WELDING - ITS PAST, PRESENT AND FUTURE

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Welding is a major technology in present-day industry, and its state of art has a decisive effect on advances in mechanical, construction and many other industries. Today, the science and art of welding encompasses a wide range of processes and procedures applicable to materials of any thickness and shape - from tiny electronics components to huge-sized machines and structures.

Starting from a chance invention of arc welding in 1881 by Slavianoff in a Russian shipyard, the process has come a long way in the last about 115 years. Although the stick electrode welding still occupies a very important position in the fabrication industry the world over, a large number of other processes have also been invented and well established and have become indispensable in their own fields of application. If we consider the role of welding starting from 1881 to say 2020, we can divide this period into three parts viz., its past, say, from 1881 to 1981, its present say from 1981 to 2000 and its future as the period beyond the year 2000 A.D. to 2020. This paper deals with the developments that have taken place so far and the future trends as they can be predicted from the present-day developments.

PAST DEVELOPMENTS

The development of coated electrodes by Kejellberg in Sweden during 1903-1908 was a big step in popularising the arc welding process and it remained the major welding process till about 1935. But subsequent development of submerged arc welding led to a spurt in the introduction of new welding processes; some of which are as follows :

1. Oxy-Acetylene Pressure Welding
2. Plasma Arc Welding
3. Plasma-MIG Welding
4. Stud Welding
5. Electroslag and Electrogas Welding
6. High Frequency Resistance Welding
7. H.F. Induction Welding
8. Cold Pressure Welding
9. Friction Welding
10. Explosion Welding
11. Ultrasonic Welding
12. Electron Beam Welding.

Brief description of each one of these processes is as follows.

Oxy-Acetylene Pressure Welding

This process is a true form of pressure welding in which the source of heat is the oxy-acetylene flame. Commonly referred to as being of the solid-phase classification, i.e., welding below fusion temperature, oxy-acetylene pressure welding is a fairly recent commercial adoption. Its main advantages are :

i. Neatness and consistency of the completed joint.

ii. Suitability to the welding of high carbon and alloy steels as well as low carbon steels.

iii. Low unit cost of production work as compared to other processes.

Description of Process

The ends of the two work pieces to be welded are prepared by squaring, cleaning, aligning and butting together with an initial pressure of about 375 N/cm^2. An Oxy-acetylene torch or head, designed to fit the contour of the workpiece is applied and uniformly heats the welding area to about 1200°C. During the heat cycle the butting pressure is gradually increased to an amount necessary to produce a predetermined degree of upset in the heated zone. **Fig.1** pictorially illustrates the fundamental steps in the described operations.

The heating hoods are usually made up of a main hollow body, which serves to conduct the oxygen-fuel gas mixture to the heating tips. The use of numerous tips in the main body ring assists materially in the uniform distribution of heat. In most of the applications the head is oscillated across the joint during the heating period as this practice reduces, somewhat, the size of blowpipes needed and prevents the possibility of locally-overheating.

Application of oxy-acetylene pressure welding is generally to all commercial metals which may be successfully butt-welded, although present field use appears to restrict the process to carbon and alloy steels in the forms of pipe, tubing, rails, structural shapes, and so on where welding is desired.

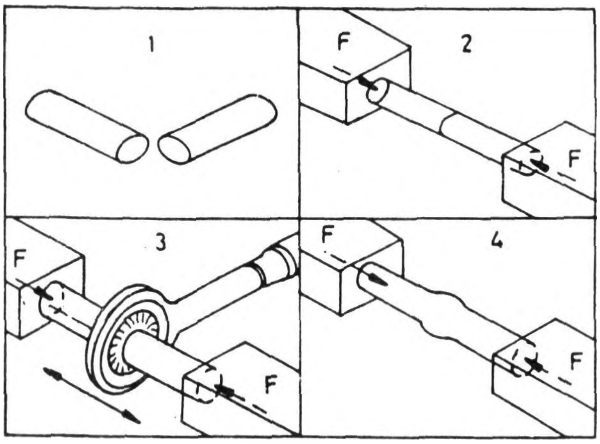


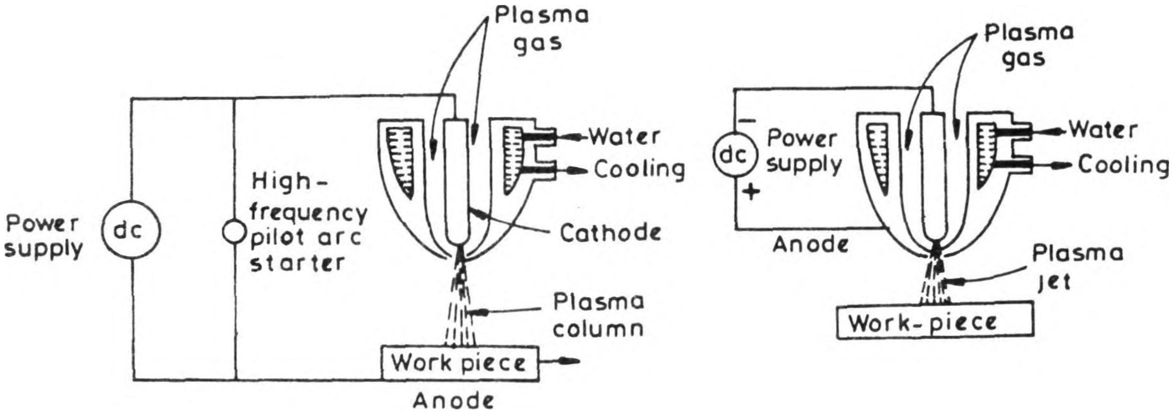
Fig. 1 : Fundamental Steps in the Oxy-Acetylene Pressure Welding Process

Plasma Arc Welding

The projection of an arc or the hot ionized vapours (Plasma) through a nozzle is carried out by means of a plasma torch, which may be applied to cutting, welding and metal spraying.

There are two main types of the plasma torch as shown in **Fig. 2.**

In the transferred arc torch the arrangement is that of a TIG torch but with a water-cooled nozzle interposed between the tungsten electrode and the work. This nozzle serves to constrict the arc column and thereby increase the anode current density and heat-



(a) : Transferred Arc Plasma Welding

(b) : Nontransferred Arc Plasma Welding

Fig. 2 : Plasma Welding Torches

ing intensity. It is so arranged that the arc should first strike the nozzle. The plasma so formed is then swept through the nozzle, and the main current path is formed between the electrode and workpiece. The transferred or the constricted arc may be used for cutting metals that are not so readily cut by the oxy-acetylene torch, notably non-ferrous metals and stainless steel. As the shielding gas is generally a mixture of argon/hydrogen or nitrogen/hydrogen, the output voltages are high and around 50 V.

The transferred arc can be used for welding as well as cutting and is used with two different techniques:

i. at low currents for welding sheet metal less than 1.5 mm thick.
ii. at currents up to 400 A for welding thick metal using the deep penetration keyhole technique.

The second type of torch embodies a non-transferred arc that is an arc between electrode and nozzle. The rate of gas flow through such a torch is moderately high, and a jet of plasma issues from the nozzle. The shielding gas may be Ar, N_2 or their mixtures with hydrogen.

A d.c.e.n. arc is generally used except for aluminium where the polarity is reversed. The orifice through which the plasma passes is about 2.5 mm dia.

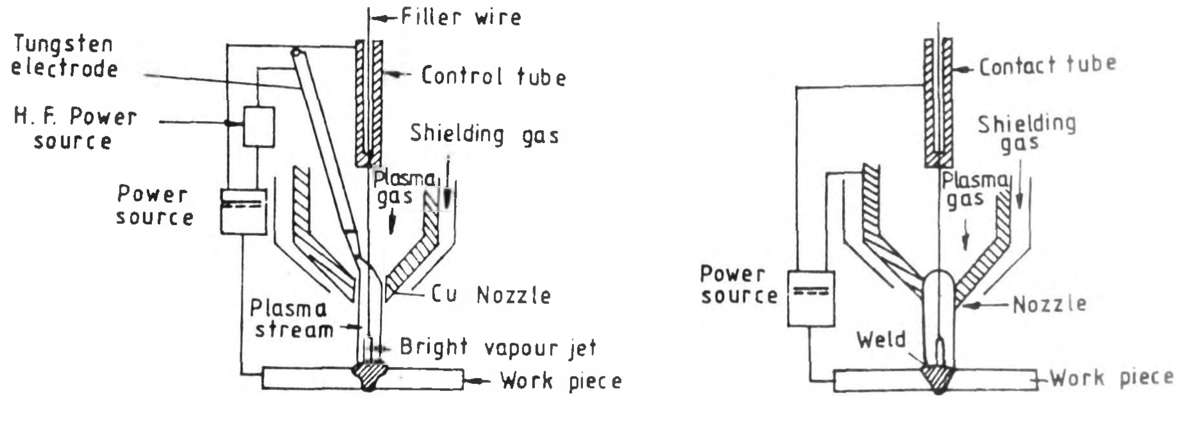
Applications

The most widely used plasma arc is the micro-plasma variation, which is particularly suited to edge welds in sheet of less than 0.5 mm thickness and for welding wire-mesh components such as filters. For m.s., stainless and heat resisting alloys an Ar-H_2 mixture is used for shielding the plasma arc. With low alloy steels, Al and Cu alloys, hydrogen must not be used because it causes cracking in alloy steels, or porosity in Al and Cu. Argon or Helium is used instead.

Plasma-MIG Welding

The Welding Group of Phillips Research Labs of Holland have developed a new process by combining the two well-known processes of plasma-jet welding and metal inert-gas welding and named it Plasma-Mig Welding. The schematic of the process are given in **Fig. 3**

Essentially, it differs from the existing MIG-Process in that the MIG-electrode is enveloped in a plasma (ionized gas) sheath which controls heat and droplet transfer in such a way that higher speeds and deposition rates are reached than with MIG welding.



(a) : with Separate Non-Consumable Electrode

(b) : with Nozzle as Non-Consumble Electrode

Fig. 3 : Plasma-MIG Welding Torch

The magnetic action of the plasma arc causes constriction of the welding arc. Spatter is absent.

A typical property of plasma-MIG welding is that at positive polarity and above certain current values (transition current) with solid steel wire types, the arc starts to rotate. This phenomenon already known from MIG-welding can be controlled in a far better way and again spatter is absent. So overlaying at high speeds has been made possible.

This process can be used for butt welding and for overlaying. It can also be used for thin and thick materials, for mild-, low alloy-, stainless- and heat resistant steels, and for non-ferrous metals such as aluminium and copper. Stainless steel sheet from one to eight mm thick can be welded at speeds varying between 0.4 and 7 m/min. The versatility characteristic for plasma-MIG welding process is stressed by the fact that the welding parameters can be practically identical for all these welds, only the speed iq2s changed.

Stud Welding

This process is basically the same as metal-arc welding in that any type of fasteners such as studs, insulation pins, buttons, lashing hooks, etc. constitutes the electrodes. In one important respect it differs from metal-arc welding in that the molten end of electrode is plunged into the molten pool to complete the joint. Stud welding primarily consists of two steps :

i. developing heat by setting up of an arc between the end of the stud and the parent metal,

ii. after a proper lapse of time, quickly forcing the molten stud into the pool of molten parent metal.

Chief advantages of stud welding are :

i. Tremendous saving in time over fillet welding

ii. High mechanical properties of weld obtained

iii. May be operated by unskilled workers

iv. Accuracy of stud location

v. Eliminates time of drilling, as required for installing bolts

vi. Accessibility of "other side" not required for installation

vii. Eliminates weakening of section by drilling or punching bolt or rivet holes

viii. Improved general neatness of finished structure

ix. Saving of weight.

The Stud Gun and Control Unit : The general outline of the stud gun resembles a pistol with an oversized barrel. The overall weight of the gun is about 2.5 Kg. A single push button switch for starting the welding cycle is also conveniently located in the gun handle. For the actuation of the gun mechanism the gun contains a heavy copper coil cast integral with the body. On pressing the trigger the necessary arc gap is set and the welding current starts flowing. After a predetermined lapse of time the current is interrupted and a spring in the gun barrel moves the stud towards the parent metal, forcing its molten end into the weld pool to complete the weld.

A note-worthy feature of the stud welding unit is that once the operator has initiated the welding cycle, it goes to completion regardless of whether or not he continues to hold down the trigger

Studs and Ferrules : A ferrule, an individual porcelain ring, is placed around the base of the stud before welding to act primarily as a shield.

The ferrule is a vital link in the stud welding process and serves the following purposes :

i. Prevents the ingress of the atmosphere

ii. Confines and concentrates the heat during the welding cycle

iii. Confines the molten metal to the weld area, thus eliminating splash

iv. Shields the operator against the arc

v. Helps in giving desired shape to the joint.

The purposes served by a ferrule at different stages of stud welding are shown in **Fig. 4**.

Applications

Common applications of stud welding are installation of con-

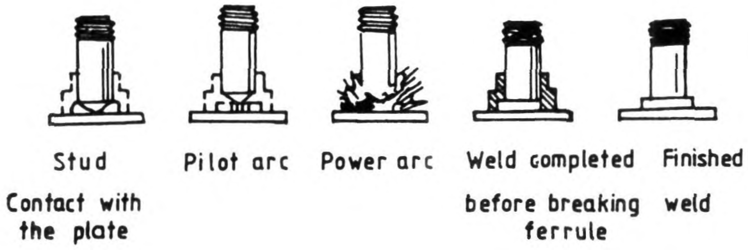


Fig. 4 : Stages in the Arc Stud Welding Process

duit, piping, insulation, plank decking, corrugated roofing, and felt. Studding of boiler tubes to secure refractory coating are typical of jobs suited to stud welders.

Electroslag & Electrogas Welding

The electroslag welding is especially adapted to the joining of thick plates. The plates are given a square edge preparation, and are set up vertically with about 25 mm gap. Wire and initially some flux are fed into the space between the plate wedges and a weld pool covered by a layer of liquid slag is formed. Weld pool and slag are retained by water-cooled copper dams, which are moved upwards with the wire feed guide as the joint is filled. Extension pieces are usually provided at start and finish, so that any unsoundness may be cut off. Initially, there is an arc, but as soon as the flux melts and becomes conductive, the arc is short-circuited and heat is generated by passage of the welding current through the slag. The slag circulates vigorously and melts both parent metal and filler metal. A little flux is added from time to time during the weld traverse in order to maintain the slag pool at constant depth. A number of wire electrodes may be used, depending upon the thickness of the plate and in some machines these are traversed to and fro laterally in order to improve the heat distribution. The power source is usually a.c., 3-phase in the case of three electrode unit, but d.c. may be preferred for alloy steel welding.

The welding speed is low and the weld pool large; consequently both weld metal and the plate adjacent to the weld are coarse-grained and in order to obtain good impact properties it is necessary to normalize carbon and low alloy steels after welding. On the other hand, the slow cooling combined with low hydrogen content of the weld metal greatly minimizes the danger of cracking of low alloy steels.

The slag pool offers a high degree of protection against atmospheric contamination, and may assist in a certain degree of weld metal refinement. The use of specially deoxidized wire is not essential, and with alloy steel compensation for loss of alloying elements is not necessary.

Electroslag welding is applied to the vertical welding of plate and sections over 10 mm thick in carbon and low alloy steels, and has been used for high alloy steel and titanium.

Electro-gas welding is superficially similar to electroslag welding. In electro-gas welding, however, heat generation is by an electric arc which is struck from a flux-cored electrode to the molten weld pool. This flux forms a thin protective layer but does not give a deep slag bath as in electro-slag welding. Additional shielding may be provided with CO_2 or argon-rich gas.

Electro-gas welding can be used for thickness between 10-75 mm for shipbuilding and site fabrication of storage tanks. Because it is an arc welding process it can be started without the necessity of a starting block. Restarting of welding, if interrupted, is easier than in electro-slag welding.

High Frequency Resistance Welding

In butt-seam welding heat is generated mainly by interfacial contact resistance as in spot or projection welding. By increasing the current supply to about 450 KHz and raising the voltage to about 100 volts, a process called high frequency resistance welding is achieved.

The current is introduced to the parts to be welded through probes which make light contact on either side of the joint. At the frequency used, the skin effect by which the current flow tends to concentrate at the surface of the conductor becomes marked. The depth of the layer in which most of the current flows is proportional to 1/f for any given material. Contact with probes is made a short distance before the two sides of the joint are forged together as shown in **Fig. 5**. The depth of the heated region is extremely shallow, generally less than 0.75 mm, and it is precisely the best position for welding. As the joint closes the heated edges are forged together to give a high quality weld. Superficial melting can occur and this thin molten layer is squeezed out as the edges meet. For this reason the high frequency resistance process is capable of welding non-ferrous metals and others which form refractory oxide skin. With the low frequency process melting does not occur so that considerable deformation would be required to rupture the oxide films and give a good pressure weld. It is also difficult to achieve a sufficient temperature gradient with a high conductivity metal. In the high frequency process surface films are flushed out with the molten metal.

Because of the high voltage (about 100 V) and the high frequency at which the current is supplied there is no difficulty in achieving good electrical contact with the probes, even on scaled material. The water cooled probes can weld many thousands of metres of tube before being replaced for wear. Another consequence of the high voltage, a result of the long current path, is that high power levels can be obtained with relatively low currents. The working range, depending on material thickness and speed, would be 200 - 5000 A. Using a 60 KW power unit, tube of material 0.6 mm thick can be welded at speeds to 90 m/min. Welding speed depends on tube thickness and not on diameter.

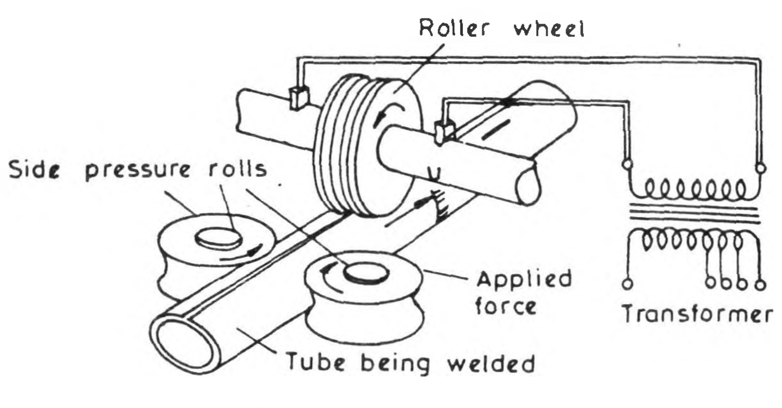


Fig. 5 : Electric resistance Butt-seam Welding of Tube from Strip (ERW process)

Although the main use of the process is for the continuous welding of tube it is clear that the principle of the method is important and has a much wider potential. Lap, Corner, and T welds can be made; in fact any type of joint in which the requirements indicated in the figure above can be provided.

High Frequency Induction Welding

This method has also been used for welding tube and resembles the high frequency resistance process in that use is made of the skin effect. The difference, however, is that instead of direct contact being made with the work, the current is induced in the surface layer by a coil wrapped around the formed tube. Surface heating and fusion occur and the weld is consolidated by a forging action on the joint. Induction welding is not limited to tubes and may be applied to other symmetrical assemblies in which the joint forms a complete loop, for example as in the welding of a cap to a tube. With this type of joint there is no forging, the edges of the component merely being allowed to melt and run together. The process is not suitable for welding high conductivity metals or those with refractory oxides as there is no active mechanism for oxide disposal. High frequency induction heating type equipment is used and fusion is completed in a few cycles of mains frequency.

Cold Pressure Welding

Where welding is accomplished at ambient temperature, solely by the application of pressure across the interface the process is termed cold pressure welding or simply cold welding. Cold welding is applied particularly to the ductile metals Al and Cu, although ductility in itself is not the sole criterion of weldability. Weldability decreases with increase in hardness and melting point, silver for example, although ductile is less readily welded than aluminium. The Joints produced are of two types: lap and butt, as shown in **Figs. 6** to **8**.

With the former, indenting dies may be forced into the metal causing deformation and flow to provide the extension of the interface. Roll bonding is a specialised form of lap welding in which behaviour is slightly different from welding with indenters. 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.

Surface preparation is probably the most important single process variable. In lap welding the preferred method is scratch-brushing after degreasing. Surfaces baked at high temperature are also suitable for welding. However, both scratch brushing and baked surfaces must be welded as soon as possible and not be subjected to any further treatment. Anodized aluminium can frequently be welded without preparation.

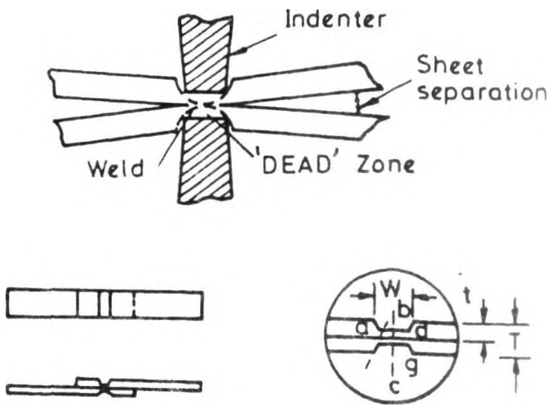


Fig. 6 : Indented Lap Weld

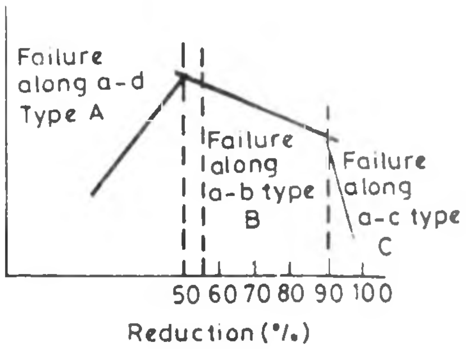
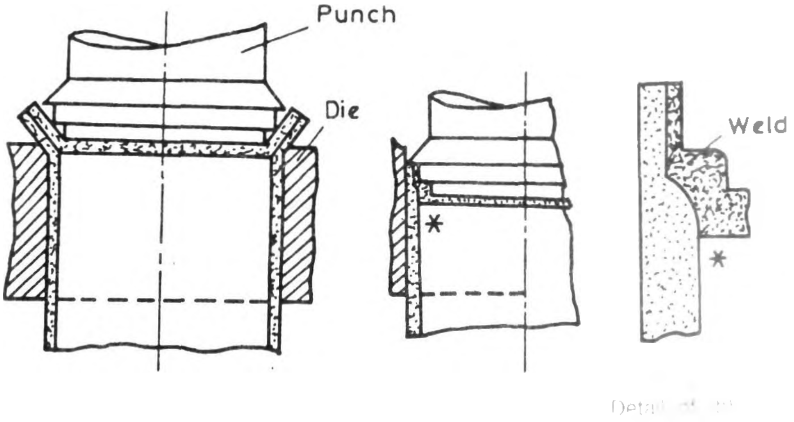


Fig. 7 : Strength/Weld reduction relationship for an Indented Lap Weld



(a) : Before Pressing

(b) : Final position

Fig. 8 : Sealing cans by Cold Welding

With butt welds between bar stock or tubes, scratch brushing is nor normally practical and it is usual to file or shear the square edges immediately before welding.

Where dissimilar metals are cold welded the softer metal deforms first and as deformation rises the harder metal begins to flow. The projection of the softer metal must be slightly greater than when similar metals are joined and considerably greater for the harder metal. A common dissimilar combination is Al to Cu where the projection of the Cu must be 30-40% greater than for the aluminium.

Applications

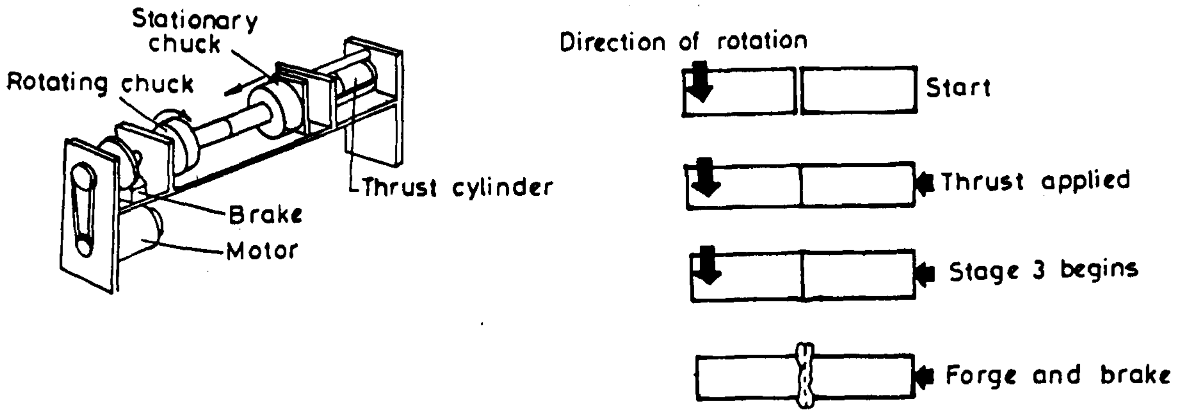
The decision to use cold welding must be taken early in the design stage of a component because allowance must be made for the deformation and design must permit the specialised form of the joint. Large number of similar joints must be required because dies must be made. Lap welds are used for can joints, longitudinal tube joints and electrical connections; butt joints for wires and tubes. Hand tools are used for small sizes, power operated presses for butt joints up to about 700 mm^2 in aluminium. The most commonly welded metals are Al and Cu.

Friction Welding

In the friction welding process the workpieces are brought together under axial load, one part being revolved against the other so that frictional heat is developed at the interface. Friction welding has been used for joining thermoplastics since 1945 but metals were first welded by Chudikov and Vill in 1956. A schematic of friction welding process is shown in **Fig. 9**.

The parts to be friction welded are axially aligned so that one part can be rotated against a stationary part. The frictional heat is regulated by the speed of rotation and the axial pressure of the non-rotating piece. As the temperature at the interface of the two pieces increases, the pieces come up to welding temperature. At this point, the forging phase takes place. The rotation is stopped and pressure is increased until the weld is completed. Welding time usually lasts between 2 to 30 secs. depending upon the material to be welded. A 12.5 mm dia. low-carbon steel rod with the welding temperature of 900°C can be joined with a contact pressure in the range of 3500 to 7500 N/cm^2 and forging pressures between 11,000 and 45,000 N/cm^2. In general it has been found that the rpm and the force applied are dependent upon the material to be friction welded. The harder the material, the higher the rpm and the axial force. Forging pressures can be as high as 50,000 N/cm^2.

The design for a friction welding machine must be such as to accurately control three vari-



(a) : Welding Equipment (b) : Sequence of operations

Fig. 9 : Diagram of continuous-drive friction welding

ables. The rotational speed, the axial pressure and the time of the contact. If the variables are not accurately controlled there will be inconsistency in the quality of the weld. The metals to be welded can be of any shape as long as they share a common axis. The process can be used only when one part rotates about an axis of symmetry. The length of the material is limited to the size of the machine. The advantages of this process include its ability to join a large range of materials with high quality and consistency by using simple and compact machinery that requires economical use of power. Also, the heat produced in the friction weld is not enough to melt the base metals, causing little or no warping. There is a burr surrounding the weld area, however, which can be machined off later.

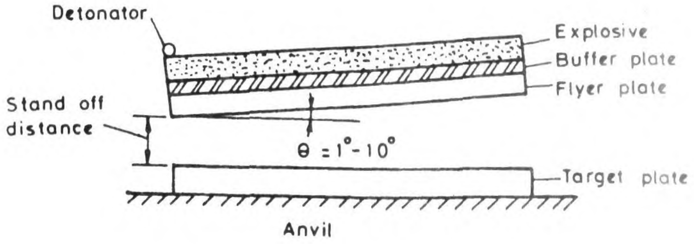
The joint configuration is limited to butt type only. It is possible to weld two pieces of round stock, either pipe or rod together or to weld a piece of round stock to a plate, but one of the parts must rotate. In spite of these limitations friction welding has three distinct advantages of speed, accuracy and economy. Metals that can be welded by the friction welding process include carbon steel, stainless steel, copper, aluminium, and titanium. Dissimilar metals can also be welded by this process, including the most difficult combination, aluminium to carbon steel.

Explosion Welding

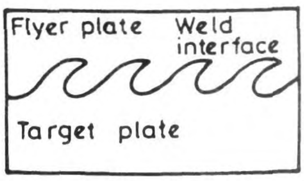
When two pieces of metals are impacted together a weld can take place at the interface provided certain conditions are met. The method that has most frequently been investigated for explosion welding is illustrated in **Fig. 10**. In this technique, known as end initiation the plates are set at an angle of 2.5° or more, the charge is placed over the top plate and detonated from the end at which the gap is smallest. Direct contact between charge and metal results in considerable burning and damage, and it is, therefore, necessary to find means of transmitting the explosion energy by means of an expendable spacer.

The usual procedure is to project the pieces to be welded together so that they impact at a high velocity. This velocity may range from 150 to 300 m/sec. Achieving these high velocities means that the detonation velocity caused by the explosives usually approaches 6500 m/sec in the denotation front. The pressures produced by the velocity at the interface range from 75000 to 750000 N/cm^2. When the velocity of impact and the angle of collapse are properly selected for the material being welded intense plastic flow at the surface will produce a high-strength weld with saw-tooth interface.

The wavy shape of the interface has the amplitude of the waves between 0.1 and 4.0 mm with wavelengths from 0.25 to 0.5 mm depending on the welding conditions. The formation of waves



(a) : Set-up



(b) : Weld Interface

Fig. 10 : Explosion Welding

appears to be a requirement for a satisfactory weld.

Strong metallurgical bonds can be produced between metal combinations which cannot be welded by other processes e.g. tantalum can be welded to steel. In critical space and nuclear application, explosion welding permits fabrication of structures that cannot be made by other means, and in some commercial applications, this is the least costly method.

The major advantages of explosion welding include the simplicity of the process; the extremely large surface that can be welded, and welds that can be produced on heat-treated metals without affecting the heat-treatment. Also explosive welded bonds do not have HAZ, incompatible materials can be bonded, and thin foils can be bonded to heavier plating.

Using a specially developed explosive material which has a lower detonation rate than normal, it is possible to join two plates that were initially parallel to each other.

Explosion welding is a specialized process which can only be applied to the variations of the lap joint. An attractive application is the fabrication of heat exchangers by welding sheets to plates in which channels had been machined. Sleeved joints in tube and tube-tube plate joints are also feasible when the charge is exploded within the tube. The process can also be employed for making welds in places inaccessible to conventional processes or for site welding where power and skill for fusion welding are difficult to obtain.

Ultrasonic Welding

When two metal workpieces are clamped together between an anvil and a vibrating probe a weld can be produced at the work-work interface. The vibrating probe called a sonotrode, induces lateral vibrations, and slip locally between the faying surfaces, disrupting surface films, raising the temperature and forming a type of pressure weld. The general arrangement for ultrasonic spot welding is shown in **Fig. 11**.

Frequencies up to 100,000 Hz are used but a common figure is about 20 KHz.

Sonotrode tips are generally made from hardened high speed steel or Nimonic alloy, materials which have been found to exhibit a low tendency for pressure welding possibly because of their high strength at elevated temperature. The tips are shaped to present a spherical contour to the work of about 75 mm radius. They may be brazed or welded to the vibrator which supplies the energy for welding.

Ultrasonic vibrators comprise the transducer, which is generally a resonant laminated magnetostricter and a velocity transformer. The latter is made of a low-loss high strength metal e.g. titanium, machined to dimensions appropriate to the frequency and material used since $f = \lambda E$, where f is the frequency, λ the wavelength and E the modulus of elasticity. Since the tip must be an antinode the length of the device will be in multiples of $\lambda/2$ while any supports must be made at the nodal points at $\lambda/4$. Vibrators must, therefore, operate at one frequency only.

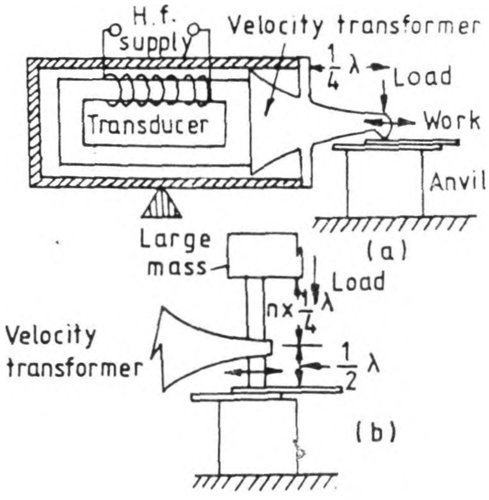


Fig. 11 : General arrangement for Ultrasonic Spot Welding (a) Directly Coupled, (b) Coupled through a Resonant bar

The parts to be welded must be supported on an anvil of sufficient size to prevent the part of the work it contacts from moving in compliance between anvil and tip. A device for applying a force between anvil and tip is required and it may be hydraulic, pneumatic or spring operated according to the size of the unit, springs being used on the smallest equipment.

The cost involved in ultrasonic welding is usually the limiting factor in its applications. If another method of welding is possible, then that would most probably be more economical than ultrasonic welding. Ultrasonic welding is superior to any form of welding and usually begins where the other processes stop.

Ultrasonic welding is capable of joining such combinations as aluminium to steel, aluminium to tungsten, aluminium to molybdenum and nickel to brass. It can also weld a large metallic object to a piece of foil. Ultrasonic welding has also made it possible to join metals with vastly different melting points, making strong rigid joints.

A disadvantage of ultrasonic welding is that its use is restricted mainly to aluminium. Also the thickness of one piece can be no thicker than 3 mm although the other material to be joined can be of any thickness. This method can also join materials as thin as 0.005 mm.

Electron Beam Welding

Electron beam welding is a joining technique in which the heat for fusion is obtained from kinetic energy in a dense beam of high velocity electrons. The electron beam welding machine resembles, in principle, a thermionic valve. Electrons are emitted by a cathode, accelerated by a ring-shaped anode, focused by means of an electromagnetic field, and finally impinge on the workpiece, as shown in **Fig. 12**.

Accelerating voltages are in the range of 20 - 200 KV, and although welding currents are of the order of mA, the total power is of the same order of magnitude as for arc welding with coated electrodes. As the accelerating voltage is increased, so the intensity of X-rays emitted from the anode increases, and in high voltage equipment means are provided to limit the X-ray emission to a tolerable level.

The focusing coils are capable of concentrating the electron beam on a spot only a few microns in diameter. With such a concentrated anode spot there is a critical voltage above which the EB penetrates the metal, and when the work is traversed relative to the beam, a weld bead which is exceedingly narrow relative to its depth is formed. This type of weld is sometimes used for joining dissimilar materials for avoiding distortion, and where the heat effect of welding must be minimized. The beam may be focused and used to preheat or

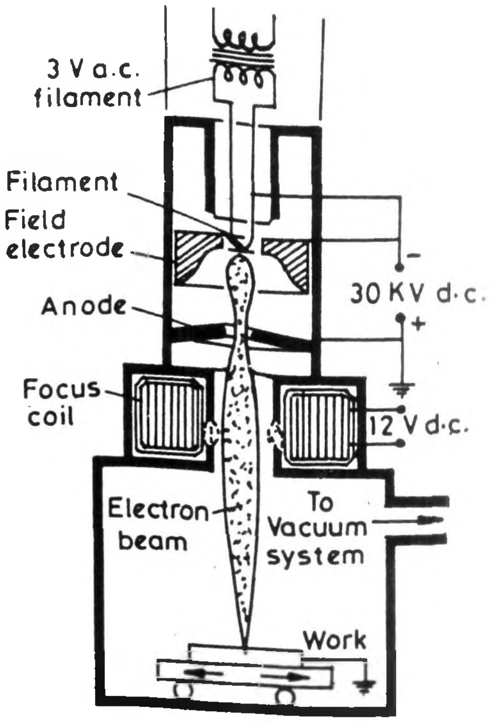


Fig. 12 : Pierce-type Electron Beam Gun (diode)

post-heat the weld. Periodic defocusing produces a pulse effect at the anode, which may be useful for welding metals having a high vapour pressure at the melting point. EBW is applicable to metals and alloys that do not vaporize excessively or emit gas when melted. It is especially valuable for dissimilar metal joints and reactive metals, for joints requiring accurate control of weld profile and penetration, and also for fabrications such as gas turbine parts where distortion is unacceptable. Its major disadvantage is the need to carry out the welding operation in a vacuum chamber.

However, a new concept in the electron beam process has recently been developed which allows the electron beam to perform its function in standard atmospheric conditions. This type of electron beam can be used for high production welding. The maximum stand-off distance for welding is approximately 20 mm. If a beam length greater than 20 mm is used, it will be too widely dispersed to operate. The maximum penetration depth of the beam is 13 mm in steel. The electrons are freed in a vacuum as in conventional EBW, but the electrons go through three vacuum pumping stages that gradually lower the vacuum within the beam-transfer column to standard atmospheric pressure.

Today EBW is widely and advantageously used in the electronics, nuclear, missile and aircraft industries. In some cases it has been employed to make gears for automobiles and cutting tools for engineering works.

PRESENT STATUS

A number of developments in welding processes and technology have taken place in the recent past which are expected to get established the world over in the next few years and yield far-reaching results to popularise welding to make an attractive technology. Some of these developments are :

i. Pulsed Arc Welding Power Sources,
ii. Inverter Power Sources
iii Plasma-Mig Welding
iv Laser Welding
v. Robotic welding Systems
vi. Narrow Gap Welding
vii. Underwater Welding

Brief description of these processes follows.

Pulsed Arc Welding Power Sources

Pulsed current finds increased use in gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) processes. Whereas in GTAW it serves the purpose of controlling the weld pool size and cooling rate of the weld metal without any arc manipulation, in GMAW it provides spray and controlled mode of metal transfer at lower welding current for a specific type and diameter of electrode used.

A typical pulsed arc welding power source normally consists of a 3-phase welding transformer cum rectifier unit in parallel with a single phase half-wave rectifier. The three phase unit provides background current and the single phase unit supplies the peak current. Both the transformer and rectifier units are mounted in a single housing with appropriate controls for individual adjustments of background and peak currents.

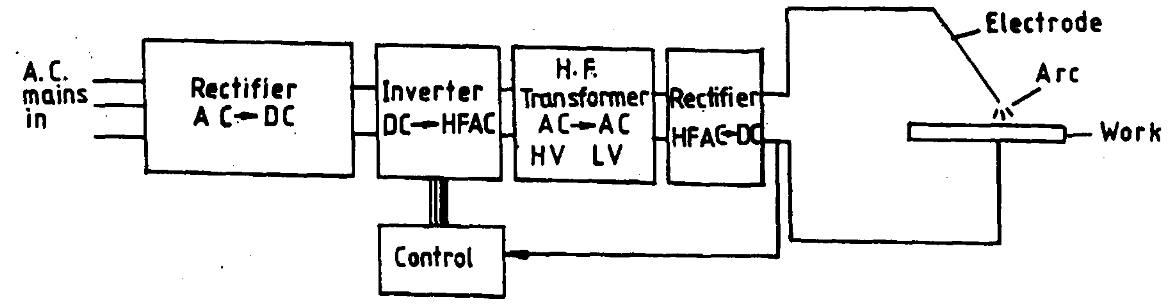
Electrode size and feed rate are accounted for by the peak current setting. The peak current is set just above the value that provides spray mode of metal transfer for that electrode diameter and feed rate. The spray transfer occurs during the peak current duration while globular transfer does not take place due to the lack of time at the background current level. Thus, it provides the deposition rate between those for continuous spray transfer and globular transfer.

Inverter Power Sources

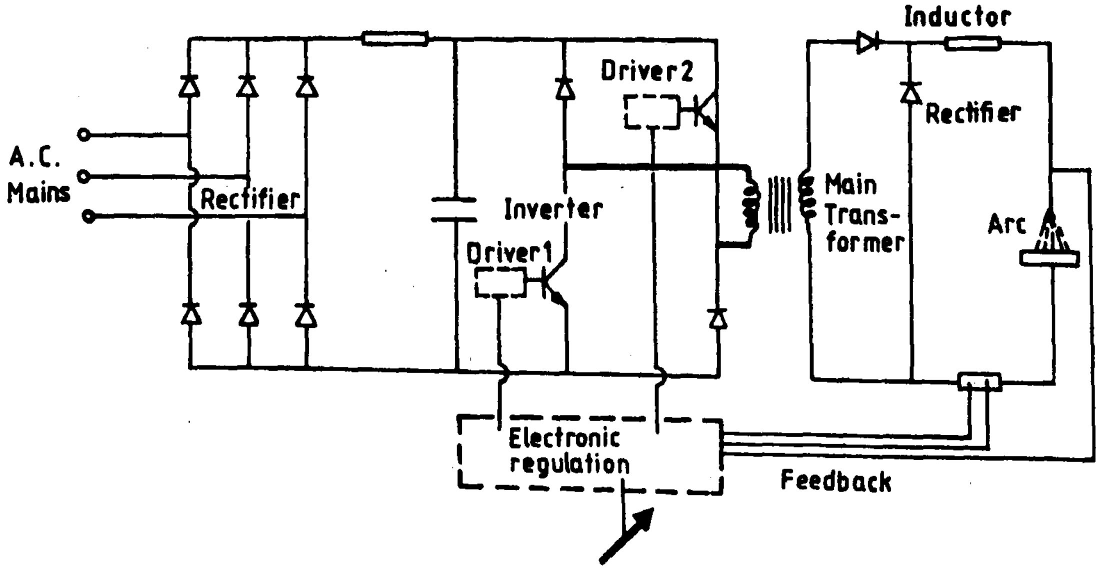
The d.c. rectifier welding power sources are generally quite heavy and the main cause of it is the weight of the transformer and the filter inductor. Earlier attempts to reduce the weight and mass by changing the copper windings to aluminium windings were not very successful. However to achieve the aim the use of inverter technology has proved very useful.

The conventional transformer operates at the incoming mains frequency of 50 Hz. Since transformer size is inversely proportional to supply frequency, reduction of up to 76% in power source size and weight are possible using inverter circuit shown in **Fig. 13(a)**. In this type of a power source the primary a.c. supply is first rectified and the resultant high d.c. voltage is electronically converted by the inverter to high frequency a.c. before feeding it to the main welding transformer. Since the frequency of operation is between 5000 and 50,000 Hz the transformer is small. Very compact and portable power supplies may be manufactured using this approach.

A typical rectifier/inverter circuit is shown in **Fig. 13(b)**. In this circuit the output power is controlled by using the principle of time ratio control (TRC). The solid-state devices (semi-conductors) in an inverter act as switches i.e. they are either 'on' and conducting or 'off' and blocking. This operation of switching 'on' and 'off' is sometimes referred to as switch mode operation. TRC is the regulation of 'on' and 'off' times of the switches to control the output. When the switch is 'on' the output voltage (V_2) is equal to input voltage (V_1). When the switch is 'off' output voltage $V_2 = 0$. The average value of output voltage, V_2 is given by,



(a) : Block Diagram



(b) : Circuit

Fig. 13 : Block Diagram and Circuit of an Inverter Welding Power Source

$V_2 = V_1 .\ (t_{on}/(t_{on}+t_{off}))$ ...... (1)

or $V_2 = V_1 .\ (t_{on}/(t_c)$

where, t_{on} - 'on' time (conducting)

t_{off} - 'off' time (blocking)

$t_c = t_{on} + t_{off}$ (cycle time)

V_2 is controlled by regulating the time ratio (t_{on}/t_{off}).

If f be the operating frequency then $f = 1/t_c$ thus, equation (1) can be rewritten as

$V_2 = V_1 . t_{on} . f$ .... (2)

TRC represented by equation (2) suggests two methods of controlling the output of an inverter welding power source viz., pulse width modulation i.e. by changing t_{on} and frequency modulation i.e. by changing *f*. The TRC controls enable the operator to select either constant current or constant voltage output and, with appropriate options, these power sources can provide pulse current outputs.

The inverter type of circuit was initially used for SMAW sources but is now being employed for GTAW and GMAW units.

Laser Welding

The world laser stands for 'Light Amplification by Stimulated Emission of Radiation'. The laser welding process is the focusing of monochromatic light into extremely concentrated beam, which when focused on a small area produces fusion. The intensity of laser beam is about 10^7 W/cm^2.

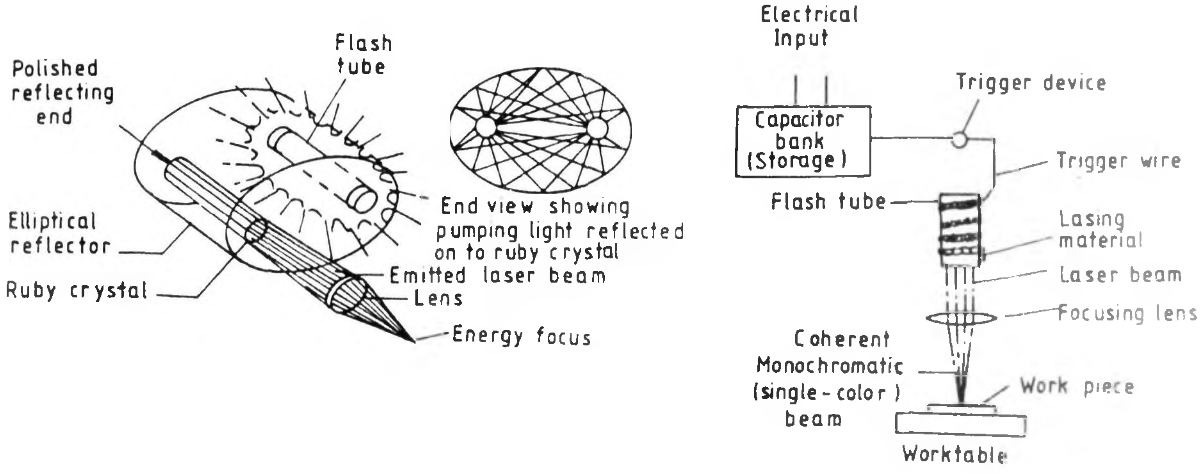
There are three basic types of lasers : the solid laser, the gas laser, and the semiconductor laser. The solid lasers are ones that rely upon some type of crystal e.g. ruby, sapphire and some artificially doped crystals e.g. Nd:YAG (neodymium-doped yttrium aluminium garnet).

The active material of a gas laser consists of a gas, or a mixture of gases, contained in a glass or quartz tube with highly polished mirrors at each end. Some of the gas lasers contained (i) 90% helium and 10% neon, (ii) mercury gas, and (iii) CO_2. The CO_2 laser is the most widely used gas laser with an efficiency of about 15% whereas most of the other lasers have efficiency range of 1 to 5%.

Both the gas laser and the solid state laser devices require a capacitor storage to store energy and then inject the stored energy into the flash tube. The semi-conductor injection type laser does not require the storage of energy or the pumping components, as the other two types do. Instead, electrical power is fed directly into laser light. Currently lasers of this type are of very low power intensities.

A laser welding system consists of an electrical storage unit, a capacitor bank, a triggering device, a flash tube that is wrapped with a wire, the lasing material, a focusing lens mechanism, and the work table which is operatable in three axes. The capacitor bank, when triggered injects energy into the wire that surrounds the flash tube. This wire establishes an imbalance in the material inside the flash tube, producing high power levels for very short period of time. The flash tube or lamps are designed for operation at a rate of thousands of flashes per second. An intense single flash source can have an output ranging up to tens of millions peak candlepower and a short arc light can have a flash duration of one microsecond. The laser is then activated. The beam is emitted through the coated end of the lasing material. It goes through a focusing device where it is pin-pointed on the workpiece. Fusion takes place and the weld is accomplished. A schematic of the laser welding system is shown in **Fig. 14.**

Laser welding is appropriately applied to enclosure welding with or without vacuum. Also, sensitive materials can be welded and glass-to-metal seals effected, such as in the construction of electrical tubes like Klystron tubes. The high temperature of the targets in the small tubes requires that cathodes be made of metals, e.g. Mo, Ta and Ti. The high m.p. of these metals make them nearly impossible to bond when using resistance welding techniques. A laser can weld these metals easily. Laser beams also have the capability to penetrate a quartz tube, welding the metal inside without harming the tube itself. In stainless steels



(a) : Principle of the Laser source

(b) : Laser Welding System

Fig. 14 : Laser Welding

welding the HAZ is virtually non-existent.

Robotic Welding Systems

Robotic welding is basically a part of the automated welding system but is being considered separately because out of all the technologies presently available robots are perhaps the most exciting and hence need special reference in welding automation. Articulated robots can closely emulate the productive actions of a man in the welding environment. and within limits provide an acceptable alternative for performing many of the monotonous and thus fatiguing tasks that are to be encountered in industry in abundance. In this context a robot can be a cost effective solution to many arc welding tasks.

At its simplest a robot is a manipulator that can be programmed at will. The manipulator is driven by actuators like electric motors and is controlled by a computer. Most welding robots have five or six axes about which they move. Some of these axes are linear and others rotational. The combination of linear and rotational axes makes a robot more or less suitable for a particular task or a range of tasks. The robot controller has a memory in which programmes can be stored and these programmes can be played at will. In this way programmes that are taught can be captured for future use. Because robots have this flexibility they differ from fixed automation which is dedicated to only one task. **Fig. 15** shows the essential elements of a robotic welding system using an articulated robot.

It is without doubt that robots cannot do all the work at present done by humans and it is doubtful whether they ever will. Where exotic materials are to be welded or where access is severely limited. where tolerance of pre-welding processes are not tight enough or where components cannot be adequately clamped during welding. the scope for using a robot is reduced. In spite of these limitations there are plenty of applications where a robot system proves its worth because welding can hardly fail to be a growth area since the operation is inherently labour intensive. often highly repetitive. and is environmentally an unpleasant occupation. thus it calls for skills which can fairly easily be transferred to the robot. It is also a coincidence that welding often involves the use of a work manipulator. a device which by virtue of its own movements can simplify the programme which

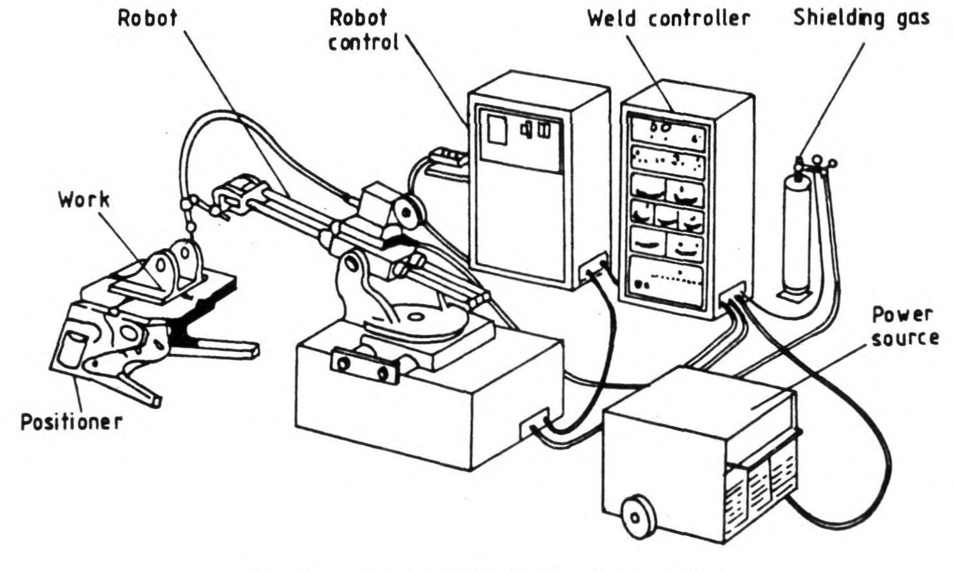


Fig. 15 : Industrial MIG Welding Robot Set-up

needs to be taught to the robot and can easily be interfaced with the latter. Thus, effective robotic welding is not only a matter of correct interfacing between control electronics and welding package but it also hinges on precision manufactured, programmable workpiece handling equipment, operating to within very narrow bands.

Narrow Gap Welding

Narrow gap welding is the term applied to any welding process used for joining of heavy sections (>30mm) with square butt or near parallel-sided edge preparation and a small gap of about 6.5 to 9.5 mm to yield a weld with low volume weld metal. Usually GMAW process is employed for making the welds but other processes like SAW and GTAW have also been successfully used.

The main aim of narrow gap welding is to reduce the weld metal with a view to achieving low cost, higher welding speed, reduced distortion and stresses, and to use one-sided welding technique. The volume of weld metal may be as low as 20% of the conventional methods as is evident from the comparison of edge preparation for SAW of 150 mm sections by the conventional and narrow gap methods shown in **Fig. 16**.

The power source used for narrow gap GMAW processes is of constant voltage type with a constant speed wire feeder but the welding head and nozzles are of special designs so as to be

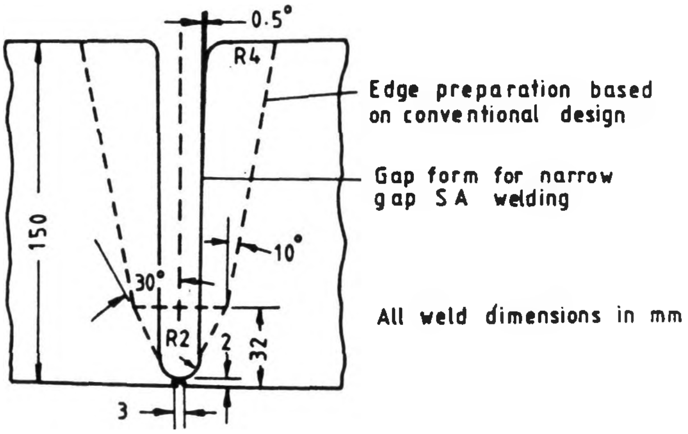
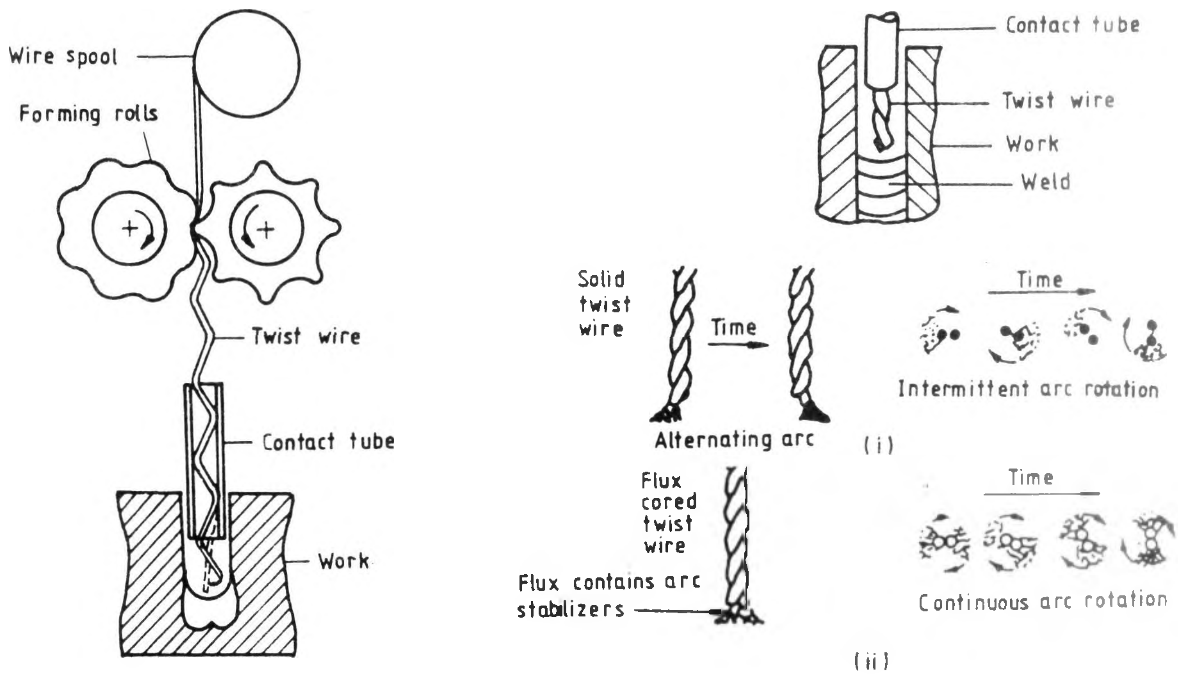


Fig. 16 : Comparison of edge preparation for conventional and Narrow Gap Welding by SAW process



(a) : Corrugated wire, with forming mechanism, for narrow gap welding

(b) : Narrow gap welding with twist wire
(i) Solid twist wire leads to intermitent arc rotation.
(ii) Flux-cored twist wire results in continuous arc rotation

Fig. 17 : Corrugated and twisted wire set-ups for Narrow Gap Welding

accommodated in the narrow gap. GMAW narrow gap process is a fully automatic method and can be used in all positions. Normally two electrode wires of about 1 mm diameter each are used simultaneously with one wire directed towards each of the walls. Each electrode requires its own constant voltage D.C. power supply and a wire feed system. The contact tubes are mounted on a carriage with fixed distance between them. However, narrow gap method can be used with one electrode wire also, which may be oscillated to achieve uniform weld deposit. The shielding gas used is a mixture of Argon with 20% to 25% CO_2.

The current used is about 230 to 250 A for 1 mm diameter electrode wire with electrode positive at 25 to 26 volts.

The travel speed is about 1-1.25 m/min resulting in heat input of 300 to 450 J/mm per electrode per pass. The nozzle tip-to-work distance is kept fixed at about 13 mm. Backing strip is required to initiate the welding process. This must then be removed usually by arc-air gouging and grinding before welding of the root runs. This is not only expensive and time consuming but also impairs the weld quality. About 4 passes are required per cm thickness of the work being welded.

To overcome the lack of side wall fusion the contact tubes are arranged so as to direct electrode wire to the proper point on the side wall, alternatively special electrode feeders are used to provide necessary curvature, corrugation or twist on the electrode wire, as shown in **Fig. 17** immediately before it goes to the contact tube. The contact tubes are normally water cooled and insulated to avoid short-circuit by contact with the side walls.

The limitations of narrow gap welding include relatively fragile welding heads, and the difficulties associated with repairs of such narrow welds. These difficulties are now being overcome by using a process with a gap of 14 to 20 mm and employing 3 electrode wires. When SAW or FCAW process is used then welding is carried out in downhand welding position but for all-position welding GMAW process with single electrode of about 3.2 mm diameter is employed with a current setting of 400-450 A and the voltage range of 30-37 volts. The shielding gas employed is usually a mixture of helium, argon and CO_2 in equal proportions.

The travel speed attained is about 40 cm/min. The power source used is of the direct current, constant voltage type but the electrode negative polarity is used. Whereas the metal transfer with narrow gap welding is of spray mode, it is globular with wider gaps. In this method the contact tube does not extend inside the gap thus it affords a long stickout with consequential considerable resistance heating of the electrode wire.

The major problem involved with both these versions of narrow gap welding is the preparation of weld joint so that the gap between the two parts to be welded is uniform. Whereas the tolerance allowed on gap geometry is (+1.5 mm/-0.0 mm) for a gap of 6 to 12 mm it may be up to (-0.0 mm/ +7.0 mm) for a gap of 16 to 20 mm.

Narrow gap welding can be used to weld carbon steels, high strength Q & T steels, aluminium and titanium. Specific applications of the process include welding of reactor pressure vessels, steam receivers and heat exchangers, large diameter drive shafts, heavy-walled high pressure water feeders, thick-walled pipes and full penetration welds in up to 900 mm thick components in nuclear power engineering.

Underwater Welding

Rapid growth in the off-shore industry in recent years has led to an increased demand for a reliable fabrication technique which can be used effectively for installation and repair of off-shore structures and pipelines. Welding with its intrinsic advantages is considered as an obvious choice.

The process of underwater welding is broadly divided into two types viz., Wet Underwater Welding and Dry Underwater Welding. Wet underwater welding is economical but results in poor quality welds with high hardness and tendency in hydrogen embrittlement. But the process is at its best in emergency repairs which can be followed up subsequently by more elaborate welding in dry docks or by excluding the water from around the site. **Fig. 18** shows the general arrangement for wet underwater welding using SMAW process.

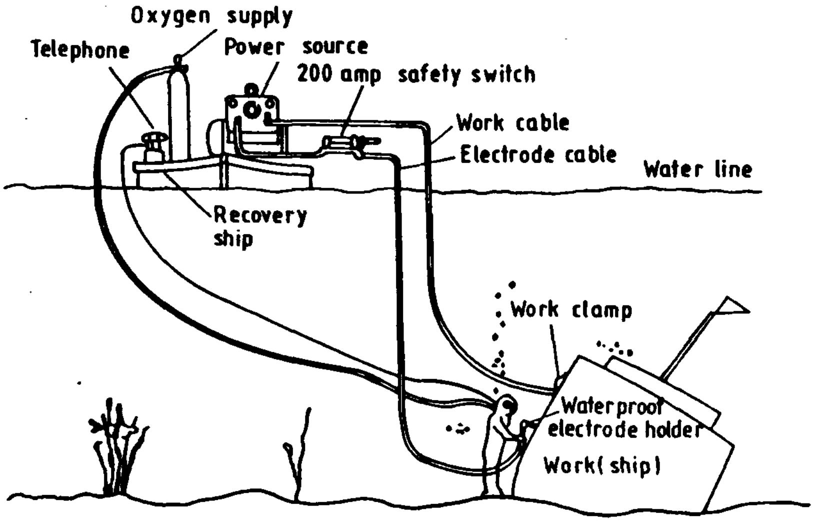


Fig. 18 : General arrangement for Underwater Shielded Metal Arc Welding

In Dry Underwater Welding the spot to be welded is covered by a chamber from which water is excluded under pressure. The welding so done is similar to that carried out in open air conditions except that the fumes and gases generated in the welding process affect the enclosed environment. However it is possible to produce high quality welds that meet X-ray and code requirements . Also, welding can be accomplished much quicker which results in major savings. **Fig. 19** shows a set-up for dry underwater welding of pipe joint. Dry underwater welding is a far more elaborate, complex and costly process than Wet Underwater Welding but gives the desired quality welds.

FUTURE PROSPECTS

With the coming-in of inverter technology. Laser welding systems and Robotic Welding units, the future seems to hold a big scope for the development of welding as an indispensable fabrication technology. Some of the developments which are really challenging and are expected to be put on firm footing in the first 20 years of the next century are:

1. Robotic systems in conjunction with laser welding and fibre optics.
2. Welding in space
3. Development of Artificial Intelligence and Expert Systems.
4. Residual Life Assessment of welded structures.

Brief description of these developments follows.

Robotic System with Laser Welding Unit

The basic features of robotic welding systems have already been described in Section 2.4. However, presently the work is in progress to use such systems in conjunction with laser welding and fibre optic technologies -- Nd : YAG laser is one such system.

Nd : YAG laser is very versatile as regards beam manipulation and also when one laser is required to work in multiple work stations. This is due to the fact that short wave length of 1.06 micron from Nd:YAG laser can be transmitted through a fibre optic with very little loss of power. This ability means that the laser beam can travel directly from the laser unit through a flexible cable to a laser gun mounted on an articulated wrist of a robot arm as shown in **Figs. 20 & 21**, without a significant loss of power. This makes Nd:YAG laser ideally suited to production automation. Moreover, the laser can be positioned at some distance from the production line and laser beam piped to it. One laser can operate

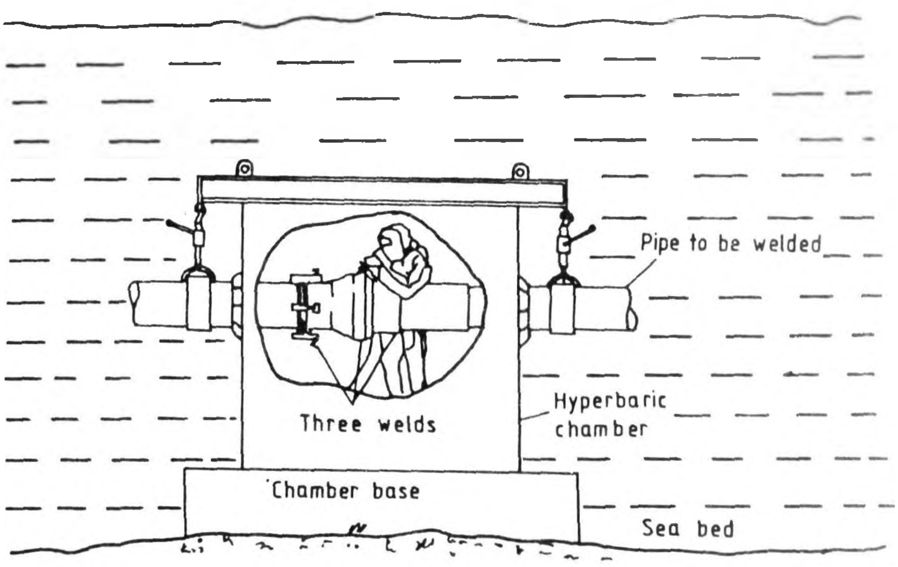


Fig. 19 : A set-up for Hyperbaric Welding of Pipe Joints

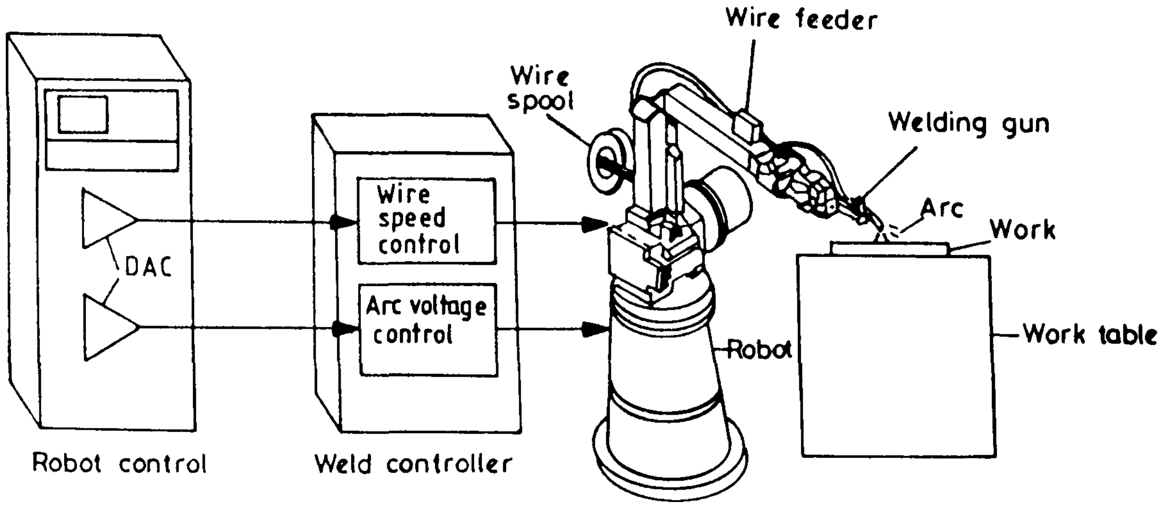


Fig. 20 : Essential elements of a Robotic MIG Welding System

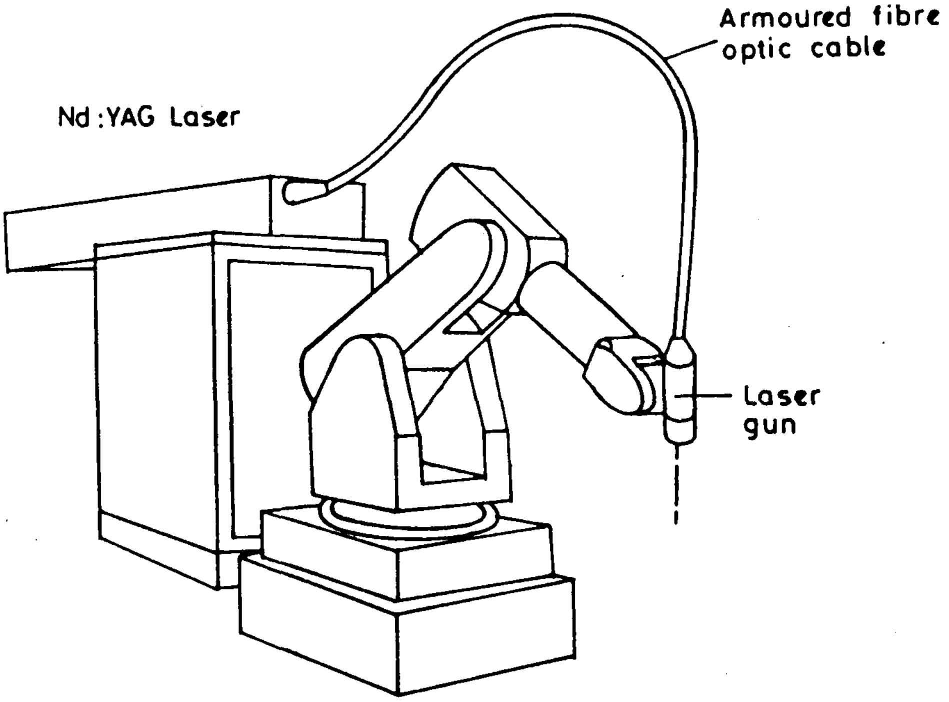


Fig. 21 : Use of Fibre Optic for transmitting an Nd : YAG Laser Beam to the Robot Welding Gun

multiple work stations for switching the laser beam from station to station; whilst welding at one station, part loading and unloading can take place at other stations. On the other hand, several very different stations can time-share one laser.

Welding in Space

With the development of large sized orbital stations housing many crew members, large sized radio telescopes, aerials, reflecting and absorbing screens, solar radiation engineering systems, etc. the need for inflight repair and recovery is growing with the extension of operation time, while the problems of deployment, assembly and erection become more and more urgent with the increase in mass and size of structures. Also, with the need for urgent attention to the sick satellites to keep the world-wide communication network running smoothly, it is becoming imperative to develop appropriate methods of material joining in space. Welding processes seem indispensable for use in space, where the conditions for welding differ radically from those on earth.

Compared with environment on earth, space is characterised by three main factors viz., zero gravity, high space vacuum and high contrast due to light-shadow boundaries.

Space and the special character of work in it require the insurance of the highest possible reliability of welding equipment, the absolute safety of the people who work with it and the elimination of risk of any spacecraft damages. Also, the tool developed should be characterised by compactness, low energy consumption, light weight and ease of operation. A versatile hand welding tool developed to satisfy all these requirements to the extent possible is based on the use of EBW and is named VHT, that is, Versatile Hand Tool. However, EBW is associated with high accelerating voltage and may result in generation of X-rays. Contact of the outer suit envelope with molten metal or electron beam can also lead to grave consequences.

In spite of the occurrence of the lack of penetration welding carried out in space is estimated highly.

Artificial Intelligence and Expert Systems

Artificial Intelligence (AI) is a field of study that is difficult to define due to the breadth of subject matter which is generally included in the definition. However, AI is often defined as the study of logic processes and concepts of understanding which are applied to activities that are usually thought of as distinctly human in nature.

AI does not necessarily require the use of computers; and for many years researchers have done a considerable amount of AI work without using computers. The computer however, represents a very powerful tool for the application of AI techniques. As a consequence, AI techniques, when coupled with the capabilities of modern computer systems, have produced amazing results.

Expert System as a part of AI is a scheme developed to emulate the behaviour of an expert. Here the expert is a person or a group of persons with identifiable expertise in a specific area of a particular field of knowledge, say welding. Expert System can take a variety of forms and when used appropriately they can have amazing results.

The expert system concept takes the knowledge of an expert and stores it on a computer disk. The information is then retrieved in a logical sequence, patterned on human reasoning. In other words, expert systems utilise the logic processes of AI and the decision-making rules of an expert to make logical deductions. Such deductions, when applied within the knowledge domain of the expert system, generally yield the same answers as the expert whose rules are incorporated in the system. Thus, in certain instances, expert systems can be used to replace human experts in decision-making situations.

An expert system is thus an intelligent computer programme designed to simulate the knowledge and reasoning of a human expert or a group of experts, and make that knowledge conveniently available to other people in useful ways. There are three fundamental modules of an expert system. These are :

1. Knowledge base
2. Inference engine
3. User interface system

The 2 and 3 modules constitute THE EXPERT SYSTEM SHELL. The relationship of these modules are shown in **Fig. 22**.

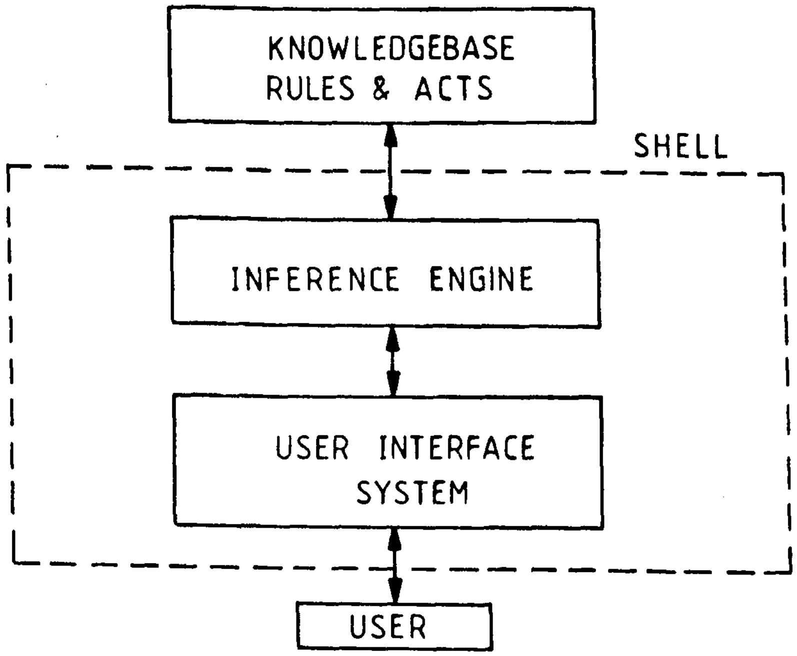


Fig. 22 : General Structure of an expert system

Residual Life Assessment of Welded Structures

All fabricated components/structures are expected to have some estimated service life. However, that does not mean that once such a component/structure is put to service it will be discarded at the end of the estimated life or that it is not ever to fail before that time. To ensure safe working without having to deal with unexpected failures, it is customary to inspect the component/structure at regular intervals to check its soundness. This is more so with welded structures as welds, almost invariably, have some discontinuities or defects which lead to premature failures. The defect which usually leads to such failures is some or the other form of crack which once it attains a critical length runs through the weld seam at unbelievably high speed leading often to catastrophic failure.

Once a crack has been detected it is imperative to repair it. However, in case it is not possible to do so, measures are taken to assess the residual life of the component/structure with the crack so that necessary steps may be taken to replace it quickly at the end of its life to avoid undue delay in recommissioning the unit. To do so it is essential to assess its fitness for service.

Fitness for Service (FFS) is generally understood as the ability of a given equipment to serve satisfactorily under a given set of service conditions for a reasonable period of time to be considered for economic operation. This, in other words, involves deducing the acceptable critical sizes of defects/cracks or extent of material deterioration beyond which the equipment cannot be adjudged as suitable for continued service.

Residual Life Assessment (RLA), therefore, can be understood as the time period through which the equipment shall retain the fitness-for-service characteristics, in spite of the presence of known cracks and other defects.