

In fully-automatic welding, the welding head is mounted on a trolley which travels along the joint.

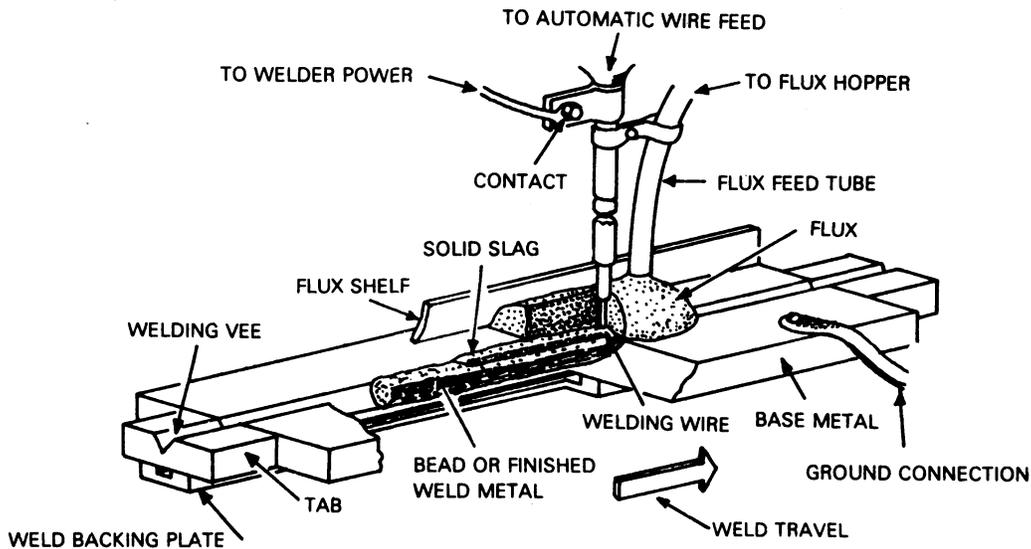Fig. 1.1: Manual metal-arc welding: (A) Welding circuit; (B) Welding arc in action.

Fig. 1.2: Diagrammatic sketch of submerged arc welding

Alternately, the welding head is stationary, and the joint moves under it.

This process gives very high productivity and excellent weld quality.

It is generally applied on mild steel, high tensile steels, low-alloy and stainless steels. It is ideal for heavy thicknesses. For thin sections, weld backing is necessary to avoid burn-through. It is commonly used for the fabrication of plate girders, pressure vessels, pipes and penstocks, for surfacing and strip cladding. In strip cladding, the electrode is in the form of a strip, usually 1.6 mm × 75 mm wide.

MIG Welding

MIG welding is an abbreviation for metal-inert-gas welding. It is also known as GMAW, which stands for gas-metal-arc welding. In this process, coalescence is achieved by an electric arc formed between the workpiece and a continuous consumable solid wire electrode which is fed through a gun at controlled speeds. Inert gas usually argon or argon mixture flows through the gun and forms a blanket over the weld puddle to protect it from atmospheric contamination.

The welding can be semi-automatic or fully mechanised. In the semi-automatic version, the welder concerns himself only with gun-to-work distance, gun manipulation, and welding speed. Wire-feed rates, electrical settings, and gas flow are pre-set. When the equipment is completely mechanised all of these variables and welding functions are performed automatically without the need for a welder.

The power source is a rectifier or motor generator giving DC. Reverse polarity is generally used (electrode positive), as it gives better melting, deeper penetration and better cleaning action (see Fig. 1.3).

NOTE: SOMETIMES A WATER CIRCULATOR IS USED

WIRE REEL

GAS SUPPLY

SHIELDING GAS

WIRE DRIVE

CONTROLS FOR GOVERNING WIRE DRIVE CURRENT GAS FLOW AND COOLING WATER IF FUSED

WELDING MACHINE   CONTACTOR

Fig. 1.3: Schematic diagram of MIG/MAG (CO_2) welding

Four distinct techniques are possible in MIG welding, depending on electrode size, shielding gas, arc voltage and welding current:

a) Spray mode of metal transfer

b) Globular mode of metal transfer

c) Short-circuiting

d) Pulsed transfer

a) This technique uses heavy wires, large currents and preferably argon-oxygen mixture. This gives high heat input, high deposition rate and deep penetration. It is preferred for heavy gauge welding.

b) When current is low, metal transfer occurs in large globules. The result is poor arc stability, shallow penetration and excessive spatter. Hence this technique is not used.

c) This technique is the most practical at currents below 200 amps and with fine wires (0.8-1.2 mm diameter). It permits welding thinner sections with ease, and is extremely practical for welding in all positions.

d) Pulsed transfer is a controlled method of spray transfer welding requiring more sophisticated power source whereas the three types of transfers described previously can be obtained with standard power sources and wire feed units. This mode of transfer can be used on mild and low alloy steels, stainless steel and is particularly useful with aluminium and alloys on light to medium plate sections.

MIG is a versatile process, and is gradually replacing manual metal-arc and TIG welding. Most metals can be easily welded including aluminium, carbon steels, low-alloy steels, stainless steels, nickel, copper, magnesium, titanium and zirconium. However, for carbon steels and low-alloy steels, MAG or CO_2 welding is often preferred, because it avoids the use of expensive argon gas.

In welding ferrous metals (i.e. carbon steels, low alloy steels and stainless steels), pure argon shield gives erratic metal transfer and shallow penetration/side-wall fusion levels and hence certain gas combinations are used, e.g.:

1) Ar + 1-2% O_2 (slightly oxidizing) for alloy steels and stainless steels

2) Ar + 3-5% O_2 or 5-8% CO_2 for carbon or low alloy steels in lower thickness range

3) Ar + 15-20% CO_2 for carbon or low alloy steels in higher thickness range

MAG (CO_2) Welding

MAG stands for metal-active-gas arc welding. This is a variation of MIG welding, in which an identical equipment is used but the inert gas is replaced by carbon dioxide, which is chemically active. The term gas-metal-

arc welding (GMAW) is also applied to the MAG (CO_2) process.

CO_2 welding has a very hot coarse arc associated with relatively high level of spatter formation. However, because of excellent fusion and wetting properties, this provides a lower cost solution for good quality welding, where spatter can be tolerated.

CO_2 welding is gradually replacing manual metal-arc welding in the fabrication of structurals, pipes, automotive products, storage tanks, machinery, etc.

Plasma-MIG Welding

This process has been dealt with later under the heading Plasma Processes.

Flux-Cored Arc Welding

This is an extension of the MIG/MAG process. The continuous solid wire is replaced by a tubular wire whose core is filled with flux. The equipment is the same as used for MIG/MAG welding (see Fig. 1.4).

The flux performs the same functions as the coating of a manual electrode. For welding alloy steels and for hardfacing applications, suitable alloying elements are also included in the flux. Flux-cored wires provide an easy means of producing alloyed and hardfacing wires of any desired composition, in small batches and at short notice. They are a big boon to the industry, since for solid wire one has to depend on a steel producer, rolling mill and a large production batch.

Flux-cored arc welding is normally performed with a CO_2 shield to protect the weld pool from atmospheric attack. Thus it becomes a gas-shielded process.

Some flux-cored wires are specially designed to be self-shielding, which means they do not require the external CO_2 shield. Such wires are widely used in the U.S.A. and Japan for structural and hardfacing applications. When such wires are used, the process is described as self-shielding or gasless.

Gravity Welding

This is a semi-automatic version of manual metal-arc welding. The bare end of a specially designed heavy-coated manual welding electrode (diameter 4.5–6.3 mm, length 600–700 mm) is clamped in a holder, which is fixed on one of the legs of a tripod. The striking end of the electrode is placed in the root of a tee joint. When the arc is struck, the electrode begins to consume and the arc length is automatically maintained due to the sleeve formation at the burning end, as in contact welding. At the same time, the holder slides down by gravity. The electrode automatically retracts and cuts off the arc when a 50 mm long stub is left (see Fig. 1.5).
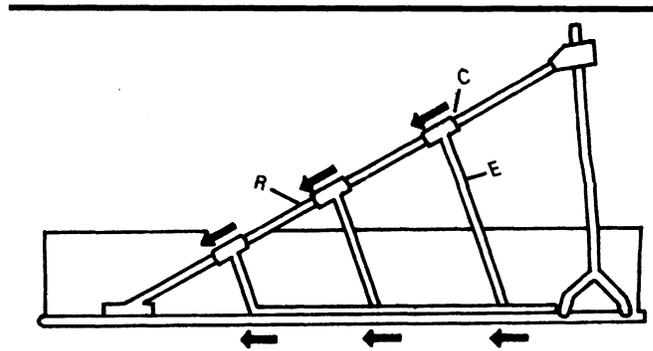
Fig. 1.5: Diagrammatic sketch of gravity welding
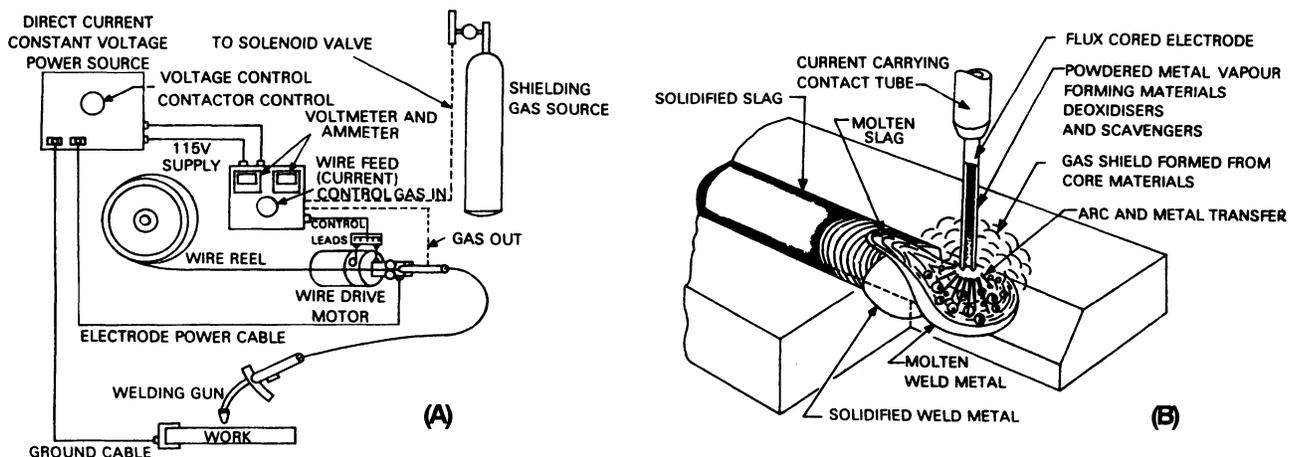
Fig. 1.4: Flux-cored arc welding: (A) Schematic diagram of the process; (B) Welding arc in action

The fillet size (throat thickness) ranges between 3.5mm and 5.5 mm, the length of weld per electrode being in the range of 600–1,000 mm. One operator can handle four tripods at a time. The process is fairly popular in shipbuilding, where it is used for depositing long and continuous fillet welds. It can be used with equal advantage in other similar structures. In Japan, this process has been successfully used for underwater welding.

Firecracker Welding

This is also a semi-automatic version of MMA welding. A specially designed heavy-coated electrode, which can be of any length up to 2 metres is laid on the seam of a grooved butt joint or along the root of a tee joint. It is then clamped down with a water-cooled copper bar of heavy square section, which is grooved to accommodate the electrode. The copper bar is nearly as long as the electrode. The bare end is clamped in a holder (see Fig. 1.6).

The arc is struck at the striking end, and the electrode gradually consumes by itself, making the butt or fillet weld
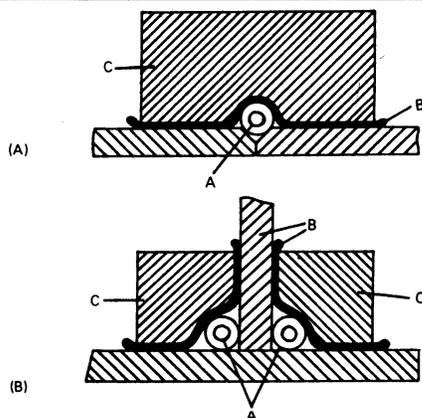
Fig. 1.6: Diagrammatic sketch of firecracker welding

of the same length as the electrode. The copper block helps to prevent overheating of the electrode and to maintain intimate contact between the electrode and the joint.

Auto-Contact Welding

This process combines the principles of gravity welding and firecracker welding. A gravity welding electrode is clamped in the holder of an auto-contact welding device. In this device, a spring actuated by a lever pushes the electrode to the welding line at a low angle (10° to 50°). The device is held against the workpiece by a permanent magnet fixed in the device. The arc is cut off automatically with a stub length of 60 mm by a simple trip mechanism. The process is commonly used in shipbuilding (see Fig. 1.7).

Carbon Arc Welding

In this process, an arc is struck between a non-consumable carbon electrode and the base metal or between two carbon electrodes, using specially designed electrode holders. No shielding is used. Pressure and filler metal may or may not be used. The process has been used for brazing operations. It has almost become obsolete with the introduction of atomic hydrogen welding and TIG (tungsten-inert-gas) welding.

TIG Welding

TIG is an abbreviation for tungsten-inert-gas. The process is also termed as gas-tungsten-arc welding and designated as GTAW.

In this process, an arc is struck between a non-consumable tungsten electrode and the base metal. The arc is shielded by the inert argon or helium or argon-helium mixture (see Fig. 1.8).

A filler wire may or may not be used. When it is used, it is fed externally into the arc in the form of rod or strip
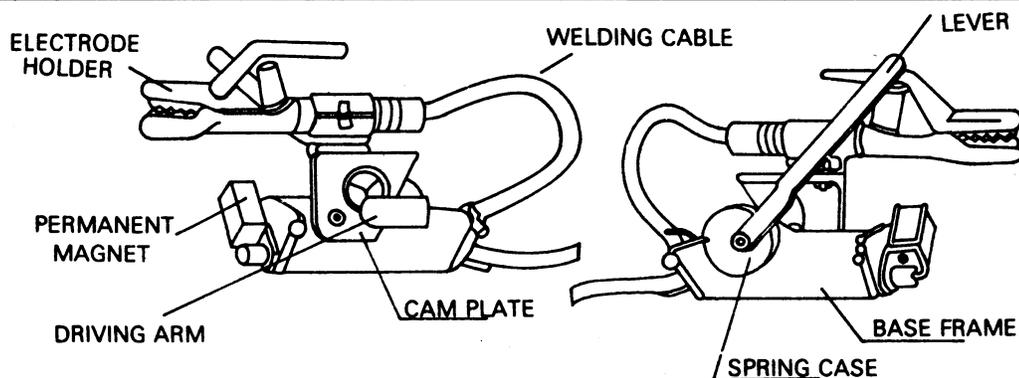
Fig. 1.7: Sketch of auto-contact welding device
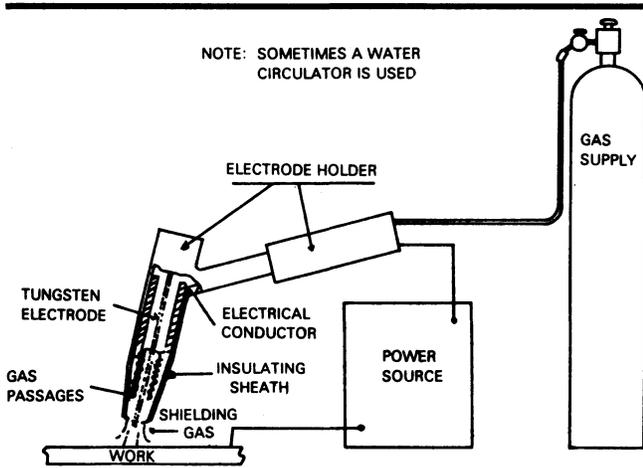
Fig. 1.8: Schematic diagram of TIG welding

by the welder. The welder also has to control the arc length and arc travel speed. An AC power source is used for welding aluminium and its alloys, while a DC source is used for all the other metals. This is an ideal process for welding non-ferrous metals and stainless steels in limited thicknesses. TIG is also preferred for depositing the root pass in the pressure piping, where welding from inside is nonpossible.

The most commonly used gas for TIG welding is argon which can be used on all metals. Helium-argon mixture give deeper penetration, greater heat input and hence faster welding. Pure helium can be used for welding aluminium and copper alloys.

The use of pulsed current greatly extends the control of the process allowing improved consistency, ability to join thick to thin material and low thickness joints without risks of burn through.

Arc Spot Welding

In this process, coalescence at the overlapping surfaces is produced in one spot by heating with an
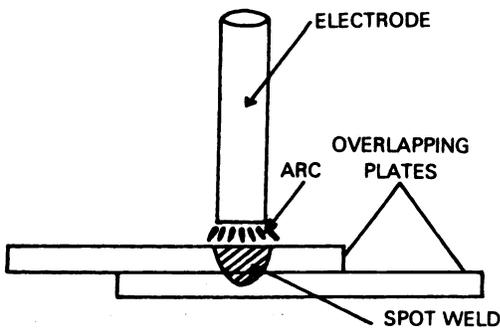
Fig. 1.9: Diagram of arc spot welding

electric arc between an electrode and the work. The weld is made without preparing a hole in either member. Filler metal or a shielding gas or flux may or may not be used (see Fig. 1.9).

The arc is produced by using either of the carbon arc, manual metal arc, TIG and MIG processes. Arc spot welding by the MAG (CO_2) process is widely used today, for which the equipment is provided with the necessary controls to achieve consistent spot welds.

While electric resistance spot welding requires access from both sides of the overlapping plates, arc spot welding can be made from one side only.

Arc Stud Welding

The word arc is often omitted, and the process is simply called stud welding. This is an arc welding process in which the arc is struck between a metal stud or similar part and the base metal. The arc heats the mating ends to a proper temperature after which they are brought together under pressure (see Fig. 1.10).

The process has two versions:
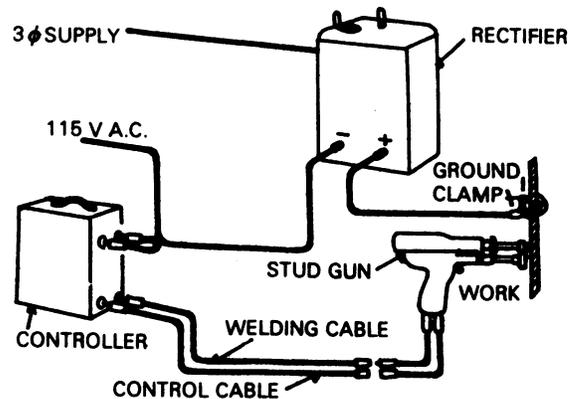
Fig. 1.10: Schematic diagram of arc stud welding

Arc stud welding and capacitor discharge welding

- Arc Stud Welding: In this case, the welding end of the stud is recessed and contains flux which is meant to stabilise the arc and act as a deoxidising agent. The stud, held in a portable pistol-shaped tool called a stud-gun, is positioned by the operator. He then actuates the unit by pressing the trigger switch. The welding time and the final driving home of the stud to complete the weld are controlled automatically by a timing device. A ceramic ferrule is used with each stud. The ferrule concentrates the heat, prevents influx of air to the molten metal and confines the molten metal to the weld zone.

• Capacitor Discharge Welding: In this case, the stud has a small cylindrical tip on its welding end and the arc is produced by a rapid discharge of stored electrical energy with pressure applied during or immediately following the electrical discharge. It employs a specially designed air gun. The gun is equipped with a collect attached to the end of a piston rod which holds the stud. Air pressure keeps the stud away from the plate until the weld is to be made. At the proper time, air pressure drives the stud against the workpiece. As soon as the tip of the stud touches the workpiece, a high-ampere, low-voltage discharge takes place. The current creates an arc which melts the entire face of the stud and a similar area of the work. The stud is then driven at a high velocity into the molten pool.

Atomic Hydrogen Welding

In this process, an arc is struck between two tungsten electrodes using AC. Streams of hydrogen gas are passed from orifices around the electrodes into the arc. Here the molecules of hydrogen dissociate into atoms with the absorption of heat from the arc. The atoms recombine into molecules at a point a few millimetres away from the arc and liberate intense heat. It is this point which is used for melting the base metal (see Fig. 1.11).

Thus, in this process, the source of heat is not the arc but the hydrogen gas acting as the carrier of heat. Filler metal may be added externally if required.

Since hydrogen is present in the arc, this process can cause hydrogen-induced cracking in hardenable steels and in heavy, restrained joints in normal steels, and porosity in high-sulphur, free-machining steels. Hence, it has been largely replaced by the TIG process.
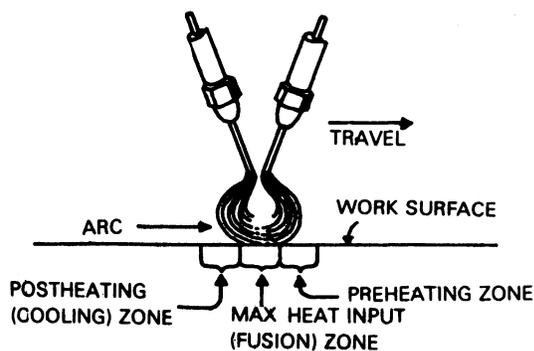
Fig. 1.11: Diagrammatic sketch of atomic hydrogen welding

Electrogas Welding

Electrogas welding is an extension of the MIG/CO_2 process and is designed for single-pass vertical welding of steel plates in the thickness range of 10–38 mm. The joining operation consists of lining up two square butt edges with a 12.5 mm gap, regardless of plate thickness. The wire electrode is introduced downward into the cavity formed by the two plates to be joined and two fixed water-cooled dams or chill blocks. The cavity is kept free of air by the shielding gas, which usually is a mixture of argon and carbon dioxide. Wire diameter may be 1.6, 2 or 2.4 mm, depending on the thickness of the plate.

The welding head is suspended from an elevator mechanism, which provides automatic control of the vertical travel speed during welding. This mechanism raises the welding head automatically at the same rate as the advancing weld metal. The welding head is self-aligning and can adjust to any misalignment in plate or joint. Once the equipment is positioned on the joint, welding is completely automatic. Wire feed and current are constant. At the end of the weld the process stops automatically (see Fig. 1.12).

This welding technique is increasingly used in shipyards and in the fabrication of storage tanks and large diameter pipes.

Plasma Arc and Micro-Plasma Arc Welding

This has been dealt with later under Plasma Processes.

Gas Welding

In this process, the melting of the base metal is achieved by means of a gas flame which derives its intense heat from the combustion of a fuel with oxygen. The most commonly used fuel is acetylene, though Mapp gas (stabilised methylacetylene propadiene) and hydrogen are sometimes used. Hence the appropriate term of this process is oxyfuel or oxyacetylene welding. Filler metal may or may not be used (see Fig. 1.13).

The oxyacetylene process depends on the chemical reaction which occurs in two stages.

Primary stage:

$$C_2H_2 + O_2 = 2\,CO + H_2$$

acetylene   oxygen   carbon   hydrogen
                          monoxide
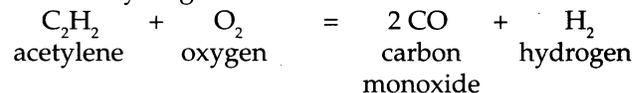
The primary combustion provides the actual flame for welding, with temperature up to 3,092° C, which is in the inner cone.
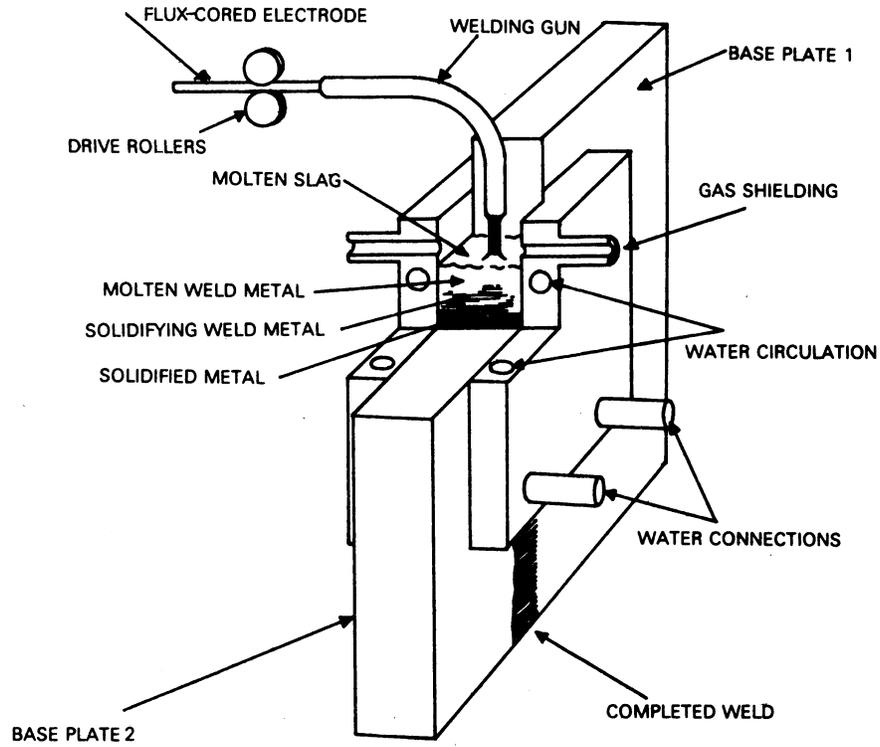
Fig. 1.12: Diagrammatic sketch of electrogas welding
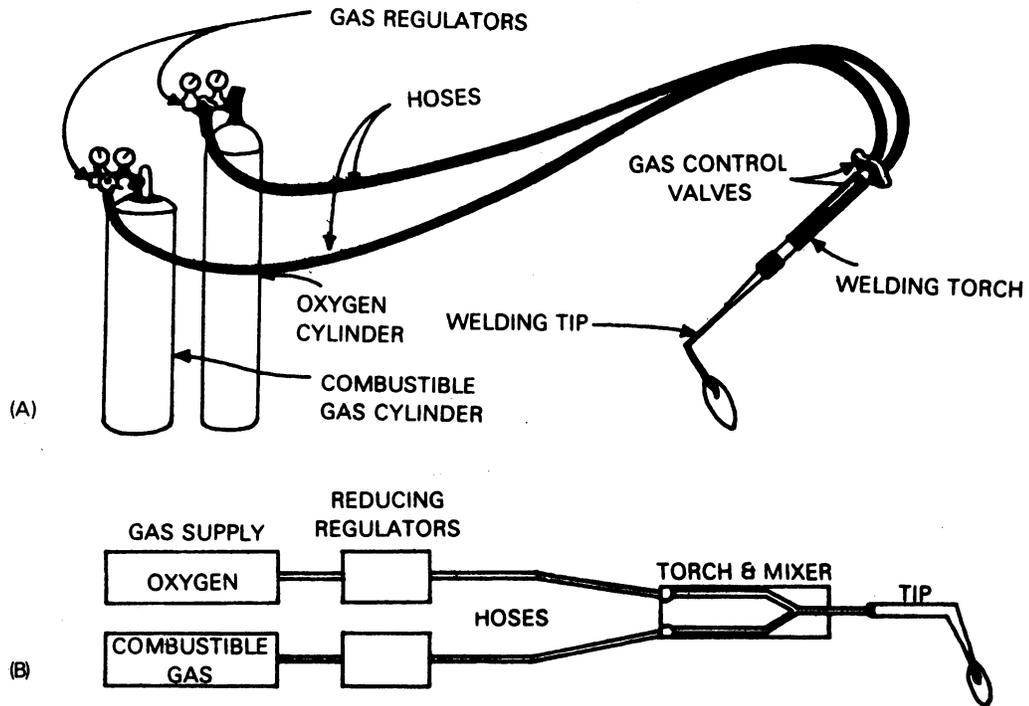
Fig. 1.13: Oxyfuel welding: (A) Schematic diagram of the process; (B) Sketch of the welding torch

Secondary stage:

$$2\,CO + H_2 + 1\tfrac{1}{2}\,O_2 = 2\,CO_2 + H_2O$$

| carbon monoxide | hydrogen | oxygen from air | carbon dioxide | water vapour |
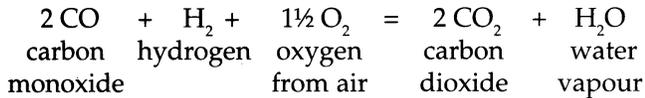
This secondary combustion occurs at the outer portion of the flame. It protects the molten puddle from attack by air and helps to preheat the base metal.

Equipment for oxyacetylene welding consists of oxygen and acetylene cylinders, pressure regulators which reduce the high cylinder gas pressure to the required working pressure, a torch where the two gases are mixed, and hoses which connect the regulators to the torch.

Gas welding has limited application for industrial production purposes, because it is much slower than arc welding processes. It is used considerably more for general maintenance work including hardfacing, welding metals of low melting points (especially non-ferrous metals) and performing such operations as brazing, soldering, and thermal spraying.

Thermit Welding

This process utilises the intense heat developed during the reaction between iron oxide and aluminium. When a mixture of three parts of iron oxide and one

part of aluminium by weight is locally heated with a special ignition powder, a vigorous reaction takes place which proceeds rapidly through the mass, resulting in the formation of aluminium oxide and iron, and a considerable amount of heat. The heat is sufficient to melt the iron and the oxide slag.

In carrying out a thermit welding operation, the thermit mixture is placed in a refractory crucible above the pieces to be welded. In practice, additional metals and compounds are often placed in the thermit mixture to alloy the iron and improve its properties. The molten metal from the thermit reaction in the refractory crucible is guided to the joint to be welded by a sand mould, which is fastened around the work. By virtue of its superheat, the thermit metal melts a portion of the base metal with which it comes in contact. Upon solidification of this melt, the weld is completed (see Fig. 1.14).

The process is commonly used for welding the rails of railway tracks. It is also sometimes used to repair heavy broken parts such as steel mill rolls.

Electron Beam Welding

In this process, fusion is achieved by focusing a high power density beam of electrons on the area to be joined. Upon striking the metal, the kinetic energy of the high velocity electrons changes to thermal energy, causing
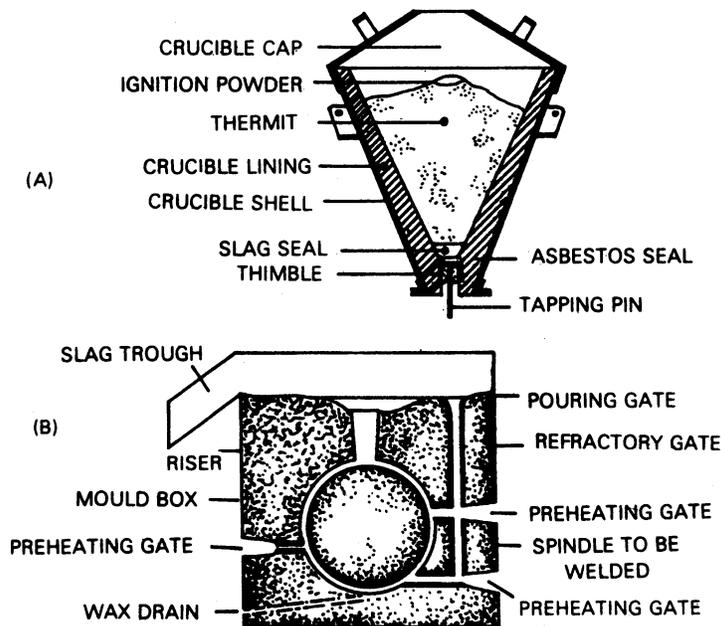
Fig. 1.14: Diagrammatic sketch of thermit welding : (A) Refractory cubicle in which thermit reaction occurs; (B) Sand mould containing the joint

the metal to melt and fuse. The electrons are emitted from a tungsten filament heated to approximately 2,000°C. Since the filament would quickly oxidise at this temperature if exposed to normal atmosphere, the unit as well as the focusing devices and workpiece are placed in a vacuum (see Fig. 1.15).

The major advantages of electron beam welding are:

- Its ability to produce deeper and narrower welds with total heat input which is much lower than in arc welding

- Good control over weld penetration and other weld dimensions

- High-purity welds free from oxides and nitrides, and

- Very high welding speeds and production rates.

Electron beam welding can join materials ranging from thin foils to sheets of 50 mm thickness. It is particularly suited for the welding of refractory metals such as tungsten, molybdenum, columbium, tantalum, and metals which oxidise readily, such as titanium, beryllium and zirconium. It also has wide application in joining dissimilar metals, aluminium, standard steels and ceramics.

An electron beam welder is very expensive, but its use is justified for critical applications such as bimetallic blades for metal-cutting saws, aircraft engine components and supercharger impellers for diesel engines.

Lately, non-vacuum electron beam welders have been developed, which give higher production rates at lower costs, because no vacuum chamber is needed for
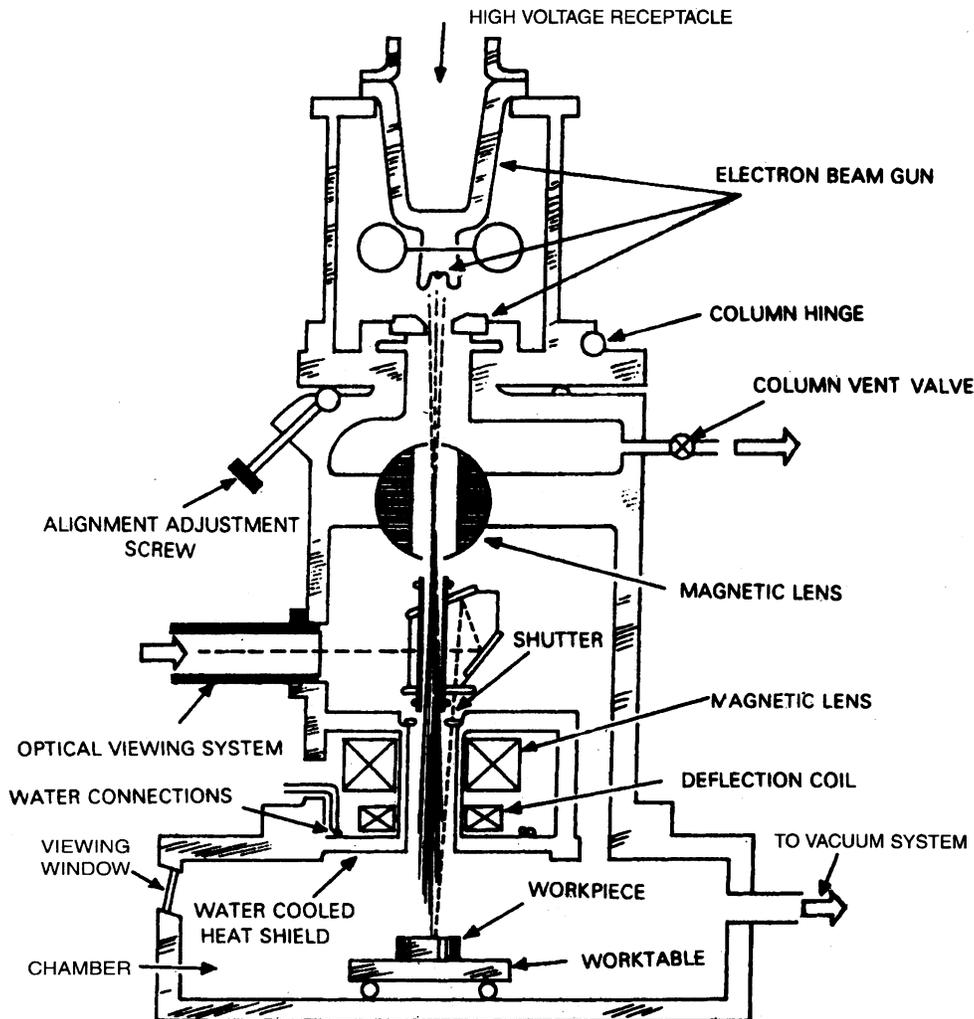
Fig. 1.15: Schematic diagram of electron beam welding

the work and no time is lost in pumping down for each load. Also work size is not limited by chamber dimensions. The non-vacuum technique, however, gives reduced penetration and the welds are not as narrow and non-tapering as those made in a vacuum.

Electroslag Welding

This process, which is similar to the electrogas process described earlier, is primarily designed for making a butt weld in the vertical position in one single pass, regardless of the plate thickness which can range between 12.5 and 500 mm. The welding heat is provided by a small quantity of flux which is converted into a conductive molten slag by its resistance to the electric current passing between the continuously fed wire or wires (one wire for thickness up to 100 mm, two wires up to 230 mm and three wires up to 500 mm) and the parent plates. The hot molten slag melts the filler wire and the joint surfaces, and also shields the weld pool which moves upward along the full cross-section of the joint as welding progresses. There is no arc, and hence the welding action is quiet and spatter-free.

A pair of water-cooled copper shoes fitted on each side of the joint retains the molten metal and slag pool and acts as a mould to cool and shape the weld surfaces. The copper shoes automatically slide upward as welding progresses (see Fig. 1.16).

The weld metal usually consists entirely of coarse or fine columnar dendrites, or of two zones: one zone of coarse columnar dendrites and the other of fine columnar dendrites. Electroslag joints made correctly in structural steel applications do not need postheating. On the other hand, joints in pressure vessels which must have optimum notch toughness, require a normalising treatment to refine and reorient the grains.

With variations in technique, this process can be applied to T-joints, corner joints, girth seams in heavy-wall cylinders, and so forth.

Consumable Guide Method

This is a modified version of the electroslag process. In this method, there is no need for the copper shoes, wire-feeding mechanism and associated equipment to move upward during welding. It uses simply a metal tube extending the full-length of the weld joint to guide the welding wire to the welding zone. The copper moulds also are full-length. These moulds and all wire-feeding equipment remain stationary, with the wire being the only moving part. The guide tube melts in the weld pool as the pool rises and adds itself to the weld metal (see Fig. 1.17).

The consumable guide is generally provided with a flux coating on the outside to:

- Insulate it electrically from the base plate, and
- To maintain the level of the slag pool till the end.

Fig. 1.16: Diagrammatic sketch of electroslag welding
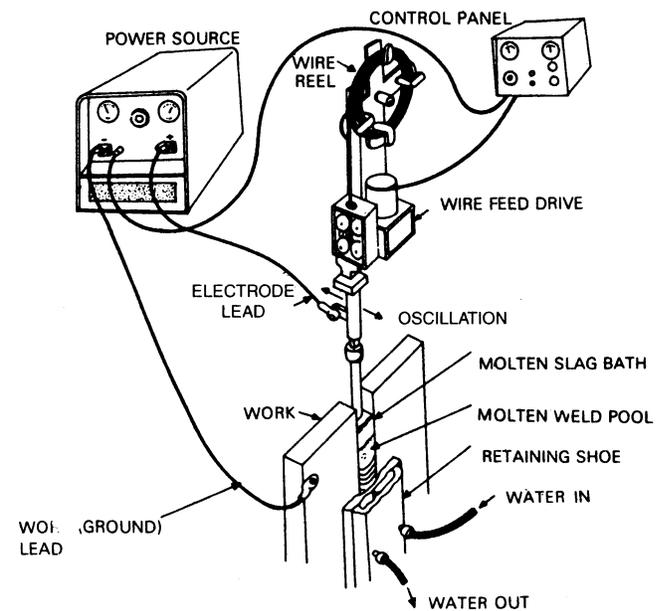
Fig. 1.17: Schematic diagram of electroslag consumable guide method

Laser Welding

In this process, fusion is achieved by directing a highly concentrated beam to a spot about the diameter of a human hair. The word laser is an abbreviation of light amplification by stimulated emission of radiation. A laser beam has a higher energy concentration than even an electron beam. Since the heat input to the workpiece is extremely small, the size of the heat affected zone and the thermal damage to the adjacent parts of the weld are negligible.

Laser can be used to join dissimilar metals and other difficult-to-weld metals such as copper, nickel, tungsten, aluminium, stainless steel, titanium and columbium. The current application of laser welding is largely in aerospace and electronic industries, where extreme control in weldments is required. Its major limitation is the shallow penetration (less than 1 mm).

The technique of projecting a laser beam is interesting (see Fig. 1.18). An intense green light is thrown on a special man-made ruby, 10 mm in diameter, containing about 0.05%, by weight, of chromium oxide. The green light pumps the chromium atoms to a higher state of energy. Each of these excited atoms emits red light and thereby excites neighbouring atoms which also give off red light which is in phase with the collided red light wave.

In other words, the red light gets continuously amplified. To further enhance this effect, the parallel ends of the rod are mirrored to bounce the red light back and forth within the rod. When a certain critical intensity of pumping is reached (the so-called threshold energy), the chain reaction collisions become numerous enough to cause a burst of red light. The mirror at the front end of the rod is only a partial reflector, allowing the burst of light to escape through it.

ELECTRIC RESISTANCE WELDING PROCESSES

In describing this group of processes, the word electric is usually omitted and simply the term resistance welding is used. In these processes, the coalescence is
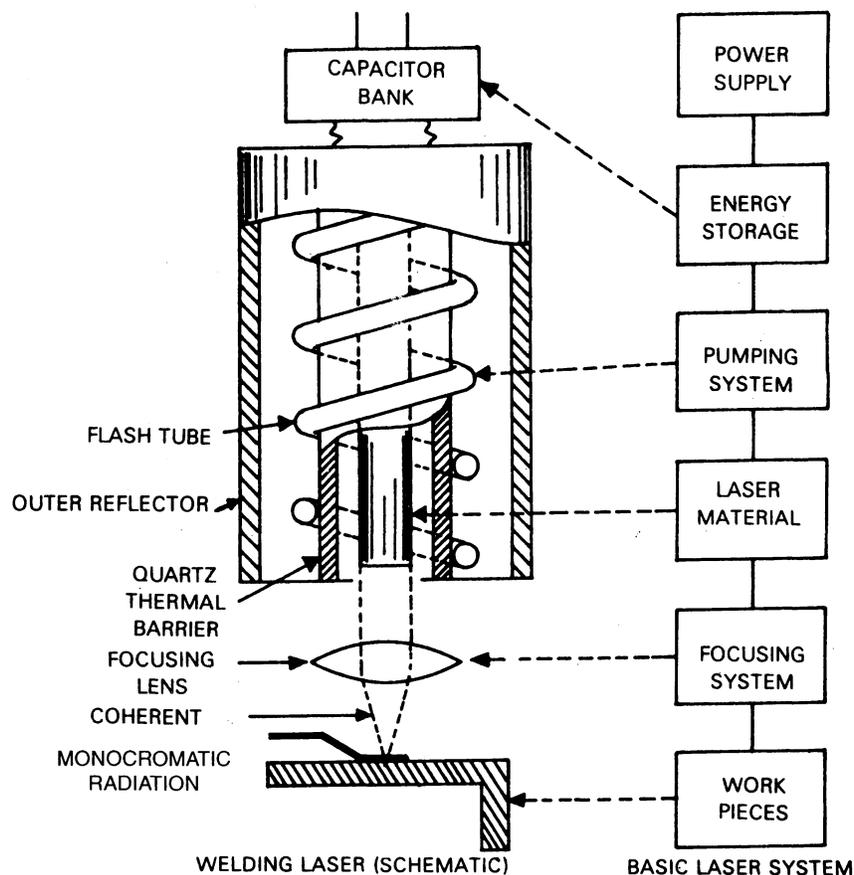
Fig. 1.18: Schematic diagram of laser welding

achieved by passing electric current through the metallic parts by inserting them into a circuit. The electric resistance produces heat at the junction of the parts. Finally, pressure is applied.

In the process chart (Table 1.1), resistance welding processes have been placed between fusion and solid phase processes, because it is difficult to decide whether they are fusion processes or solid state processes as evident from the following examples:

- Resistance butt welding is a solid state process in which melting of the joint is totally avoided by controlling the parameters.
- Spot, seam and projection welding are also solid state processes, except for a small molten nugget which is formed in the weld. The size of the nugget is kept as small as possible.
- In flash, percussion and high frequency welding, the surfaces to be joined do get fused, but the fusion zone is controlled to an extremely narrow zone, almost to 0.005 mm. If the fusion is not restricted, molten metal will fly off under pressure and the weld will not take place.

Resistance Butt Welding

This process is also known as upset welding or simply butt welding. Here, the temperature of the joint is raised by the resistance to the passage of an electric current across the interface of the joint. The parts to be joined (usually wires and rods) are held in clamps, one stationary and the other movable, which act as conductors for the low-voltage electric supply and also apply force (see Fig. 1.19).

This force or pressure is applied only after the abutting surfaces have reached a temperature slightly below the melting point, which results in the upsetting of the metal. Uniform and accurately mating surfaces are desirable to exclude air and give uniform heating. The process is commonly used during rod rolling and wire drawing operations to join the ends.
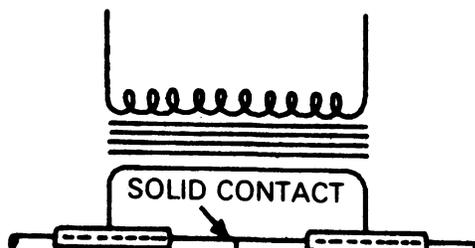
Fig. 1.19: Sketch of resistance butt welding

Flash Butt Welding

This process is an extension of resistance butt welding. The parts to be joined are gripped in the clamps, and their interfaces are gradually brought into contact to complete the secondary circuit. When the welding voltage of up to about 10 is applied at the clamps, current flows through the initial points of contact causing them to melt. These molten bridges are then ruptured and small short-lived arcs are formed.

The platen on which the movable clamp is mounted is moving forward while this takes place, and fresh contacts are then made elsewhere so that the cycle of events can be repeated. This intermittent process, during which much of the metal contained in the molten bridges is expelled violently in a spectacular manner, is called flashing.

Flashing is allowed to continue until the surfaces to be joined are uniformly heated or molten. By this time the moving platen will have advanced, at an increasing rate, to close the gap as metal is expelled, the total distance up to the point of upset being known as the flashing allowance. At this point the rate of movement of the platen is rapidly increased and a high force applied to forge the parts together and expel the molten metal on the surfaces (see Fig. 1.20).

Typical applications of this process are: rails, steel strips, window frames and automobile rear axle casings. Special purpose machines are designed for each of these applications.

Spot Welding

In this process, a spot of weld is made between overlapping sheets by means of two cylindrical copper-alloy electrodes, one on top and the other at the bottom, which carry a high current. The electrodes also clamp the work and apply pressure when the metal at the joint gets sufficiently heated by electrical resistance (see Fig. 1.21).

A tiny button of fused metal results at the sheet interface which is called the nugget. The electrodes are retracted after the weld is complete. Spot welding is always performed with a machine in which all the parameters can be controlled. The process is used on a large scale in automotive production, and in sheet-metal fabrication.

Stitch Welding

This is an extension of spot welding, in which a series of overlapping spot welds are made in the same manner as stitching cloth. Stitch welding may be performed with a normal spot welding machine or with a specially designed one, which automatically makes spot welds in a continuous series.
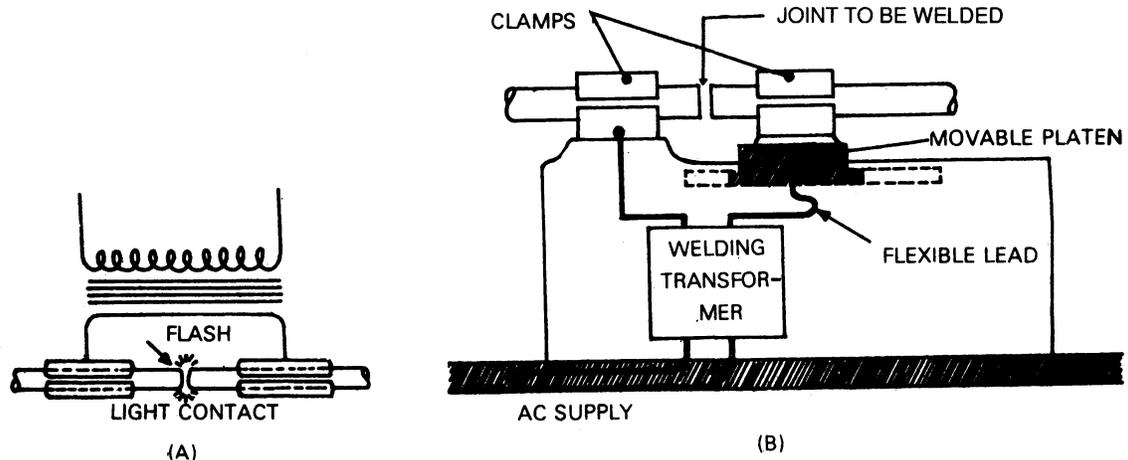
Fig. 1.20: Flash butt welding: (A) Sketch of joint set-up; (B) Schematic diagram of equipment
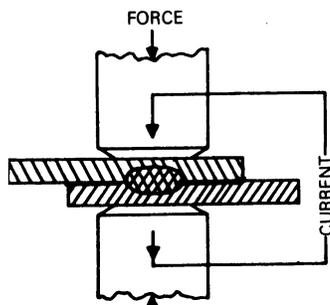

Fig. 1.21: Sketch of spot welding

Multiple Spot Welding

This is a modification of spot welding, in which two or more welds can be obtained from each transformer secondary. Four typical types are shown in Fig. 1.22.

Series Spot Welding

In series welding (see Fig. 1.22A), a portion of the secondary current bypasses (shunts) any weld nugget being formed. This shunt current passes through one of the panels being welded. Generally, two welds are made per transformer secondary.
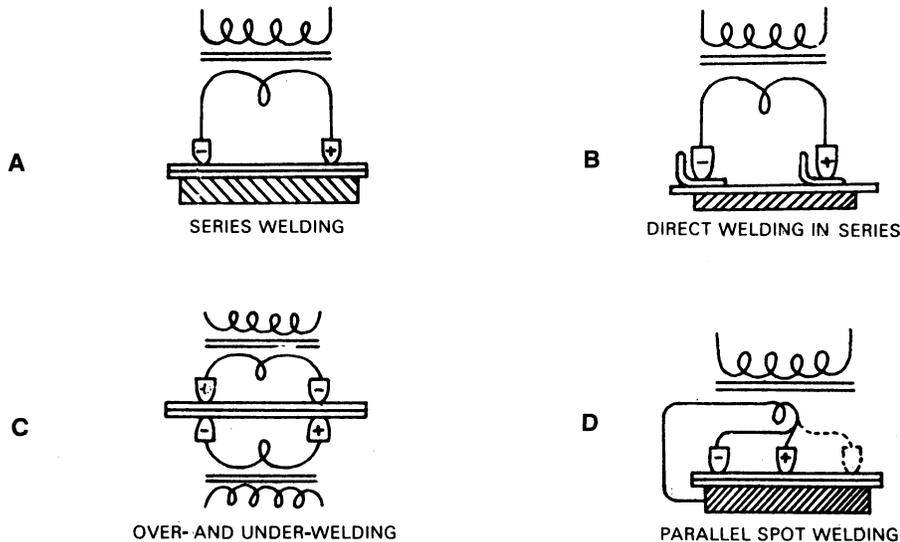
Fig. 1.22: Sketches showing four methods of multiple spot welding

Roller Spot Welding

In this process, a series of intermittent spot welds are made using wheels or rollers as electrodes. The rollers are power driven and are stopped while individual welds are made. Current is passed intermittently when the electrodes are stationary (see Fig. 1.23).

Seam Welding

Seam welding is similar to spot welding, except that the copper-alloy electrodes are in the form of circular rollers. The overlapping sheets are held under constant pressure between the roller electrodes, which rotate at constant speed and carry current (see Fig. 1.24).

A series of spot welds, whose nuggets overlap each other, are formed which give the appearance of a continuous weld seam. A common application of seam welding is in the manufacture of steel drums.

Butt Seam Welding

This is similar to seam welding, except that the sheets to be joined are in the same plane instead of being overlapped.
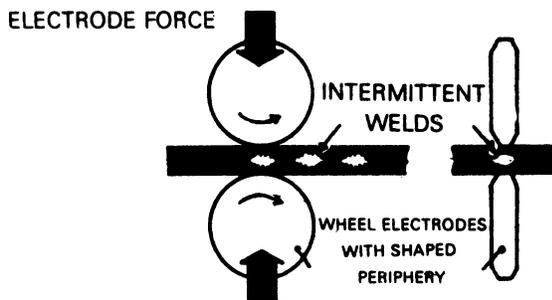
Fig. 1.23: Sketch of roller spot welding
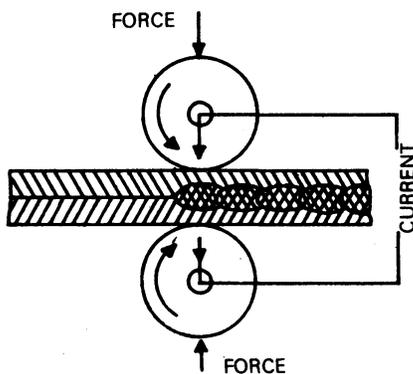
Fig. 1.24: Sketch of seam welding

The joint edges are in intimate contact and the roller electrodes travel directly over the seam. Figure 1.25 shows the process being used in the production of welded tubes.

Foil Butt Seam Welding

This is a modification of seam welding, in which thin narrow strips of metal are introduced between one or both of the circular electrodes and the workpiece. The joint edges are held in the same plane instead of being overlapped. The strips help to localise the melting and to avoid reduction of section thickness at the joint (see Fig. 1.26).

The process is being used successfully on the shells of railcoaches.

Projection Welding

This is a modified method of making single or multiple spot welds. Projection welds are made by providing an embossment or projection on one or both of the contacting base metal surfaces to localise the pre-ssure and current flow at a particular point (see Fig. 1.27).

This reduces the amount of current and pressure required to produce a spot weld between two pieces of metal. Other advantages would include:

- Maintaining proper heat balance between two workpieces of markedly different mass
- Better control of size and shape of fused area
- Making of multiple welds simultaneously between a single set of electrodes or contact platens and
- Forming of welds from one side of the assembly by series welding two separated projections, provided adequate pressure can be applied.

Percussion Welding

Percussion (or percussive) welding is unique and of considerable interest, because butt welds can be made with incredible speed, in almost any combination of dissimilar materials and without the expulsion of a fin or flash around the joint.

The pieces to be joined are held a short distance apart in clamping dies which carry current and apply pressure. The ends to be welded are prepared for accurate mating. An extremely heavy electric current is delivered (electrical energy from discharging condensers or capacitors) to the pieces as a very short impulse, perhaps for only 0.001 second, and flows across the gap between the pieces as an arc. The heat of this high-energy arc produces superficial melting over the entire end surfaces of the bars. An instant after the arc has struck,
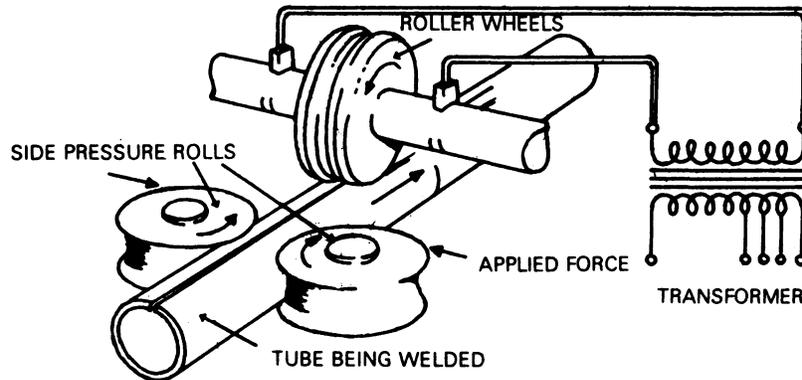
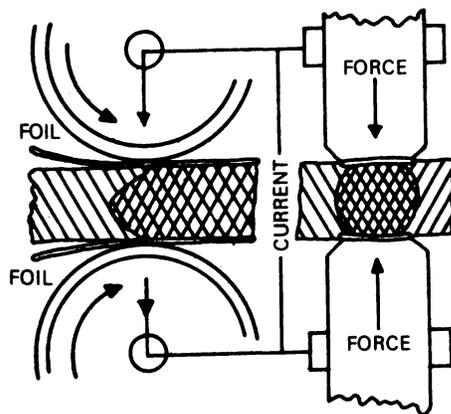**Fig. 1.25: Diagrammatic sketch of butt seam welding**

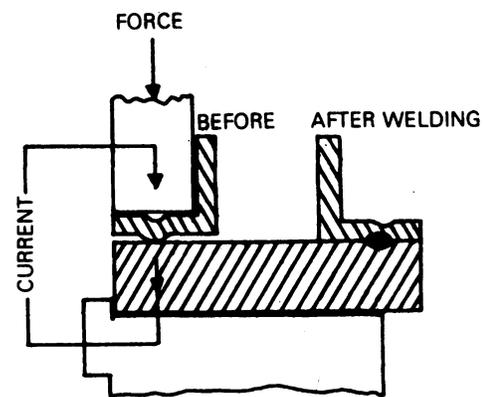**Fig. 1.26: Sketch of foil butt seam welding**

Fig. 1.27: Sketch of projection welding

the pieces are brought together with an impact blow (hence the term percussion) to complete the weld (see Fig. 1.28).

High Frequency Resistance Welding

This process is mainly used in the upset butt welding of tubes as a continuous process. The tube formed out of a continuous strip passes under the electrodes, which transfer the high frequency welding current (alternating currents ranging from 200 to 4,50,000 cycles) into the material being welded and through a set of rolls, which provides the welding force (see Fig. 1.29).

The amount of upset is regulated by the relative position of the welding electrodes and the rolls applying the upset force. The required welding heat is governed by the current passing through the work and the speed at which the tube goes through the rolls.

SOLID PHASE WELDING

This is a group of processes in which coalescence is produced essentially below the melting point of the base metals being joined, without the addition of brazing filler metal. In some of them pressure is used. With the exception of cold welding and ultrasonic welding, all the processes involve heat.

Forge Welding

This is the age-old process used by the village blacksmith. It consists of heating the surfaces to be joined (may be on a charcoal fire or any other handy source of heat), placing these surfaces in contact, and hammering them together to form a weld. The surfaces are heated below the melting point, so that they are in a plastic state. The oxidising flame of the fire produces a liquid film of iron oxide on the surface, which is squeezed out more or
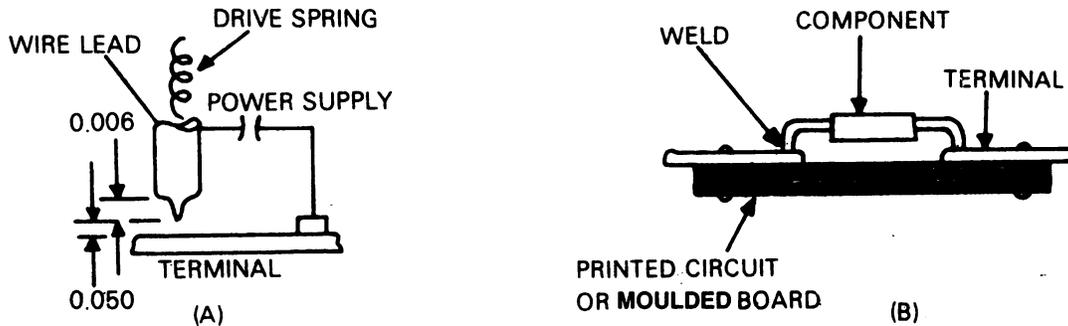
Fig. 1.28: Diagrammatic sketch of percussion welding:
(A) Wire end for capacitor discharge; (B) Percussion welded assembly
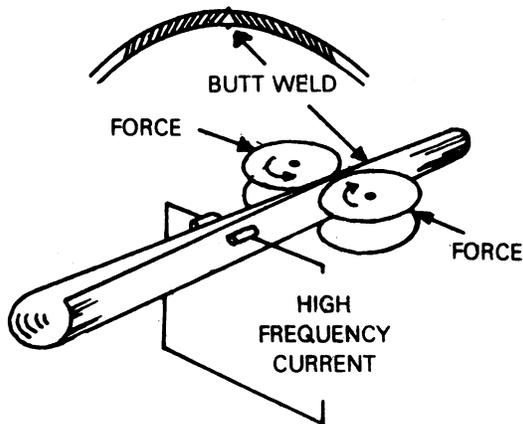
Fig. 1.29: Sketch of high frequency resistance welding

less completely when the solid surfaces are hammered together.

The historic Iron Pillar in Delhi consists of several ingots of pure iron forge-welded together.

Hammer Welding / Die Welding / Roll Welding

These are the refined variations of forge welding.

Hammer welding is a semi-automatic or automatic process in which a heavy hammer is powered by steam, hydraulic or pneumatic equipment and the hammer blows are applied at low velocity to forge the weld.

In die welding, the parts are heated in a furnace and the pressure is applied by means of dies. The dies also form the work while it is hot.

In roll welding, the pressure is applied on heated parts by means of rollers. Roll welding is used mostly for the manufacture of clad steel plates and sheets. First, an assembly of the steel plate and the cladding material such as nickel or stainless steel is formed.

The assembly or sandwich is then welded at the periphery to exclude air as well as to hold the parts together during rolling. In rolling, the high temperature and working create a solid-phase weld between the steel and cladding metal.

Production of clad plate by hot rolling a pack or sandwich is an example of roller forge welding.

Gas Pressure Welding

This is another modern adaptation of forge welding, in which the joint, held in compression, is locally heated by oxy-acetylene flames to a temperature somewhere below the melting point. When the joint is held for a sufficient length of time at this temperature under pressure, welding takes place.

This process has been successfully adapted for the welding of rail ends.

High Frequency Pressure Welding

This process differs from high-frequency resistance welding described earlier. The difference is that instead of direct contact being made with the work, the current is induced in the surface layer by a coil wrapped round the workpiece. This causes heating. When a suitable temperature is reached, the weld is consolidated by a forging action of the joint (see Fig. 1.30).

The process is also referred to as high-frequency induction welding. It is used in the manufacture of tubes.

Magnetic Pulse Welding (MPW)

This is basically a solid state welding process, still in its infancy, in which bonding is produced by an oblique, high velocity collision between the two bodies to be
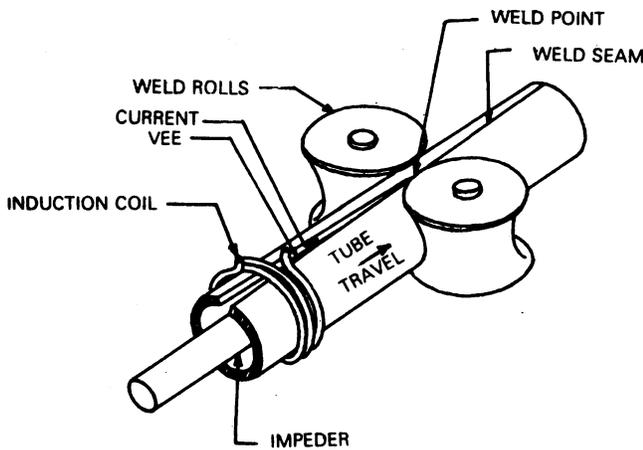
Fig. 1.30: Sketch of high-frequency pressure welding

welded. The principle of magnetic repulsion effect is utilised in this process.

A wide range of tubular materials have been joined using MPW technology. Dissimilar metals like steel to copper, steel to aluminium, copper to aluminium etc. can be joined using no filler metal or gases. Fig. 1.31 illustrates the basic principle of the process.

Cold Welding

In this process, welding is obtained at room temperature solely by the application of pressure across the interface. The contact surfaces have to be specially prepared by degreasing, scratch brushing and other operations. The joints are either lap or butt. For making lap joints, indenting dies may be forced into the metal causing deformation and flow to provide the extension of the interface. The butt method is used for joining wires, tubes and bar stock, the parts being gripped in dies and forced together to cause lateral flow.
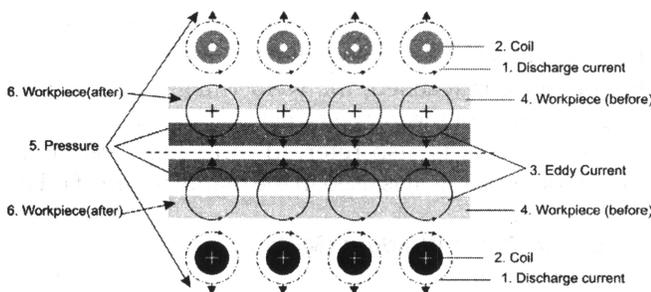
Fig. 1.31: Sketch of magnetic pulse welding

Cold welding is generally done on ductile metals like copper and aluminium.

Diffusion Bonding

In this process, union between specially prepared mating surfaces takes place as a result of diffusion, which occurs due to high temperature and pressure exerted for a sufficiently long time. The pressure is low enough to ensure that there is no plastic flow or deformation. The extended time of several minutes at elevated temperatures (which will cause oxidation) requires that the joint is made in protective atmosphere or vacuum. Sometimes thin inserts are placed between the mating surfaces to speed up diffusion and ensure strong welds.

Explosive Welding

In this process, two pieces of metal are impacted together at an extremely high velocity of impact achieved by the detonation of an explosive charge. The result is a solid-state weld completed in microseconds without any noticeable deformation (see Fig. 1.32).
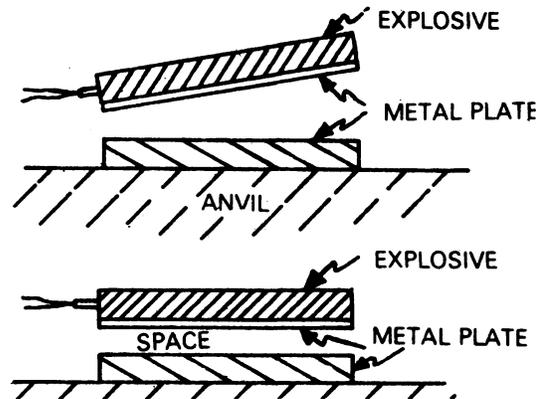
Fig. 1.32: Sketches of explosive welding

The process has been used to prepare clad plates involving dissimilar metals, and in welding tubes to tube-plates in heat exchangers.

Friction Welding

In this process, friction is employed to generate heat between two sliding or rotating metal surfaces. The process is usually carried out by placing the pieces to be welded in chucks on a common horizontal axis. One part is rotated while the other remains stationary. Pressure is applied to generate enough heat to reach a bonding temperature within a few seconds. At this point, rotation is stopped very quickly and pressure is maintained or increased until welding is complete (see Fig. 1.33).
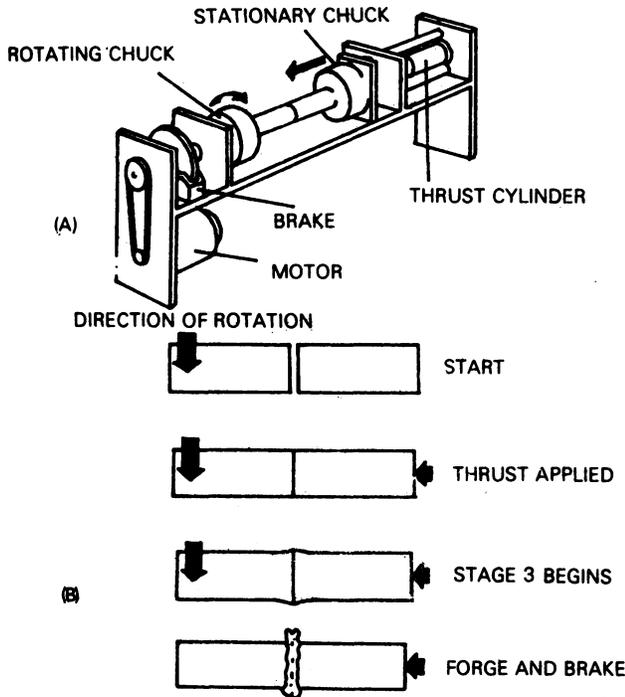
Fig. 1.33: Diagrammatic sketches of friction welding:
(A) Main components of the equipment;
(B) Stages of weld formation

To accommodate awkward or unusually long sections, an intermediate slug or disk can be rotated between the sections to be joined.

In applying the process, one uses a specially designed machine called the friction welder. It helps one to produce consistently high quality joints, each within a few seconds, in various similar and dissimilar metal combinations.

Friction Stir Welding

Friction Stir Welding (FSW) uses a new solid phase welding technique which has been developed in the 90's primarily for joining aluminium alloys. FSW is a derivative of conventional friction welding enabling the advantages of solid phase welding to be applied to the fabrication of long butt and lap joints, with very little post-weld distortion. The concept of FSW is shown in Fig. 1.34

Ultrasonic Welding

Ultrasonic welding is a solid-state process for joining similar or dissimilar metals by application of high-
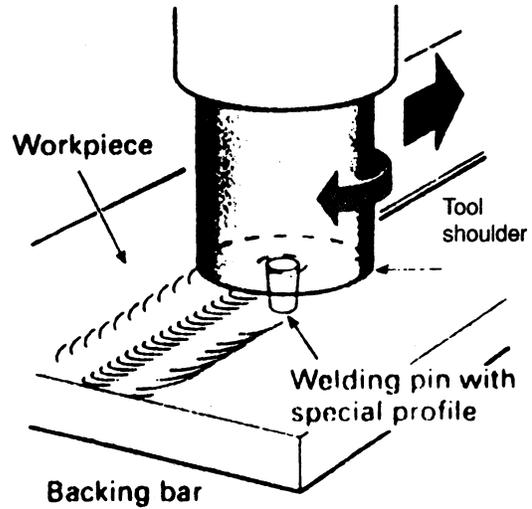
Fig. 1.34: The friction stir welding concept

frequency vibratory energy to workpieces held together under moderate static pressure (see Fig. 1.35).

The process has proved to be an economical substitute for resistance welding of electrical conductors: it welds faster, uses less power, and usually requires lower capital investment.

The vibrations break up and disperse oxides, surface films, and some types of insulation at the joint surface to permit bare metal contact. Inter-atomic diffusion occurs across the facing surfaces and results in a metallurgical bond without application of heat. The joints so produced possess electrical resistance and mechanical strength almost equal to that of the parent materials.

The equipment consists of a frequency converter which changes 60-cycle line power to the high frequency (15 to 60 kHz) required by the ultrasonic head. The head incorporates a piezoelectric transducer, which converts the high frequency electrical output into vibratory mechanical motion, and waveguides which transmit the vibratory waves to the tools and into the weldment. Static clamping force is applied to the head by a pneumatic or hydraulic cylinder. High production operations use a high-speed cam-operated anvil to position the work.

The process has been successfully used in the electrical equipment production in the U.S.A. Typical applications include:

• Almost all commonly used armatures. On tang type armatures, the tang is bent and welded during the ultrasonic cycle. Vibratory energy im-
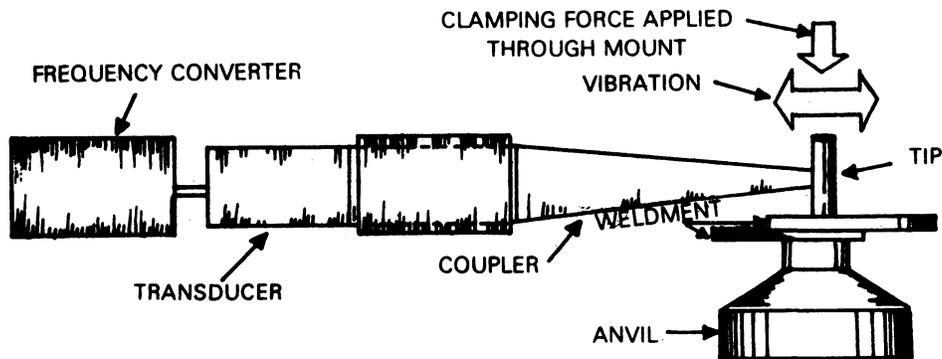
Fig. 1.35: Diagrammatic sketch of ultrasonic welding

parted to the wire scrubs away the insulation and makes a tack weld between tang and commutator and between wire and tang

- Slotted commutators
- Starter motor armatures
- Commutator armatures for motors of electric door locks and windshield wiper-washers
- Field coils, field coil assembly, wire harness systems, wire terminal connections, and induction coils
- Joining of braided brush wire to brush plate
- A wide variety of wire terminals

BRAZEWELDING

This process is similar to brazing which is described below, except that the molten filler metal is not distributed in the joint by capillary action. It gets filled up in a groove or gets piled up as a fillet weld. In other words, brazewelding is similar to normal welding, but the filler metal used has melting point above 450°C but below the melting point of the base metal.

A typical example of this process is what is popularly called bronze welding, used for making joints in mild steel and cast iron. The filler rod is a special copper alloy which melts at approximately 800°C. It is used in combination with flux. The filler rod is melted with an oxyfuel flame. The molten metal fills the V-groove in a butt joint or piles up as a fillet weld and makes a joint without causing the base metal to melt.

Brazing

In brazing, the coalescence between metallic parts is obtained by

(a) heating them to a suitable temperature,
(b) using a filler metal with melting point above

450°C but below the melting point of the base metal, and

(c) heating the filler metal till it melts and gets distributed between the closely fitted surfaces by capillary attraction.

Like welding, brazing is used in the fabrication of a variety of metallic products ranging from tea kettles and bicycle parts to heat exchangers and aerospace structures. In recent years, hundreds of new constructional alloys have been developed, and at the same time new brazing filler metals have been perfected to join them. Today thousands of tonnes of carbon steel components brazed with copper alloy filler metals are produced annually by the fabrication industry.

Brazing is being used for the production of large foil heat exchangers, automobile radiators, turbojet engine components, and many such critical items.

The range of materials which can be successfully brazed is very wide and includes beryllium, titanium, superalloys, refractory metals, dispersion strengthened metals, all-metal composites, dissimilar metals and special ceramic-to-metal combinations.

Resistance Brazing

In this process, the heat is provided by the resistance of the parts to the flow of low-voltage, high-current power supplied from a suitable transformer and from the heat conduction from the high resistance facing materials on the contacting electrodes. The electrodes are usually of carbon, molybdenum, tungsten or steel. This process is extensively used when small areas are to be brazed and when the material has high electrical conductivity.

Dip Brazing

In this case, the heat is provided by a molten chemical bath or molten metal bath. In the former, the bath may

act as a flux. In the latter, the bath provides the filler metal.

The parts to be brazed are first cleaned. Filler metal inserts are pre-placed in the joints in the case of flux bath brazing. In the case of metal bath brazing, the parts and joint surfaces are protected with flux. They are then assembled in a fixture which is usually of stainless steel. Next, they are preheated to a suitable temperature in a furnace and finally introduced into the molten bath.

Flame Brazing

This is the most common process which uses the standard oxyacetylene flame and equipment.

Furnace Brazing

Here the parts are assembled in a jig, filler metal is pre-placed in the joints, flux is also applied at the joints, and the entire assembly is heated in an electric or gas/oil heated furnace where the temperature can be controlled within ±5°C. Sometimes a special atmosphere is used in the furnace instead of the flux.

Vacuum is used for special stainless steels, superalloys, Ti alloys, etc.

Induction Brazing

In this case, heat is obtained from the resistance of the work to induced electric current. Parts to be heated act as the short-circuited secondary of a transformer, where the work coil, which is connected to the generator is the primary. The heating results from the resistance of the parts to the currents induced in the parts themselves by the transformer action. High frequencies are usually used, the most common being 10,000 Hz obtained from a motor-generator set.

Salt Bath Brazing

This is similar to molten flux bath dip brazing described earlier. Here a salt of suitable melting point is used instead of the flux.

Diffusion Brazing

Here the parts to be joined are heated to a suitable temperature, and braze filler metal is introduced between the contacting surfaces by preplacing or by capillary action. Sometimes a liquid phase develops *in situ* at the contacting surfaces, which acts like a filler metal. The filler metal or this liquid phase gets *diffused* with the base metal, with the result that the joint properties are changed to approach those of the base metal.

MIG Brazing

Conventional brazing joins materials with the aid of melted filler, the melting temperature of which lies below that of the parent metal, which is wetted to form the joint but not melted. In MIG brazing, this technique is extended in semi-automatic or even in fully automatic mode, similar to MIG process. Pure argon is the shielding gas most often used in MIG brazing although addition of 1% oxygen is not uncommon. Many types of copper-based welding wires are available—common amongst these are Si-Mn alloys, aluminium-bronze and phosphor-bronze. Modern inverter type MIG power sources are most suitable for this process.

THERMAL CUTTING

Thermal cutting processes involve melting of the metal to be cut. The word thermal distinguishes them from the mechanical methods of cutting.

Oxygen Flame Cutting

In this process of metal-cutting, popularly known as oxyacetylene or gas cutting, the cut is started by preheating a section of metal to the ignition temperature with an oxyacetylene flame. Oxygen is then turned on, which ignites the iron or steel at the upper surface. This burning (oxidation) releases heat and thereby raises the temperature of the metal below the surface and melts it. The cutting oxygen now ignites the molten metal, which in turn releases heat to the metal below. The same action progresses downward until the metal is severed (see Fig. 1.36).

The slag which is mainly iron oxide (Fe_3O_4) is blown out of the cut by the force of the oxygen stream.
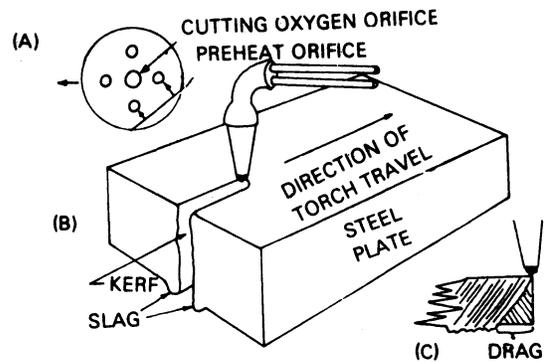

Fig. 1.36: Oxygen flame cutting:
(A) Cutting tip showing arrangement of orifices;
(B) Sketch of cutting action;
(C) Drag formation

The process uses the normal gas welding equipment and a specially designed cutting torch, which is equipped with a special lever for the control of the oxygen and a cutting tip, which has an orifice in the centre surrounded by several smaller ones. The smaller holes provide the heating flame while the centre opening allows the flow of cutting oxygen.

Powder Cutting

The normal oxygen cutting process is ineffective for cutting metals that form refractory oxides such as aluminium, bronzes, and high-nickel alloys. To cut these metals, iron powder is fed into the oxygen stream. A mixture of iron powder and aluminium powder is sometimes used for cutting brass, copper and high-nickel alloys. The aluminium releases more heat than just the iron powder alone. Iron powder also produces a rapid cutting action on stainless steels and is very effective in getting smoother cuts in cast iron.

Powder cutting makes use of a special torch which is equipped with a powder tube, nozzle, and powder valve. The powder is stored in a dispenser and is carried to the powder valve by compressed air or nitrogen where it is fed to the flame. In operation the powder valve is opened first and then the oxygen valve.

Oxygen Lancing

This is an oxygen cutting process in which the base metal is first preheated with a normal cutting torch, and then oxygen is fed by means of a long steel pipe called oxygen lance. The lance pipe is moved suitably to regulate the metal being cut or pierced. The pipe gets consumed gradually in the process (see Fig. 1.37).

Lancing and another similar process called scarfing are used to remove the surface defects of steel blooms, slabs and billets before finish rolling in a steel mill.

Oxygen Arc Cutting

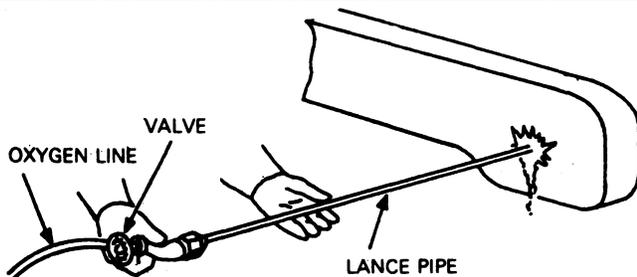In this case, a hollow (tubular) coated electrode makes an arc with the base metal causing it to melt. A stream of oxygen is blown through the hollow core to oxidise and eject the metal (see Fig. 1.38).

The coating helps to melt, oxidise or dilute the molten base metal. In the case of oxidation-resistant metals, the coating helps the molten metal to flow from the cut. The cutting is very rapid.

This process was primarily developed for underwater cutting. It can be effectively used by foundries and scrap yards and for dismantling work, since it is capable of cutting all types of metals in all positions.

Carbon Arc Cutting

In this process, the arc formed between a non-consumable carbon electrode and the base metal is used for cutting. This process was formerly in use along with carbon arc welding, but is now almost obsolete.
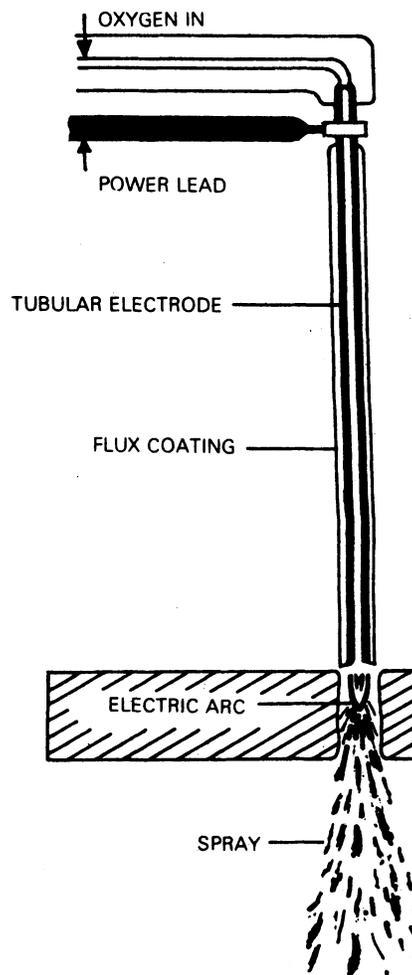

Fig. 1.37: Sketch of oxygen lancing

Fig. 1.38: Diagrammatic sketch of oxygen arc cutting

Metal-Arc Cutting

Here a manual welding electrode having a penetrating arc is used to cut the metal (see Fig. 1.39). Some arc-cutting electrodes are also capable of chamfering and gouging metals.
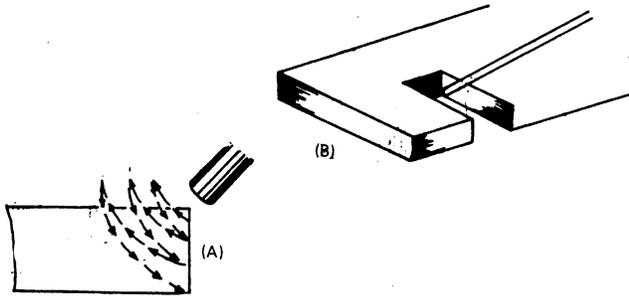

Fig. 1.39: Metal arc cutting: (A) Swinging action of electrode; (B) Form of cut

Air-Arc Cutting

In this process, which is widely used in fabrication shops and foundries, an arc is formed between a non-consumable copper-coated graphite electrode and the base metal; the molten metal is blown away with a high velocity jet of compressed air, parallel and external to the electrode. Since this process does not depend on oxidation, it works equally well on metals which do not readily oxidise (see Fig. 1.40).

A special holder is used to clamp a carbon-graphite electrode in such a position that air emitted from orifices in the electrode holder is directed parallel to the electrode. The air then strikes the molten metal immediately behind the arc. The electrode holder also contains an air control valve and a cable which carries both the current and the air. This cable is connected to a welding machine as well as to a source of compressed air.
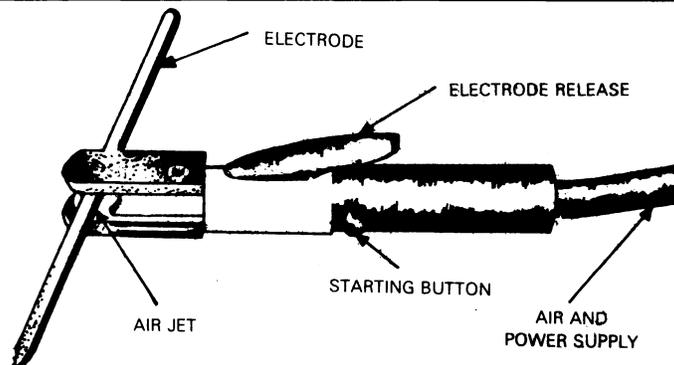
Plasma Arc Cutting

This is dealt with later under Plasma Processes.

Spark Erosion Cutting

This process makes use of spark-discharge machines to perform unique shaping and piercing operations on hardened steel.

Electron Beam Cutting/ Laser Cutting

These processes are based on the same principles as electron beam welding and laser welding described earlier.

THERMAL SPRAYING

Thermal spraying is a group of processes in which a metallic or non-metallic material in the form of wire, rod or powder is heated to a molten or semi-molten state and then sprayed in atomised form onto a surface (called substrate) to form a coating. The heating is commonly done with an oxyfuel gas flame, an electric arc or a plasma arc. A mechanical contrivance called the spray gun is used to propel the hot material to the surface by means of a gas jet. The plastic or molten particles flatten and form thin platelets when they strike the surface. The bond between the spray deposit and the substrate may be mechanical, metallurgical, chemical or a combination of these.

Thermal spraying is also sometimes called metallising or metal spraying, which implies that the material being sprayed is metallic.

Flame Spraying

In this case, the metal to be sprayed, which is in the form of wire or finely divided powder, is passed through an oxyacetylene flame (see Fig. 1.41). In the case of the wire, a stream of high-velocity gas (air, nitrogen or CO_2)
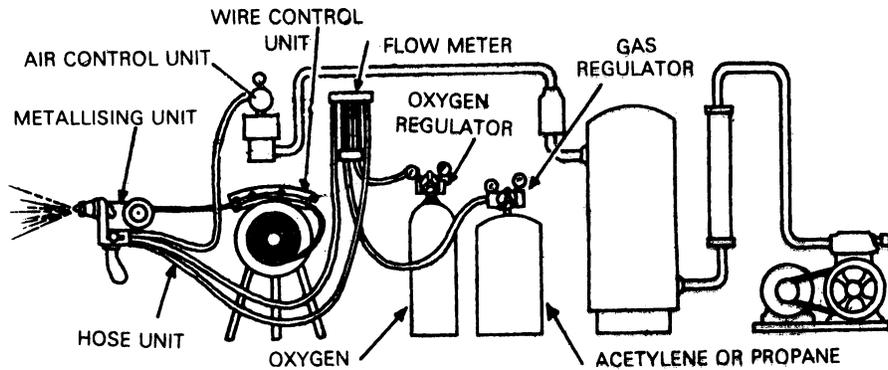

Fig. 1.40: Diagrammatic sketch of air-arc cutting torch gripping a carbon-graphite electrode

Fig. 1.41: Schematic diagram of flame spraying

is also passed over the flame to divide the molten metal into fine particles and carry them to the work surface. In certain cases, the stream of gas also serves to feed the wire into the flame.

Electric Arc Spraying

Here two current-carrying wires are continuously fed into a gun through wire guides. The wire ends meet in front of the gun nozzle and form an arc. An air jet is blown through the gun nozzle on to the arc. It ejects molten metal particles and carries them to the work surface (see Fig. 1.42).

Plasma Spraying

This process is discussed under Plasma Processes.

PLASMA PROCESSES

Plasma is considered the fourth state of matter, the other three being solid, liquid and gas. Plasma is a superheated gas which has dissociated into positive ions, neutral atoms and negative electrons. Plasma is formed

when an electrical discharge takes place in a gas, and also in an electric arc (the blinding light of an arc comes from the plasma). In normal arc welding processes, the plasma is easily blown away by moving gas streams. But in plasma processes which are listed below, the plasma is contained and used effectively:

- Plasma arc welding
- Micro-plasma arc welding
- Plasma-MIG welding
- Plasma arc cutting
- Plasma spraying.

In all these processes, based on DC supply, a specially designed torch, which is a modification of the TIG torch, concentrates the plasma energy and ensures its most efficient utilisation for welding, cutting and spraying. The tip of the tungsten electrode (DC negative) is located within the torch nozzle, while the nozzle has a small opening which constricts the arc. As gas (usually argon) is fed through the arc, it becomes heated to the plasma temperature range (30,000 to 60,000°F). The plasma tail-
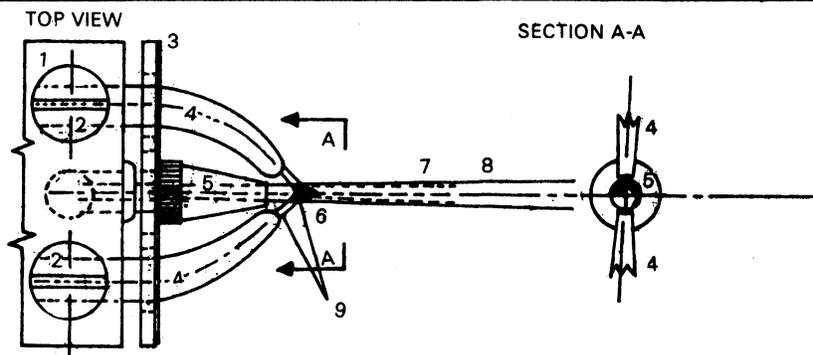

Fig. 1.42: Schematic diagram of electric arc spraying gun
1. Insulated housing for contact piece; 2. Contact piece; 3. Heat resistant protective plate; 4. Wire guides;
5. Atomizing air nozzle; 6. Arc point; 7. Metal particles; 8. Atomizing air stream; 9. Wires.

flame issues from the torch nozzle as a jet of tremendous velocity.

The plasma-arc is of two types: transferred arc and non-transferred arc. In the former, the arc is formed between the electrode and the workpiece. In the latter, the arc is formed between the electrode and the constricting orifice inside the torch (see Fig. 1.43).

Plasma Welding

Plasma welding is an extension of TIG welding. The main difference as explained above is the constriction of the arc column, resulting in much higher heat transfer rate. The torch is further modified to provide an outer sheath of cool gas around the central plasma core, as shown in Fig. 1.44. Plasma welding makes use of the keyhole technique. When the plasma jet strikes the metal, it cuts or keyholes entirely through the workpiece producing a small hole, which is carried along the weld seam. During this cutting action, the molten metal in front of the arc flows around the arc column, then gets drawn together immediately behind the hole by surface tension forces and reforms as a weld bead. Thus butt welds of 12.5 mm or larger thickness are possible in a single pass without edge preparation or fillet metal. The process can weld carbon steels, stainless steels, copper, brass, aluminium, titanium, monel and inconel.
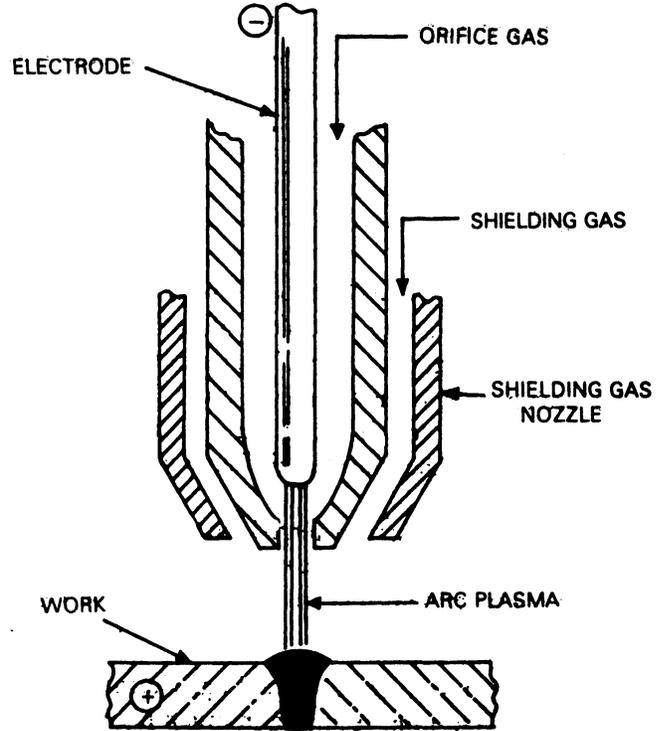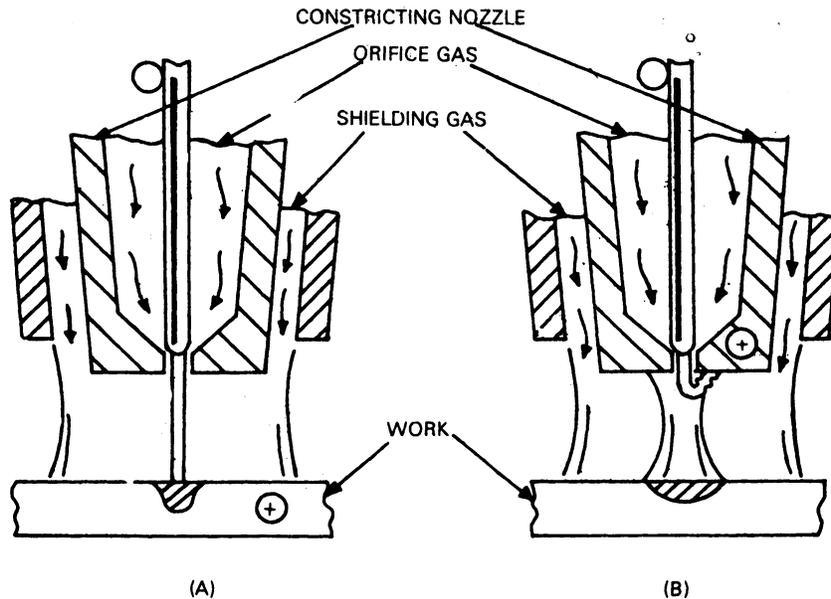
Fig. 1.44: Sketch of plasma welding torch

Fig. 1.43: Sketch of plasma arc torch: (A) Transferred arc; (B) Non-transferred arc

Micro-Plasma Arc Welding

This is a modified process using DC current range of 0.1–10 amps. It is capable of welding extremely thin sheets and foils in the thickness range of 0.05–1.6 mm.

Plasma-MIG Welding

This is an extension of plasma arc welding in which the non-consumable tungsten electrode is replaced by a consumable continuously-fed metallic electrode (see Fig. 1.45).
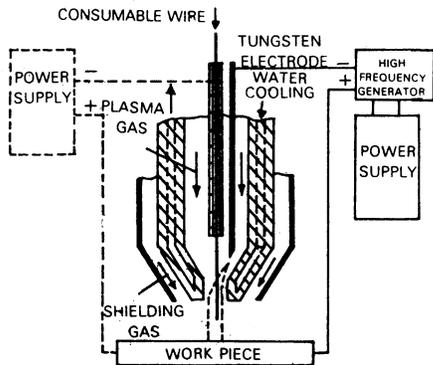

Fig. 1.45: Schematic diagram of plasma-MIG welding

Plasma Arc Cutting

This process shown in Fig. 1.46, uses DC source with open circuit voltage of 120 or more. Hence as a safety precaution against electric shock, it is preferably used as a mechanised process.

Dual gases are often used: one as a cutting gas and the other as a shielding gas. The typical combination is argon/ hydrogen or nitrogen/ hydrogen for cutting aluminium and stainless steels, in which argon and nitrogen are for cutting while hydrogen is for shielding.
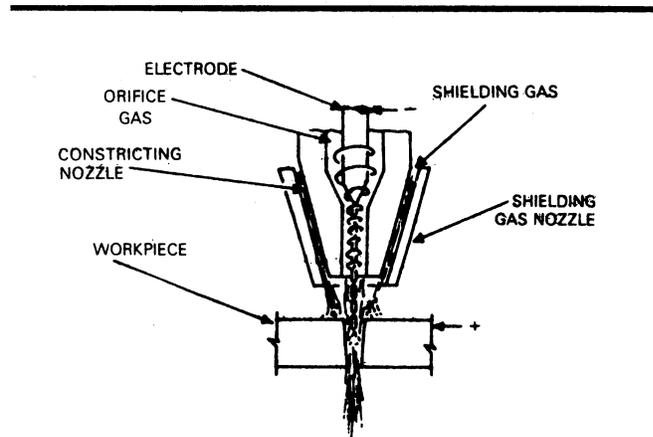

Fig. 1.46: Sketch of plasma arc cutting

For cutting carbon steels, nitrogen is used as a cutting gas while oxygen is also passed into the plasma to provide additional heat from the iron-oxygen reaction at the cutting point. A transferred arc is used, that is, the arc is formed between the tungsten electrode (–) and the workpiece (+).

Plasma Spraying

In this process, a special plasma spray gun is used in which a non-transferred arc forms between the tungsten electrode (–) and the nozzle (+). Plasma gas is passed through the arc in the nozzle bore. The spraying material, in powder form is fed into the nozzle bore or into the flame just beyond the end of the nozzle. The plasma flame melts the particles and impels the molten material onto the workpiece (see Fig. 1.47).

The gas is either nitrogen or argon or 5–25% hydrogen mixed with nitrogen or argon.
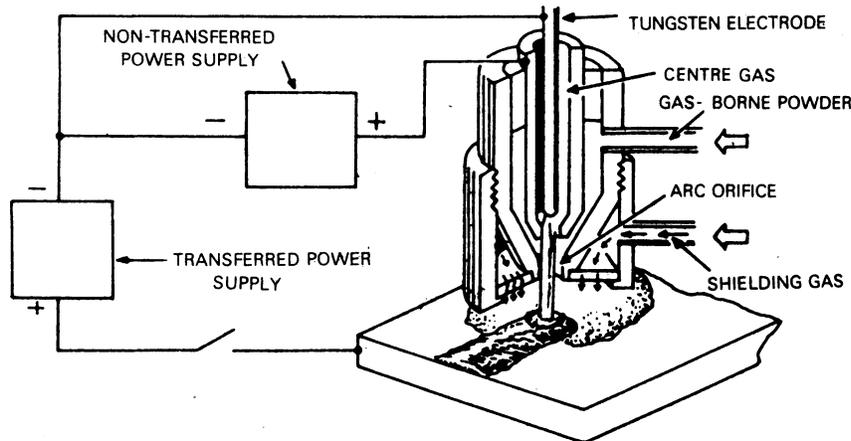

Fig. 1.47: Schematic diagram of plasma spraying

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