INTRODUCTION TO WELDING AND ALLIED PROCESSES

INTRODUCTION:

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

A large number of welding & allied processes have come into industrial use in the last 30 years. Variations & extensions of these processes are being developed & put to practical from time to time. The wide range & variety of these processes enables the modern engineers to join almost all-commercial metal & alloys in many different sizes & in thickness ranging from a fraction of a millimetre to 2000mm and above.

Welding of plain carbon steels, low alloy steel, & heat resisting steels, and many non-ferrous metals & their alloys (such as aluminium, nickel copper) are in routine commercial application and metals such as Titanium, Columbium, Molybdenum & Zirconium are welded extensively for missile, jet aircraft, & nuclear power plant industry. Modern industrial products such as automobiles, railway rolling stocks, transmission pipe lines, pressure vessels, storage tanks, machinery, power generation equipment, offshore platforms, oil refineries, and fertiliser plants which have contributed to material prosperity of man kind, owe their development and efficient performance to Welding.

DEFINATION OF WELDING:

The American Welding Society (AWS) defines weld as a localised coalescence of metal or non-metal produced either by heating the materials to suitable temperatures, with or without application of pressure, or by the application of pressure alone, and with or without the application of filler materials.

Indian Standard IS: 812-1957 defines the weld as “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 affect 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 materials between the parts. A filler material, the melting point of which is of the same order as that of the parent materials, may or may not be used.”

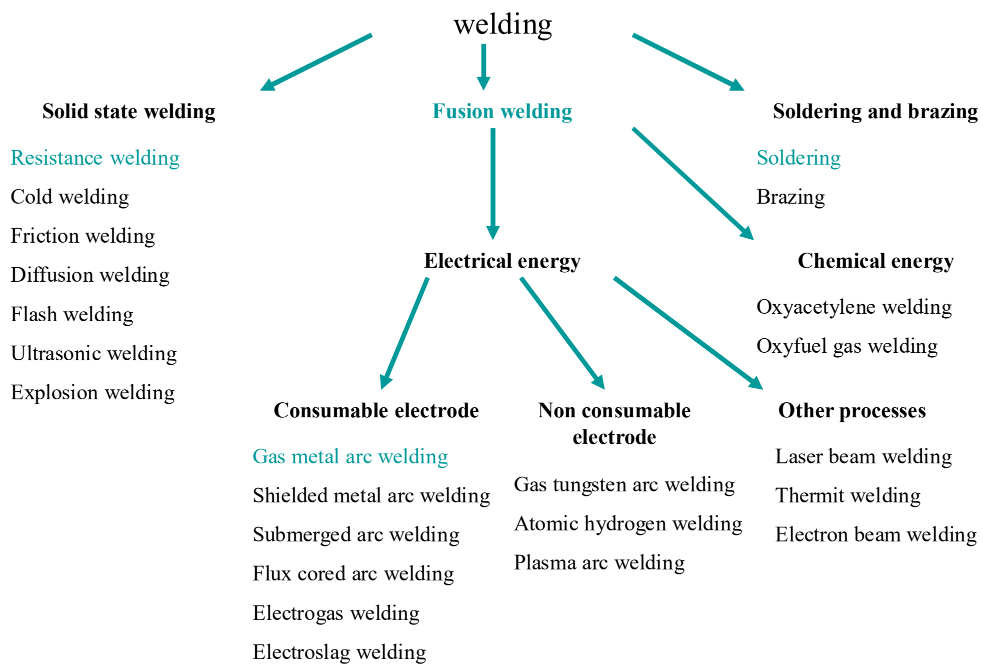
To elaborate, a weld is a localised coalescence (unite into a body) or union of metals. This implies that in welding, the abutting surfaces grow together into a common mass, so that the joint has metallic continuity. The ideal weld is one in which there is perfect continuity between the parts joined, such that every part of the joint is indistinguishable from the metals in which the joint is made.

The ideal joint is never achieved in practice, because the microstructure & mechanical properties are not identical over the entire joint & the original metal. Yet, welds which give satisfactory service can be obtained by selecting proper welding processes, type of joint & Procedure.

WELDING & ALLIED PROCESSES: Welding has a large number of variation and diversity. However, Welding and allied activities may be broadly classified in four distinct categories, namely:

- Welding.
- Braze welding.
- Brazing.
- Soldering
- Thermal cutting.
- Thermal spraying

Diversity of welding processes



BASIC REQUIREMENTS OF A WELDING PROCESS:

In welding, energy is the basic requirement to effect coalescence. Almost in all cases, the energy is used in the form of heat to melt the joint interface or to bring it to a plastic state. The source of energy is widely varied; starting from mechanical working, electrical energy, chemical energy, sound energy, about all forms of energy are used including even light energy and kinetic energy! However, electrical energy and chemical energy are the two most common forms in use. Naturally, the welding equipments to convert these energies to heat also vary widely.

The next most important aspect in welding is protection of molten and very hot metal from oxidation. This shielding is done either by producing fumes by burning fluxes or by supplying jet of gasses (inert or active) separately near the weld area during welding. The flux may be provided along with the consumable electrode as in Manual Metal Arc (MMAW) and Flux Cored (FCW) welding or separately as in Submerged Arc (SAW) and Electro Slag (ESW) welding.

Apart from shielding the molten and hot metal, flux also has the function of refining the molten metal. De-oxidiser like Silicon, Manganese etc. are added to flux, which reacts with metal oxide to form slag and float at the top thus leaving a clean metal below. Alloy addition, when needed to control the weld metal chemistry is also done through flux. However, except in FCW, alloy addition through flux runs a risk of non-homogeneity of weld metal chemistry.

The third important consideration in welding is filler metal. If the thickness of the material is such that the whole cross section can't be melted in a single pass, edge preparation by the way of beveling and maintaining some distance between the two plates are necessary to reach the bottom cross section. To fill up the gap, filler metal is to be provided. The core wire in MMAW and the continuous wires in other types of welding are used for this purpose. For joining thin sections, filler metal may not be necessary. In such cases, non consumable type electrodes or other devices are used to provide the heat.

CLASSIFICATION OF WELDING PROCESSES:

There are many ways of classifying welding processes, like:

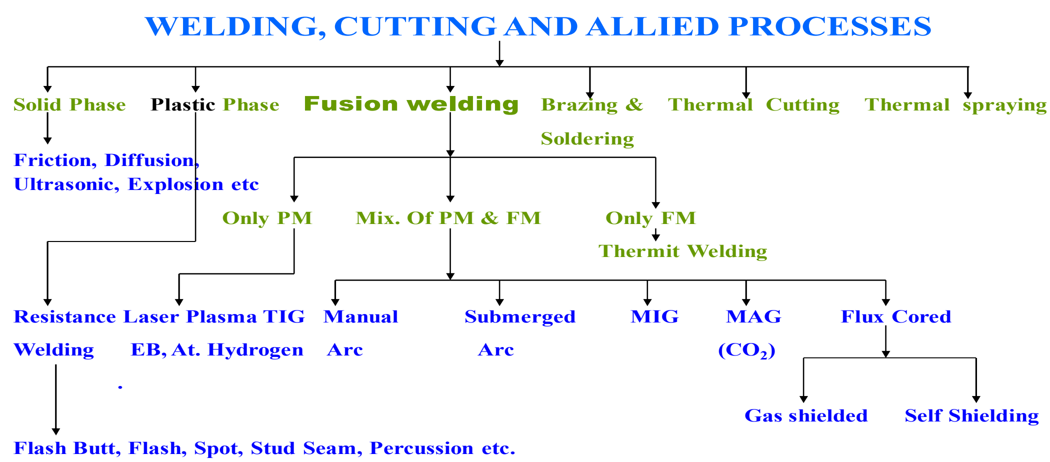
- Based on Source of Energy
- Based on State of Weld Zone
- Based on Weld pool composition
- Based on Degree of Automation etc

We will adopt the classification based on State of Weld Zone & Weld pool composition. In Indian Railways, majority of application is of fusion welding. By far, worldwide it is the most commonly used welding process for almost all materials. As the name suggests, melting of metal at the joint face and subsequent solidification is involved. This leads to gross change of metal composition (in case of using filler material), microstructure and associated material properties. The process is prone to various defects as both welding defects and casting defects are involved.

Some commercial application does not call for thorough melting and solidification along the join interface. In such cases and also in applications where lesser welding defects are desired, joining is accomplished by applying pressure after bringing the material into plastic state by application of heat like Flash Butt Welding, Spot Welding, Friction welding etc. Though in lesser degree, change in material properties is unavoidable due to change in micro structure during application of heat

In some very specialized applications where service requirements are met through close control over microstructure, even heating to an appreciable degree is also not permitted. In such cases, bonds are formed by pressure alone like explosive welding.

There are processes which are combinations of these principles by application of heat over a very small area, may be in the atomic scale. Electron Beam Welding, Atomic Hydrogen welding, LASER welding etc. are examples of such processes.



THE KINGDOM OF WELDING

From the figure above, it is evident that variety of processes has been evolved to meet various requirements. In Indian Railways mostly Fusion welding and a few Plastic phase welding are followed. The basic operating principles of some important processes are discussed below.

FUSION WELDING PROSESSES:

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 addition of filler metal. A fusion weld made without the addition of filler metal is called Autogenous. In most cases, fusion welding involves the use of filler metal.

Metal arc welding:

Manual metal arc welding:- This is a group of processes in which heat required for fusion is generated by the electric arc formed between a metallic electrode & the base metal. The electrode is consumed in the arc & provides the filler metal for the joint. The electric arc is an ideal source of welding heat. The extremely high arc temperature of over 5000^0C permits it to supply a large amount heat to a small area. Hence the melting in the base metal is restricted to a narrow zone. Among the arc processes, **manual metal arc** is the most common, versatile and inexpensive one and account for 60% of the total welding in advanced countries and over 90% 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 wire (diameter 6.3-1.6mm, length 450-250mm). It needs a power source, either a transformer supplying AC or generator/ rectifier supplying DC.
The process is suitable for the entire range of plate thickness, 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 (Fig-1).

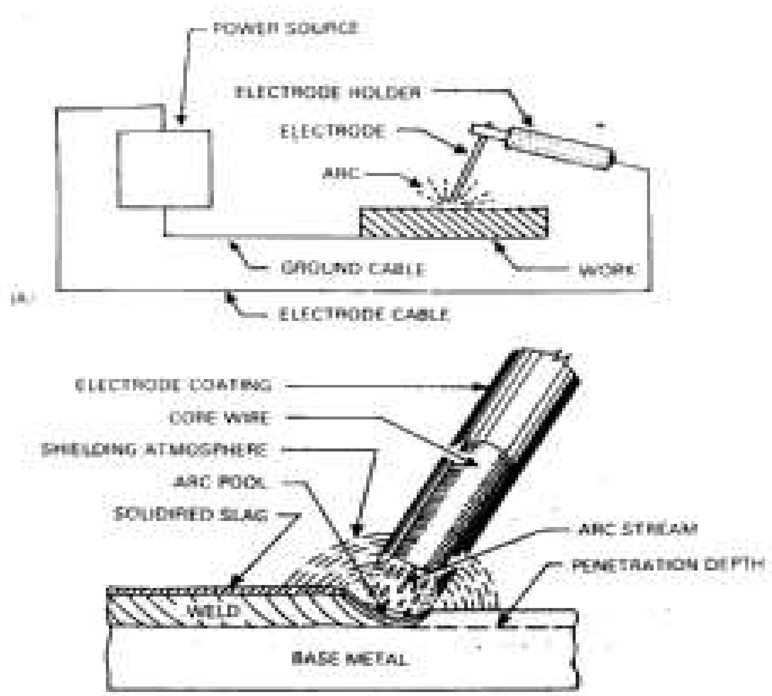


Fig 1: Manual Metal Arc Welding (a) welding circuit (b) welding arc in action

Submerged-Arc Welding: -This is mostly used as a fully- automatic process, and sometimes as a semiautomatic 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 fed into the welding groove, which performs the same functions as the coating of a manual electrode. The arc is created between the continuous wire lowered through the flux and the base plate. The arc remains covered by the flux, hence the name. As the arcing continues either the welding or the welding head moves, feeding the flux ahead of flux from a hopper. The arc length is automatically controlled. The power source can be a transformer (AC) or a generator/rectifier (DC). It is generally of high capacity, say 750 or more, even up to 3,000amps.

In semiautomatic welding, the operator guides the flexible welding head along the groove. In doing so he controls the speed of travel and the line of travel. Controlling the line is difficult, because the arc is submerged. Hence this version is usually restricted to fillet weld and grooved butt weld.

In fully- automatic welding, the welding head is mounted on a trolley, which travels along the joint. 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, and stainless steels. It is ideal for heavy thickness. For thin sections, weld backing is necessary to avoid burn-through. It is commonly used for fabrication of plate girders, pressure vessels, pipes and penstocks, for surfacing & strip cladding. In strip cladding, the electrode is in the form a strip, usually 1.6mm X75mm wide (Fig-2).

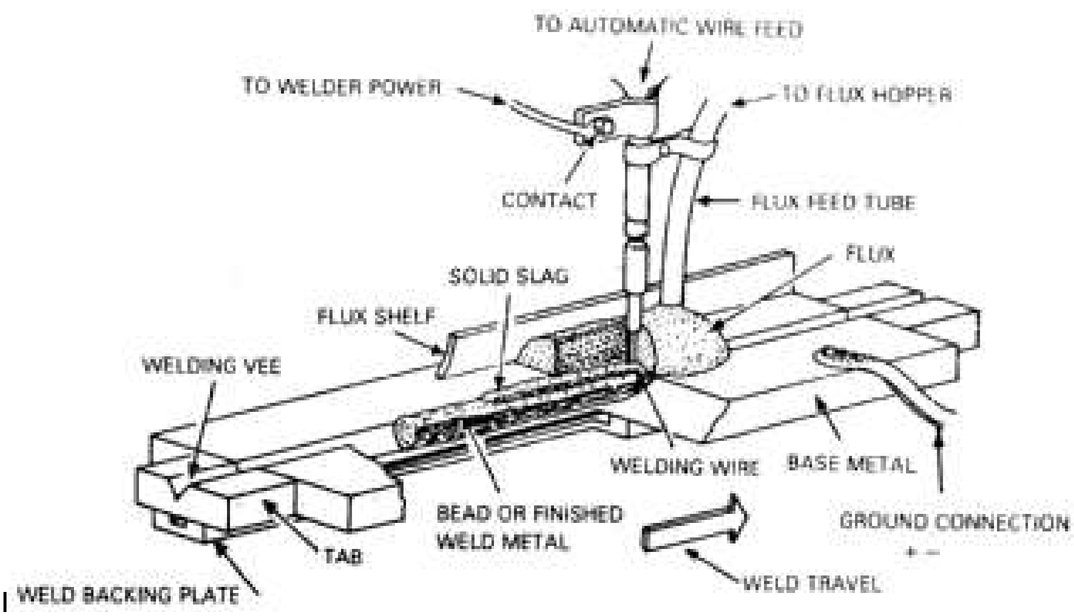


FIG 2: Diagrammatic sketch of Submerged Arc Welding (SAW)

MIG Welding: MIG (Metal–Inert-Gas Welding) is also known as GMAW (Gas–Metal-Arc Welding). In this process, coalescence is achieved by an electric arc formed between the work piece and a continuous consumable solid wire electrode, which is fed through a gun at controlled speeds. Inert gas flows through coaxial passage in the gun and forms a blanket over the weld puddle to protect it from atmospheric contamination.

The welding can be semiautomatic or fully mechanised. In semiautomatic version, the welder concerns himself only with gun-to-work distance, gun manipulation, welding speed. Wire feed rates, electrical settings, and gas flow is pre-set. When the equipment is

completely mechanised, all of these variables and welding functions performed automatically without the need for a welder.
The power source is a rectifier or motor generator giving DC. DCRP (Direct Current Reverse Polarity i.e. electrode to positive terminal and job to negative terminal) is used, as it gives better melting, deeper penetration and better cleaning action.

MIG is a versatile process, and is gradually replacing manual metal-arc and TIG welding. Most metals can be easily welded including aluminum, 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 preferred, because it avoids the use of expensive argon gas (Fig-3).

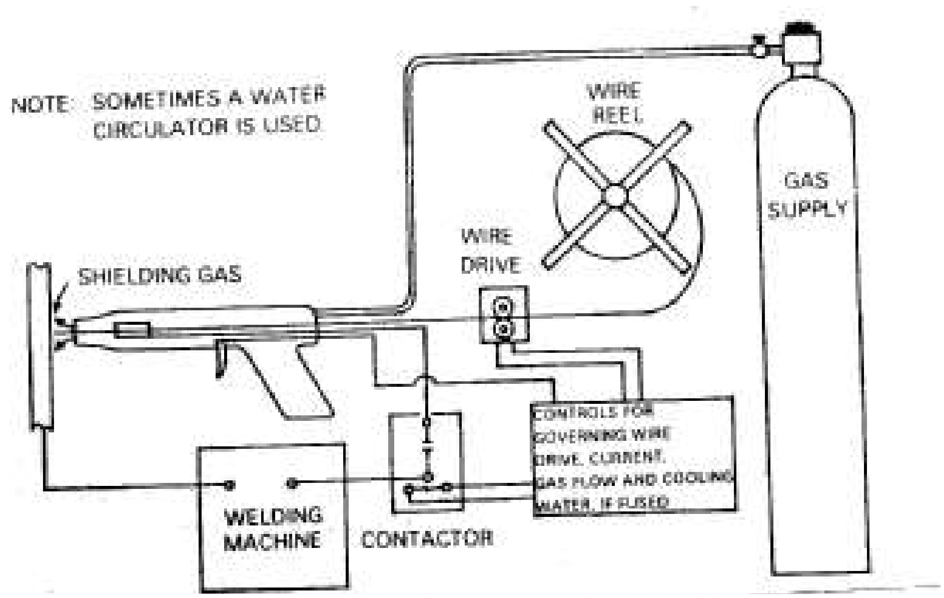


Fig 3: Schematic diagram of MIG/MAG (CO_2) Welding

MAG (CO_2) Welding: MAG stands for metal active-gas arc welding. This is a variation of MIG welding, in which identical equipment is used but chemically active gas mixture or carbon dioxide replaces the inert argon gas. However, the CO_2 gas tends to form Dry Ice while coming out from high pressure cylinder. To prevent choking, one tubular heating arrangement is kept just at the outlet, through which the gas is passed. The term gas-metal-arc welding (GMAW) is also applied to the MAG (CO_2) process. CO_2 welding is gradually replacing MMAW in the fabrication of structural, pipes, automotive products, storage tanks, and machinery, etc. (Fig-3). In RCF a proprietary gas mixture containing 90% CO_2, 5% Argon and 5% Oxygen is being used.

Flux-Cored Arc Welding: This is an extension of the MIG/MAG process. A tubular wire whose core is filled with flux replaces the continuous solid wire. The equipment is the same as used for MIG/MAG welding. The flux performs the same functions as the coating of a manual electrode. For welding alloy steels and for hard-facing applications, suitable alloying elements are also included in the flux. Flux-cored arc welding is normally performed with a additional 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 USA and Japan for structural and hard facing applications. When such wires are used, the process is known as self-shielding or gas less (Fig-4).

The process gives the best of both worlds. It is versatile like MMAW as the basic shielding moves along with the wire. Again it can give high degree of automation and high rate of production due to the continuous nature of the electrode. Moreover unlike other welding processes, where alloy steel core wire is to be used, alloy addition is most simple in FCW. Plain mild steel sheath is used in all the cases and varying amount of alloy addition depending on the end product requirement is added in the flux. This gives a high degree of flexibility and scope of inventory control for manufacturer.

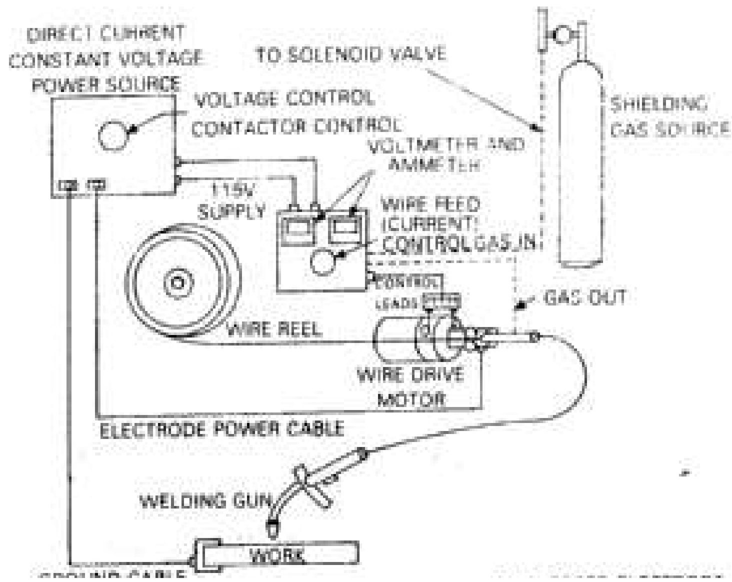


Fig 4: Schematic diagram of Flux Cored Arc Welding (FCAW)

TIG Welding: TIG (Tungsten-Inert-Gas) welding is also termed as GTAW (Gas-Tungsten-Arc Welding). In this process, an arc is struck between a non-consumable tungsten electrode and the base metal. The inert argon or helium or argon-helium mixture shields the arc. A filler wire may or may not be used. When it is used, the welder feeds it externally into the arc in the form of rod or strip. The welder also has to control the arc length and arc travel speed. An AC power source is used for welding aluminum & its alloys, while a DC source is used for other metals. This is an ideal process for welding non-ferrous metals and stainless steels of limited thickness. TIG is also preferred for depositing the root pass in the pressure piping, where welding from inside is not possible (Fig-5).

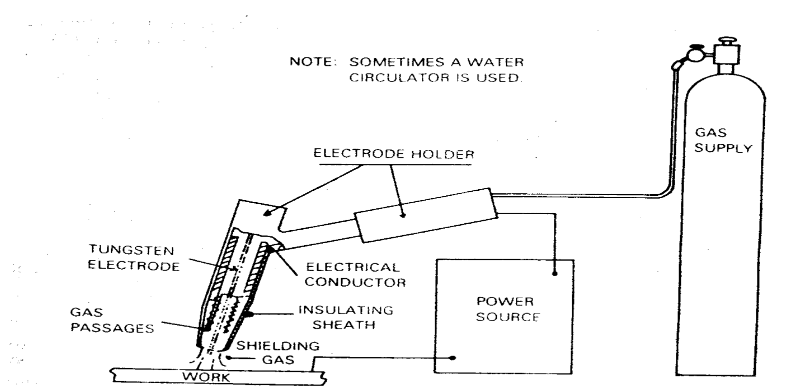


Fig-5 SCHEMATIC DIAGRAM OF TIG WELDING

Arc Spot Welding: In this process, coalescence at the overlapping surfaces is produced in one spot by heating with an electric arc between an electrode and the work. The weld is made without preparing a hole in either member. Filler metal or shielding gas or flux may or may not be used. The arc is produced by using either of the carbon arcs, TIG, MIG processes. Arc spot welding by 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 from one side only (Fig-6).

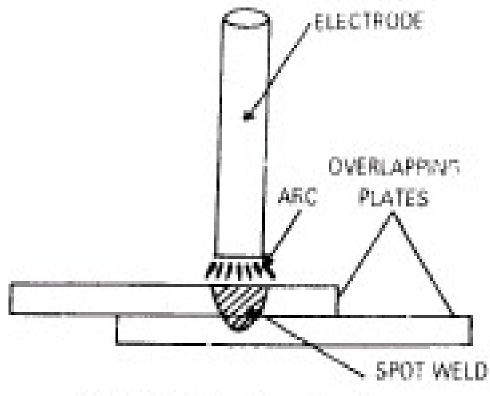


Fig 6: Schematic diagram of Arc Spot Welding

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, and hydrogen is sometime used. Hence appropriate term of this process is oxy fuel or oxyacetylene welding. Filler metal may or may not be used.

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

Primary stage: $C_2H_2 + O_2 = 2CO + H_2$

The primary combustion provides the actual flame for welding, with temperature up to $3{,}000^0C$ in the inner cone.

Secondary stage: $2CO + H_2 + 11/2\ O_2 = 2CO_2 + H_2O$

Oxygen
from air

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 that 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 process. It is used considerably more for general maintenance work including thin sheet welding, hard-facing, welding metals of low melting points (especially non-ferrous metals) and performing such operations as brazing, soldering and thermal spraying (Fig-7).

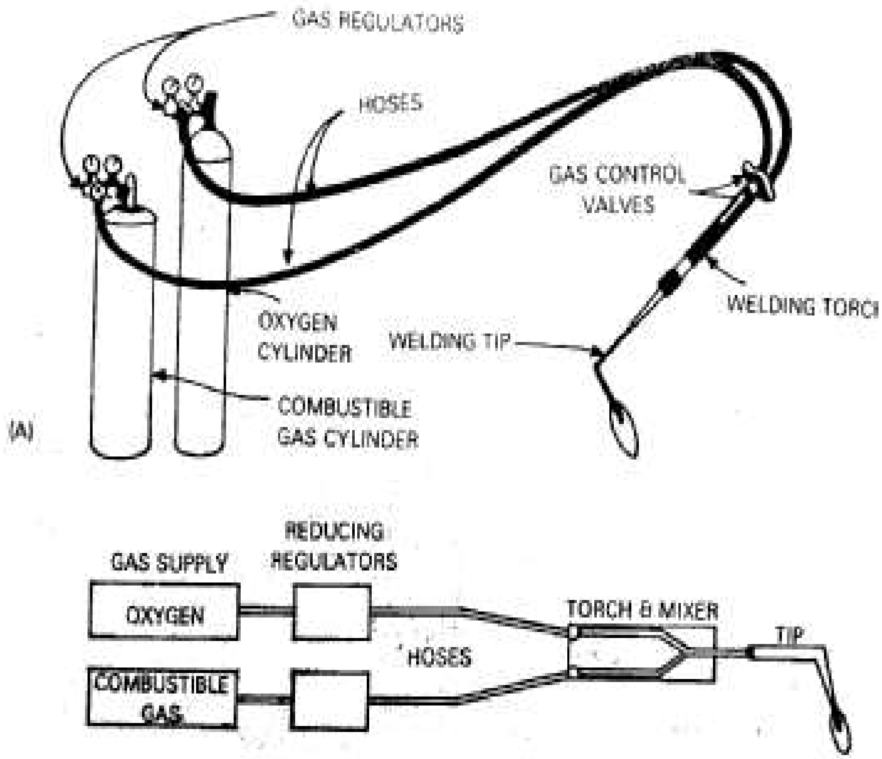


Fig-7:Oxyfuel welding: (a) Schematic diagram of the process
(b) Sketch of the welding torch

Neutral flame **Oxidizing flame** **Carburizing flame**

Fig 8: Different flames produced by controlling the gas flow

Thermit Welding: This process utilises the intense heat developed during the reaction between iron oxide and aluminum. When a mixture of three parts of iron oxide and one part of aluminum by weight is locally heated with a special a special ignition powder, a vigorous reaction takes place which proceeds rapidly through the mass, resulting in the formation of aluminum oxide and iron, and a considerable amount of heat.

The reaction

$$Fe_2O_3 + 2Al = 2Fe + Al_2O_3 + 181.5 \text{ K. Cal}$$

$$3FeO + 2Al = 3Fe + Al_2O_3 + 160 \text{ K. Cal}$$

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, the 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 preheated joint to be welded by a sand mould, which is fastened around the work.. By virtue its super heat, the Thermit metal melts a portion of the base metal with which it becomes in contact. Upon solidification of this melt, the mould is removed and the extra metal is chiseled out while red hot.

The process is the only effective process for welding the railway tracks in situ. It is also sometimes used to repair heavy broken parts such as mill rolls (Fig-9).

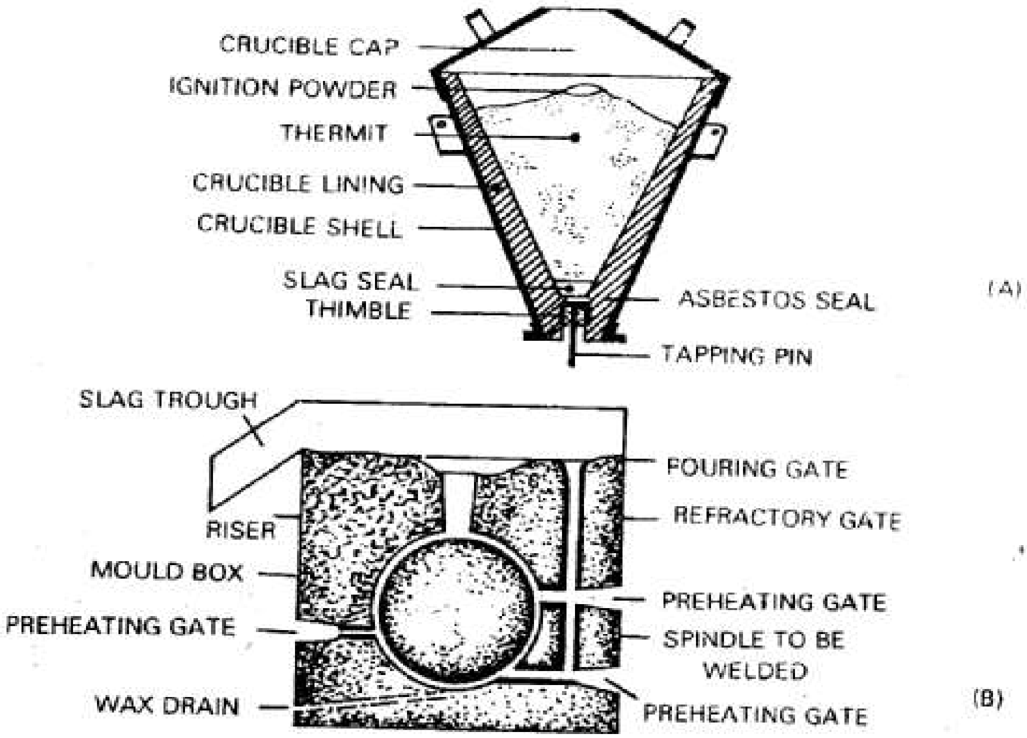


Fig 9: Diagrammatic sketch of Thermit Welding (a) Refractory crucible For Thermit reaction (b) Sand mould containing the joint

LASER welding: In this process, fusion is achieved by directing a highly concentrated beam of light about the diameter of a human hair to the spot to be welded. LASER (Light Amplification by Simulated Emission of Radiation) has a higher energy concentration than even an electron beam. A monochromatic spatially coherent beam of light of 0.001 inch diameter can be produced with very high heat concentration. Since the heat input to the work piece is extremely small, the size of the heat-effected zone and the thermal damage to the adjacent parts of the weld are negligible. Carbon-di-Oxide, Nd:YAG (Neodymium Ytrium Garnet), Ruby are the commonly used LASER producing materials. Laser can be used to join dissimilar metals and other difficult-to weld metals such as copper, nickel, tungsten, aluminum, stainless steel, titanium and columbium. The current application of laser welding is largely in aerospace and electronic industries, where extreme control in weldment is required. Its major limitation is the shallow penetration (less than 5mm). In ICF and RCF, LASER welding is being used for joining thin sheets and cutting of SS. During cutting high pressure, 14bar, N_2 gas is used for blowing off molten metal. During welding, the same gas is used at the flow rate of 40L/min for providing shielding.

Plasma Welding: Plasma is considered the fourth state of matter, the other three being solid, liquid, and gas. Plasma is a gas, which has partially dissociated into positive ions, and negative electrons. Plasma is formed when an electric 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, moving gas streams easily blows the plasma away. 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 utilization 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 or air) is fed through the arc, it becomes heated to the plasma temperature range ($30,000^0$ to the $60,000^0$F). The plasma tail-flame comes out of 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 work piece. In the latter, the arc is formed between the electrode and the constricting orifice inside the torch.

Plasma arc 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. When the plasma jet strikes the metal, it cuts entirely through the work piece 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. Butt welds of 12.5 mm or larger thickness are possible in a single pass without edge preparation or filler metals. The process can weld Carbon Steels, Stainless Steels, Copper, Brass, Aluminium, Titanium, Monel, and Inconel (Fig-10).

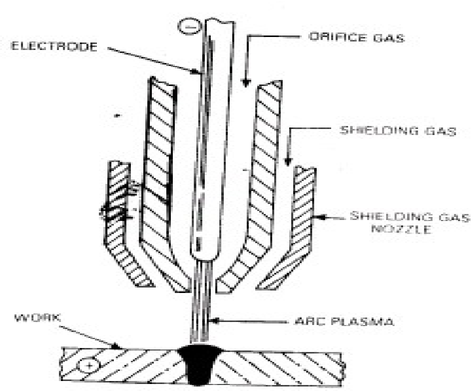


Fig 10: Sketch of Plasma Welding

Plasma MIG welding is an extension of plasma arc welding in which the non-consumable tungsten electrode is replaced by a consumable continuously fed metallic electrode.

PLASTIC PHASE WELDING:

These processes may also be termed as Electrical Resistance Welding Process as resistivity property of a metal to the passage of electricity is invariably used in all cases. In these processes, the coalescence is achieved by passing electric current through the metallic parts by inserting them into a circuit. The electric resistance produces heat particularly at the joint interface because of the micro gap. When the interface becomes plastic because of high temperature, then pressure is applied to effect final bonding. These types of welding are placed in between the fusion and solid phase processes, because it is difficult to decide whether they are fusion processes or solid state processes as evident from below:

- 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, but a small molten nugget 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 0.005mm.

Resistance Butt Welding: This process is also known as upset butt welding or simply butt-welding. Here, the temperature 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 acts as conductors for the low voltage electric supply and electric current is passed through. Force 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 11).

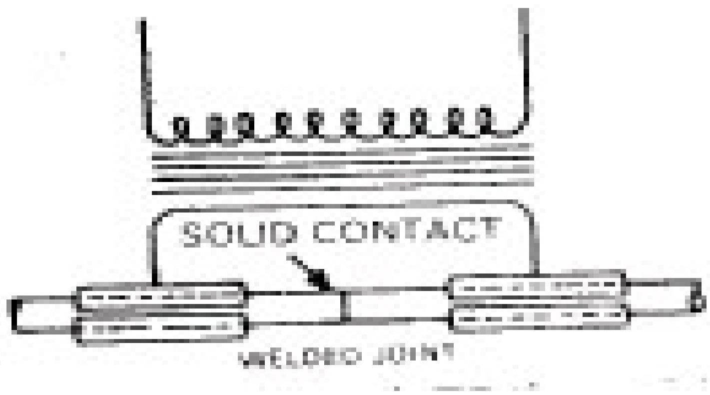


Fig 11: Sketch of Resistance Butt Welding

Flash Butt Welding: This process is an extension of resistance butt-welding. The parts to be joined are mounted on platen and gripped in the clamps attached to secondary circuit. By forward movement of platens, the end faces, which are machine cut to ensure parallelism, are gradually brought into contact to complete the secondary circuit. When the welding voltage of about 10V is applied at the clamps, current flows through the initial points of contact causing them to melt. These molten bridges are then ruptured by moving the platen in reverse direction and small short-lived acres are formed.

The platens on which the movable clamps are mounted move forward again, making fresh contacts elsewhere and the cycle of events are repeated. In these subsequent cycles, voltage also is increased gradually. All the parameters are pre-set in the control panel. After a few such strokes, the metal contained in the molten bridges starts expelling violently in a spectacular manner by flashing.

Flashing is allowed to continue until the surfaces to be joined are uniformly heated or molten. After a predetermined number of cycles, the current is put off and the platens are moved forward with force so that the end faces collide with pre set force. The molten metal containing oxides is expelled. The total distance up to the point of upset is known as the flashing allowance. 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. (FIG12)

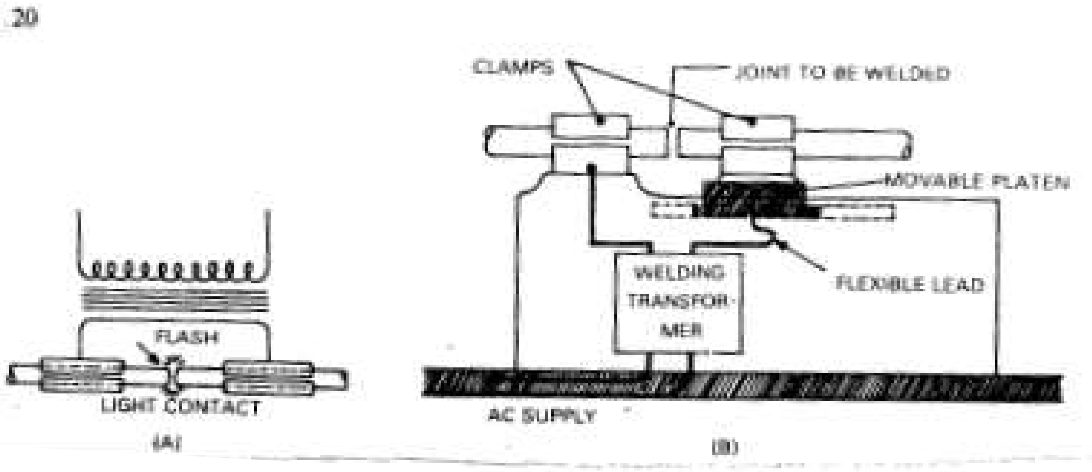


Fig 12: Flash Butt Welding: (A) Sketch of Joint Set Up (B) Schematic diagram of equipment.

Resistance 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, the current is switched off and more pressure is applied through the electrodes. 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 performed with a machine in which all the parameters can be controlled & preset. The process is used on a large-scale in ICF for fabrication of super structure, automotive production and in sheet-metal fabrication (Fig 13).

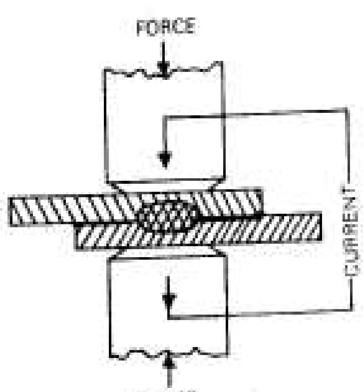


Fig 13: Sketch of Resistance Spot Welding

Roller Spot Welding: This is an extension of the earlier process devised for faster production**.** 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 at a predetermined distance while individual welds are made. Current is passed intermittently when the electrodes are stationary (FIG 14).

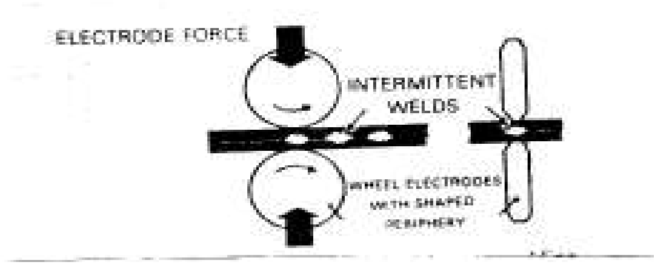


Fig 14: Sketch of Roller Spot Welding

Roller Seam Welding: Seam welding is similar to spot welding, except that the copper-alloy electrodes in the form of circular rollers carry current continuously. The overlapping sheets are held under constant pressure between the roller electrodes, which rotate at constant speed and carry current. A series of spot welds whose nuggets overlap each other, is formed which give the appearance of a continuous weld seam. A common application of seam welding is in the manufacture of steel drums (Fig-15).

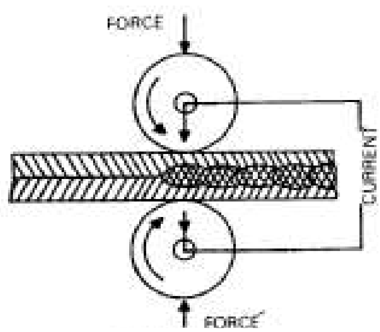


Fig 15:Sketch of Seam Welding

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. The joint edges are in intimate contact and the roller electrodes travel directly over the seam. The process is used in production of welded tubes (Fig-16).

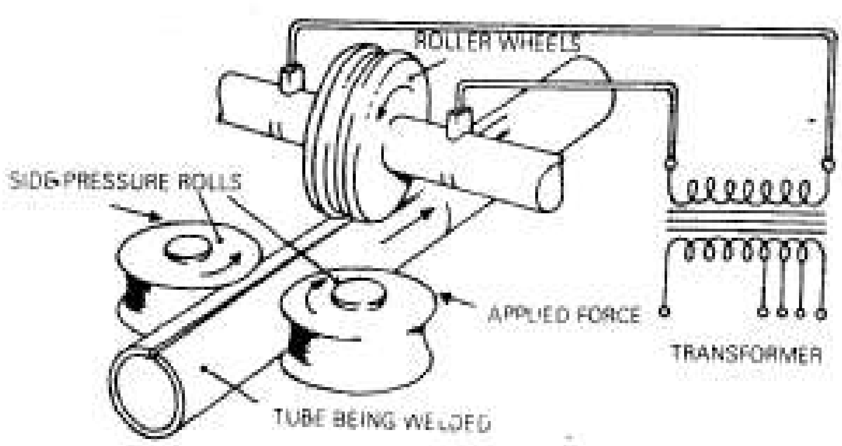


Fig 16: Diagrammatic Sketch of Butt Seam Welding

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 filler metal. In some of them pressure is used. With the exception of cold welding and ultrasonic welding, all the process involves 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 sources of heat), placing these surfaces in contact, and hammering them together to form a weld. The surfaces are heated below the melting point to make them somewhat plastic. The oxidizing flame of the fire produces a liquid film of iron oxide on the surface, which is squeezed out more or 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 semiautomatic or automatic process in which a heavy hammer is powered by steam, hydraulic or pneumatic equipment and the blows are applied at low velocity to forge the weld. In die forging, 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.

Gas Pressure Welding: This is another modern version 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 welding of rail ends.

Cold Welding: In this process, welding is obtained at room temperature solely the application of pressure across the interface. The contact surfaces have to be specially prepared by degreasing, scratch brushing & other operation. The joints are either lap or butt. The butt methods are used for joining wires, tubes, & bar stocks. Cold welding is generally done on ductile metals like Cu & Al.

Explosive Welding: This process has been used to prepare clad plates involving dissimilar metals & in welding tubes to tubes plates in heat exchanger. In this process, two pieces of metals are impacted together at an extremely high velocity by the detonation of explosive charge. The result is a solid-state weld completed in micro seconds without any noticeable deformation.

Friction Welding: In this process friction is employed to generate heat between two sliding or rotating metals surfaces. The process is usually carried out by placing the pieces to be welded in chucks on the 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 rapidly and pressure is maintained or increased to complete welding

Ultrasonic Welding: Ultrasonic welding is a solid-state process for joining of similar or dissimilar metals by application of high frequency vibratory energy to work pieces held together under moderate static pressure. The process has proved to be an economical substitute for resistance welding. It welds faster, uses less power, and usually requires lower capital investment. The vibration breaks up and disperses 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.

Braze Welding: This process is similar to brazing, except that the molten filler metal is not distributed in the joining by capillary action. It gets filled up in a groove or gets piled up as a fillet weld. In other words, braze welding is similar to normal welding, but the filler metal used has melting point above 450^0 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.

BRAZING & SOLDERING:

Brazing & Soldering are two similar processes. The only difference between them is that in soldering the filler material has a melting point above 450^0C and below the melting point of the base metal, whereas in soldering the filler material has a melting point below 450^0C. Brazing is done for mechanical joint whereas soldering is normally done to get good electrical contact. In both the cases, coalescence between the metallic parts is obtained by:

- Holding the base materials closely and heating them to a suitable temperature.
- Melting filler material over the joint.
- Heating the filler metal till it gets distributed between the closely fitted surfaces by capillary attraction.

WELDABILITY OF STEELS

INTRODUCTION:

Weldability is capacity of a metal to be welded under fabrication condition imposed into specific suitably designed structure and to perform satisfactorily in the intended service.
The ISO definition is "A metallic substance is considered wieldable to a stated degree by a given process and for a given purpose when metallic continuity can be obtained by Welding using suitable procedure so that the joint comply with the requirement specified in regards to both their local properties and their influence on the construction of which the form is a part.

To summarize, we can say that steel is weldable if:

1. There is no crack formation in the weld metal.
2. There is no crack formation in the HAZ.
3. The strength of welds metal matches with original strength of the metals being joined.
4. There is no damage in property like impact strength, yield strength, corrosion resistance etc. in the HAZ.

THERMAL CYCLE DURING WELDING:

During fusion welding, the interfaces of the parts being joined are heated above fusion temperature and a pool of molten metal is produced by melting filler metal and/or base metal. When the weld metal cools, it solidifies in union with the base metal forming a continuous entity. As the heat is taken away very quickly from weld metal through base metal, we get typical cast columnar grains perpendicular to the interface.

The portion in the vicinity of the weld undergoes thermal changes to a varying degree. Maximum temperatures attained at various locations exceed various critical temperatures. As a result original microstructure is disturbed. The various distinct regions of the HAZ as we go away from the weld are Grain Growth region, Grain refined region, Transition region etc. on both sides of the weld. Generally, for carbon steel, no appreciable change in microstructure or properties is noticed if the peak temperature does not exceed 600^0C. **The area up to which the metallurgical or physical properties change due to thermal cycle is known as Heat Affected Zone (HAZ).**

In plain carbon steel the structure is generally Ferrite-Pearlite. Instead, due to fast cooling, we might get Martensitic structure in the HAZ.

FACTORS AFFECTING WELDABILITY:

The major problem during welding is crack formation, either during welding or subsequently during service. Stress generated in the weld is the predisposing factor for crack development. Martensite formation is predominant reason for stress development leading to crack development. The key factors for martensite formation are the **position of the TTT curve (composition of the metal) and the cooling rate of the weldment**. Some important factors are listed below; all of them can be correlated with TTT curve and cooling rate. Apart from that other factors inducing crack formation are also discussed.

1. Parent metal composition
2. Parent metal thickness
3. Weld metal composition
4. Welding process
5. Welding procedure

PARENT METAL COMPOSITION:

In low carbon steel, the position of the TTT curve is quite close to the vertical 'Temperature axis' and hence the critical cooling rate is relatively high. So, the chance of martensite formation in the HAZ is remote and even formed is not so harmful as the hardness of such martensite will be low due to low carbon. **That is why mild steel is readily weldable.**

As the carbon content increases, the chance of formation of hard martensite increases due to shifting of TTT curve to right making the steel progressively less weldable. The lattice distortion of martensite also increases with increase of carbon, generating lot of stresses & possible crack formation.

Not only carbon, other alloying elements also contribute to shifting of TTT curve to right and formation of brittle martensite in the HAZ. Over the years, attempts have been made to provide single index to characterise the weldability of steel in general terms or to cover HAZ hardenability. The effect of major/common alloying elements has been expressed in terms of carbon and the total effect is shown as carbon equivalent (CE), an Index for weldibility.

The IIW formula (empirical) for carbon equivalent of carbon steel & alloy steel.

CE = C+ Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15

- CE < 0.35, The steel is weldable using rutile electrode without any pre-heat
- CE 0.35-0.45, either preheat or low hydrogen electrode is required
- CE 0.45-0.55, Both preheat & low hydrogen electrode is required
- CE > 0.55, the steel is theoretically not weldable unless special care such as preheat, low hydrogen electrode, post weld heating etc. is taken.

Effect of Hydrogen:

Hydrogen has a very low solubility in solid steel. Due to quick solidification of liquid Weld metal, excess hydrogen in atomic state gets entrapped in the solid Weld metal. Because of low atomic size, they have a high degree of mobility and wander freely amongst interstices and vacancies. When two such atoms meet, molecule is formed. The volume of a molecule is much more than the combined volume of atoms, thus exerting stress. GB, an intrinsically weak region is a preferred site for this coalescence. The process continues long after welding is done, even during service also. This stress coupled with martensite formation may cause Delayed cracking or Underbead cracking. This is also known as hydrogen induced or cold crack. Using low hydrogen basic coated electrodes can reduce the problem. However, these electrodes are highly hygroscopic and needs to be preheated to drive out the moisture. **Rusted core wire for MMAW or continuous wires are major source of H_2 and should never be used for welding**.

PARENT METAL THICKNESS:

Effect of plate thickness in welding is directly opposite to its effect during conventional heat treatment where an increase in plate thickness reduces cooling rate. But in welding, as cooling is mainly due to conduction of the heat through base metal only, the cooling rate increases with plate thickness. Hence, there is more chance of the cooling rate not touching the 'Pearlite nose of TTT curve', leading to martensite formation.

Again, the cooling of a welded joint depends o the number of heat flow paths available. Actually, two-dimensional cooling changes to three-dimensional cooling if thickness exceeds a critical value. Therefore, to asses the cooling rate of the HAZ, combined thickness of the joint should be considered.

In some empirical preheating formulate thickness is also incorporated.

P.H. Temp °C = $350\sqrt{CE(1+0.005t)-0.25}$ where 't' is the thickness in mm.

WELD METAL:

The composition of weld meal has a significant effect on weldability. Weld metal mechanical property should match with that of the base metal and composition need not necessarily be the same as that of base metal composition, except the situation where corrosion resistance property is important. Hot cracking or solidification cracking is a common phenomenon due to presence of impurities with low melting point which can be tackled by keeping sulphur level low in weld metal and Mn:S ratio $>$ 36. Carbon content of the weld metal should be lower than 0.20%.

For welding high strength steel, beneficial effect of low hydrogen electrode in reducing hydrogen cracking has already been stated

In some cases weld metal is entirely different from the base metal in order to make it more weld able.

For example, for welding Cast Iron Ni filler metal, Ni-Iron filler metal, and Monel filler metal is used. For Ferritic stainless steel, Austenitic SS filler metal is used for ductility of the joint.

WELDING PROCESS:

Heat input & dilution level are the two main aspects that vary with different welding process. With ultrasonic welding heat input is zero, whereas in submerged arc welding process heat input and dilution is extremely high. So, a particular welding (Given base metal composition and thickness) may not be readily weldable in normal MMAW method but becomes weldable in SAW because of larger heat input which effectively reduces the cooling rate. Therefore welding process has an important influence on weldability by affecting the rate of heat input and subsequent cooling rate.

Some processes are suitable only for joining sheets whereas others are used for plate. Some process require highly skilled worker and some require a minimum experience.

WELDING PROCEDURE:

The choice of welding procedure to be used with the given process is very important in determining the composition and microstructure of the deposited metal. Voltage, Current, Arc length & Travel speed are the normal variables in a welding process. All these variables has an bearing on the rate of Heat input which in turn determines the amount of metal melted the size of weld bead, size of HAZ and also cooling rate of the HAZ. The effects can be summarized as below:-

Rate of heat input increases with increased current and reduced travel speed.

1. Use of lower size electrode i.e. more no. of pass increases the extent of HAZ & more grain coarsening.
2. In some cases, weaving is helpful & in other stringer bead is desired fro the point of view of rate of heat input.
3. Polarity affects penetrations & melting rate. This also affects the total heat supplied to the weld. When the electrode is connected to positive polarity, about two-third heat is generated in the electrode and the total heat to weld metal reduces. When the electrode is in negative polarity, penetration and breaking of oxide films over the base materials are better. These facts may be considered while deciding the polarity of electrode in a particular job.
4. Pre-heating and post-heating reduces HAZ hardness & chance of cracking by affecting the cooling rate. Covering the weld area by lime, sand etc. immediately after welding also helps reducing cooling rate of the weld thus avoiding martensite formation.
5. Back step welding, skip welding reduces heat input.

WELDABILITY TEST:

As already stated earlier, weldability is not an intrinsic property of a metal as it is affected by all the significant variables encountered in fabrication and service. Therefore, no single test or combination of test can duplicate the condition of a real structure. Within these limitations weldability testing can provide data on new alloys, welding procedure, welding process for comparison with data for known alloys. Welding tests are normally of two types:

1. Fabrication Weldability Test, Service Weldability Test

Fabrication Weldability Tests can be Hot Cracking Tests like Varestraint Test, Murex Test, Leigh Restraint Test etc.Delayed Cracking Test OR Underbead Cracking Test like CTS Test, CRYCIFORM Test, Longitudinal Test etc.

Given below is weldability of some common engineering materials against some joining processes.

Materials	AW	OAW	EBW	RW	B	S	AB
Cast iron	7	10	1	1	3	1	7
Carbon Steel, low-alloy steel	10	10	7	10	10	3	7
Stainless steel	10	7	7	10	10	5	7
Aluminum	7	7	7	7	7	1	10
Magnesium	7	7	7	7	7	1	10
Copper, Copper alloys	7	7	7	7	10	10	7
Nickel, Nickel alloys	10	7	7	10	10	5	7
Titanium	7	1	7	7	3	1	7
Lead	7	7	1	3	1	10	10
Zinc	7	7	1	3	1	7	10
Thermoplastics	10*	10**	1	7***	1	1	7
Thermosets	1	1	1	1	1	1	7
Elastomers	1	1	1	1	1	1	10
Ceramics	1	1	7	1	1	1	10
Dissimilar metals	3	3	7	3	3-7	N/A	10

- **Notes:**
  - 10 = Excellent, 5 = Fair, 1 = Seldom/never used
  - * : Heated tool, ** : Hot gas, *** : Induction
  - **AW:** Arc welding, **OAW:** Oxyacetylene welding, **EBW:** Electron beam welding, **RW:** Resistance welding, **B:** Brazing, **S:** Soldering, **AB:** Adhesive bonding

WELDING PROCEDURE FOR JOINING VARIOUS TYPE OF STAINLESS STEELS WITH MILD STEEL AND CORTEN STEELS

(Based on RDSO PROCEDURE N0. MC – 97)

INTRODUCTION:

During fabrication of railway carriage & wagons, the use of carbon steels in rolled; forged & cast conditions were prevalent till last decade, which are prone to corrosion. Over the last few years, IR is switching over progressively to SS and Corten steel for manufacturing super structures and trough floors of railway carriages & wagons to get better service life and aesthetics. In this process of change, various types of **similar and dissimilar joints between Stainless steels, Carbon steels and Corten steel** are encountered. Welding of SS and dissimilar metals is definitely a tricky job and if close control over the process and procedure is not exercised, the basic objectives may get defeated. Keeping this in view, detailed guideline for joining SS with SS and other type of carbon and corten steels has been issued by **RDSO** vide **Procedure No. MC-97**. Salient features of MC-97 are reproduced here.

1. MATERIAL:

There are various types of stainless steels of different grades used in IR. The most commonly used stainless steels are:

i) AISI – 301, 304 (Austenitic) and other similar steels.
ii) AISI-409M & 3Cr12 grade of IRSM-44(Ferritic)

S. No	Class of Steel	Composition				Application
		C%	Cr %	Ni %	Ti%	
1	301 (Austenitic)	0.15	16-18	6-8	-	Trough floor, inside panelling, vendor compartment deck sheet, drivers cabin etc. of EMU
2	304 (Austenitic)	0.08	18-20	8-12	-	Roof and trough floor of LHB Coach, trough floor, roof and side panel above window of all SS EMU, Break pipe of EMU.
3	409M (Ferritic)	0.08	10.5-11.75	-	6 X %C	Side wall & End wall of LHB coach, side wall below window of EMU, Under-frame & Side panel below window of SS EMU
4	3Cr12 of IRSM-44 (Ferritic)	0.03	10.8- 12.5	-	0.75 (Max)	Side wall, Extension, Side Sill and Centre Sill of BOXN CR wagon.

Table 1: Application & Chemical composition of commonly used SS in IR

Other steels are:

i) Corten steel to IRS: M-41
ii) Structural steel to IS: 2062 in different grades including copper bearing and other carbon steels.

2. WELDING PROCESS:

A. For joining of Stainless steel together:

TIG, MIG/MAG or SMAW process shall be used. The process TIG & MIG/MAG is considered beneficial in fabrication of carriages & wagons where as during their repair MMAW & MIG/MAG process may be convenient & beneficial.

B. For joining of Corten steel together –

MIG/MAG, MMAW & SAW process shall be used. The process SAW & MIG/MAG is considered beneficial in fabrication of carriages & wagons whereas during their repair MMAW & MIG/MAG process may be convenient & beneficial.

C.For joining of structural and other carbon steels –

MIG/MAG, MMAW & SAW process shall be used. The process SAW & MIG/MAG are considered beneficial in fabrication of carriages & wagons where as during their repair MMAW & MIG/MAG process may be convenient & beneficial.

D. For combination joints between stainless steels with Carbon/Corten steels-

MIG/MAG & MMAW process shall be used for both fabrication & repair work.

3. WELDING CONSUMABLES:

A. For joining of AISI 301, AISI 304 & other similar steels together:

i) MMAW electrodes approved under **class M1 as per IRS: M-28-02** shall be used.
ii) MIG/MAG welding filler wires approved under class **VI as per IRS: M46-03** shall be used.

B. For joining Gr. 409M or 3Cr12 grade of IRS: M-44 & equivalent and combination joint with A. above:

i) MMAW electrodes approved under class **M2 as per IRS: M-28-02** shall be used.
ii) MIG/MAG welding filler wires approved under class **VI as per IRS: M46-03** shall be used.

C. For joining all types of SS under A. & B. with Carbon steel/Corten steel:

i) MMAW electrodes approved under class **M4 as per IRS: M-28-02** shall be used.
ii) MIG/MAG welding filler wires approved under class **VII as per IRS: M46-03** shall be used.

4. WELDING PROCEDURE:

Any welding activity may be subdivided into three sub-activities, i) Activity prior to welding ii) activity during welding & iii) Activity after welding. Some **DOs and DON'Ts at different stages for welding SS with SS or Corten/Carbon steels** are detailed below:

a) **Prior to Welding:**

i) The area about 15 mm from each side of the area to be welded shall be properly cleaned.
ii) The area to be welded shall be free from dust, dirt, grease, oil, paints etc. Any non-corrosive and suitable organic solvent (Kerosene oil, Benzene etc) can be used for removing grease, oil & paints.
ii) Chlorine based solvents shall not be used.
iii) Stainless steel wire brushes should be used to remove tenacious layer of Chromium oxide for better strength of joint.

b) **During Welding**:

i) The welding parameter in the machine shall be set as per commendation of manufacturer.
ii) If welding is carried out by MMAW process, connect the electrode with positive terminal of welding equipment (DC+) when welding with DC.
iii) Use 70 OCV (min) transformers while welding with AC.
iv) Keep the welding current on lower side (as possible) of the range as recommended by the manufacturer of the consumables.
v) Maintain short arc length to minimize the loss of alloying elements during welding.
vi) Put stringer beads, weaving shall not be more than two times of the diameter of electrode used.
vii) Use small diameter electrode according to thickness of base metal to minimize heat input.
viii) De-slag each run property by using stainless steel brushes and chisels.

c) **After Welding:**

i) The stainless steels are susceptible to corrosion if the surface is rough. To avoid the corrosion, surface should be made smooth & polished. It is therefore, necessary to finish the stainless steel joint by grinding & subsequent polishing using fine grinder.
ii) Mild steel & corten steels both are anodic to the stainless steels, hence any small portion of Mild steel & corten steel in contact with stainless steel will corrode severely in short time. Proper & quick corrosion protection is therefore, required in these locations.

Special features of Joining SS with Corten/Carbon Steel:

Dissimilar metal joints are common in fabrications of carriage & wagons on Indian Railways. The welding of dissimilar metals is little more troublesome than welding of carbon structural steels together or stainless steels together. The difference in physical properties Like Thermal Conductivity, Melting Point, Coefficient for Thermal Expansion etc. creates special problems during welding. Dilution of the deposited filler material with either of two base materials leads the variety of problems. **During welding of dissimilar metals, following general points will be helpful:**

i) Minimum heat input shall be provided to joint, so that diffusion can be restricted and dilution is minimized. To achieve this, low welding current and small diameter electrodes shall be preferred.
ii) Proper filler material compatible with both the joining steels is to be used.
iii) Dilution must be reduced as low as possible. Dilution depends on the welding process, process variables and penetration. Hence, proper welding process shall be used with proper setting of process variables (Current, Voltage, Travel speed, Polarity etc.).
iv) When using gas metal arc welding (MIG/MAG) reduced current density is to be employed, so that only dip transfer of metal occurs.
v) The problem of dilution and formation of inter-metallic phases can be minimized by buttering one or both joint faces with a layer of compatible material.

General Precautions for all type of welding involving SS:

- i) MMAW electrodes of diameter 2.5 mm/3.15 mm/4.0 mm shall be used depending upon the thickness of plate.
- ii) For continuous wires the diameter of wire shall preferably be 0.8 mm/ 1.2 mm.
- iii) Electrodes are to be re - dried before use to about 150°C for at least one hour or as recommended by the manufacturers.
- iv) Always use stainless steel brushes during welding of stainless steels.
- v) The heat conductivity of stainless steels is about 50% of that of mild steel. This will increase the localized heating of work piece. To reduce the effect of localized heating, usage of current in the lower side of the recommended range will be helpful.
- vi) Because of lower Melting Point, melting rate of stainless steel electrodes is higher than mild steel electrodes. This is another reason to use low current for welding of stainless steel components.
- vii) The thermal expansion of stainless steels is about 50% more than that of mild steel. This will increase the chance of warping & buckling of the component. Thus suitable fixture must be used while welding of stainless steels.
- viii) The electrical resistance of stainless steel is 6 to 12 times more than that of mild steels. This may create problem of overheating in electrodes. To avoid this use low welding current & small length electrodes.

5. EDGE PREPERATION:

- i) No edge preparation is required when welding up to thickness 3/16"(5 mm approx.).
- ii) For higher thickness between 3/16" to ½" (5-12 mm approx.) bevel preparation is necessary.
- iii) For joining of plates of unequal cross section in butt joints, taper shall be given to thicker part to reduce thickness equal to thinner part at the end. The slope i.e. tan θ of taper should lie between 1 in 6 to 1 in 4 (see Fig.1) below.

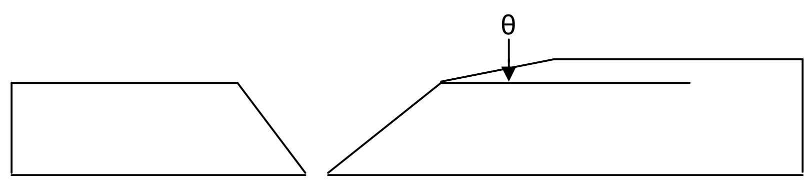


Fig.1 Butt joint of unequal cross section

6. CUTTING OF STAINLESS STEELS:

For cutting of stainless steels plasma cutting or machine cutting shall be used. Manual metal arc cutting followed by grinding may also be used in case plasma arc cutting facility is not available.

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CODIFICATION OF MMAW ELECTRODES AS PER IS: 814-1991

A1 **Prefix Letter**: Letter 'E' shall indicate a covered electrode for manual Metal arc welding manufactured by extrusion process.

A2 **Types of Covering**: Letter(s) indicating to type of covering as described below: -

(A) **Acidic:** The covering contains besides oxide of Iron or Manganese a fairly high percentage of Ferro-manganese and or other de-oxidizers. The slag is easily detachable.

(B) **Basic:** This type of covering contains appreciable quantities of calcium or other basic carbonates and fluorspar. The slag produced is dense and brown in color. This slag is also easily removable.

(C) **Cellulosic:** The covering of cellulosic type contains a large quantity of combustible organic substances producing easily detachable slag.

(R) **Rutile:** This type of covering contains large quantity of rutile or component derived from titanium oxide. The slag produced is easily removable.

(RR) Same as rutile type electrode but having higher coating factor.

(S) Covering of any other type not classified above.

A3 **First Digit**: Indicates ultimate tensile strength in combination with the yield strength of the weld metal deposits given below: -

Designating Digit	**UTS (N/sq.mm)**	**YS min. (N/sq.mm)**
4	410-510	330
5	510-610	360

A4 **Second Digit** Indicates the percentage elongation in combination with the impact values of weld metal deposited as given below. These values are as per two tensile ranges as given by first digit.

<u>For tensile range 410-510 N/sq.mm</u>

Designating digit	%Elongation on $5.65\sqrt{a}$	Impact (in joules) (min)
0	No elongation & Impact requirements.	
1	20	47J (+ 20°C)
2	22	47J (-0°C)
3	24	47J (-20°C)
4	24	27J (-30°C)

For Tensile Range 510-610 N/sq.mm

0	No elongation & impact requirements.	
1	18	47J (+ 27°C)
2	18	47J (0°C)
3	20	47J (-20°C)
4	20	27J (-30°C)
5	20	27J (-40°C)
6	20	27J (-46°C)

A5 **Third Digit** Indicates welding positions in which electrode may be used.

Indicating digit	Welding Position
1	F,H,V,D,O (All position)
2	F,H,V,O
3	F,H
4	F only
5	F and HF
6	Any other position or combination of Positions not classified above.

NOTE: F - Flat position

H - Horizontal Vertical

V - Vertical up

D - Vertical down

O - Overhead

HF - Horizontal Fillet

A6 **Fourth Digit** Indicates the current condition in which electrode is to be used as given below :

Digit	DC Recommended Polarity	AC Open Circuit Voltage (min.)

0	(+)	Not recommended
1	(+)OR (-)	50
2	(-)	50
3	(+)	50
4	(+) OR(-)	70
5	(-)	70
6	(+)	70
7	(+) OR(-)	90
8	(-)	90
9	(+)	90

Suffix letters: The following letters indicating the additional properties of electrodes may be used:-

(a) H1, H2 & H3 indicating hydrogen controlled electrodes as explained below :
H1 = Diffusible hydrogen up to 15 ml/100 gm.

H2 = " " " 10 ml/100 gm.

H3 = " " " 5 ml/100 gm.

(b) Letters J, K & L indicating increased metal recovery as given below :

J - 110 to 129%

K - 130 to 149%

L - 150% and above.

(c) X - Indicating radiographic quality.

Note:

It is mandatory to indicate the first six alphabets/numeric's on the packet to get BIS approval. The remaining codes are optional for the manufacturer if he wants to emphasize on those characters also. Apart from that, recommended current range is also indicated on the packet.

Example:

If Code is E B 5 4 2 6 H3 J X

Covered electrode — E

Type of covering (Basic) — B

Strength characteristics (UTS-510-610 N/sq.mm and YS=360 N/sq.mm) — 5

Elongation & impact properties (Elongation 20% min. and Impact = 27J min. at -30^{0} C) — 4

Welding position (all positions except vertical down) — 2

Welding current & Voltage condition (D+ and A 70) — 6

Hydrogen controlled electrode (5 ml/100 gm. Max.) — H3

Increased metal recovery (110-129%) — J

Radiographic quality electrode — X

<u>Packing:</u>

To guard against ingress of moisture and damage during transportation storage till its consumption, the following packing system shall be incorporated in IRS M-28, which has to be followed by the electrode manufacturers:

1. The counted/weighed electrodes shall be kept in moisture proof polythene bag and sealed.

2. This sealed bag shall further be kept in card board carton printed with name of the manufacturer, electrode brand name, batch number, date of manufacture, size, current condition and welding parameters, quantity, cautionary note on safety during welding, BIS Code and any other special recommendation. The total weight should not exceed 7 Kg.

3. This carton shall be sealed and put in polythene bag and sealed/shrink sealed.

4. A counted number of sealed cartons shall be kept in suitable wooden/card board boxes and stripped tightly.

The shelf life of the electrodes should be a minimum of 12 months from the date of receipt in Stores or 18 months from the date of manufacture, whichever is more.

GUIDELINE FOR PROCUREMENT OF ELECTRODES AND PLACING INDENT:

(a) **Choosing of class of Electrodes & IS Code:** The class of electrodes shall be chosen as per classification and their purpose of use as per IRS M-28 (as described in Chapter-I).

(b) **Diameter of electrode**: The diameter of electrode shall be as per thickness of job. For thin sheets the diameter of electrodes should not be more than thickness of sheet. The root runs in the grooves shall be given by using small diameter of electrodes preferably 3.15/4.0 mm to avoid lack of penetration & slag inclusions.

(c) **Type of coating:** Medium, heavy or super heavy-coated electrodes shall be used according to the job & welding positions. A medium coated electrode shall be used for positional welding. Higher coating will increase production & also produce superior quality of weld but may create problem in overhead & vertical down welding positions.

Type of coating	Coating factor (i.e. Ratio to overall dia Including coating to core wire dia
Light coated	1.25 to 1.35
Medium coated	1.36 to 1.50
Heavy coated	1.51 to 2.20
Super heavy coated	more than 2.20

(d) **Type of covering**: Normally mild steel manual metal arc electrodes have following type of covering. The salient features of each type are given below:

Acidic (A)

(i) The slag is easily detachable.
(ii) High fusion rate.
(iii) Good penetration.
(iv) Most suitable for welding in flat position.
(v) Can be operated both on AC & D.C.

Basic (B)

(i) Slag is easily removable.
(ii) Penetration is average.
(iii) Suitable for welding in all positions but difficult in vertical down position.
(iv) Can be operated both on AC & D.C. but D.C. (+) is generally preferred for critical applications.
(v) Good quality of weld is obtained with low hydrogen content.
(vi) Electrodes should be dried to about 250°C for at least two hours before use.

Cellulosic (C)

(i) Highly penetrating arc.
(ii) Uneven spaced ripples.
(iii) Usually suitable in all positions.
(iv) Suitable for use on D.C. with electrode positive. Some electrodes are also suitable with AC

Rutile (R)

(i) Smooth arc.
(ii) Little spatter.
(iii) Can be used in all positions.
(iv) Can be operated on both AC & D.C.
(v) Slag is easily removable.

Other types (S): No general guidance on special covering electrode characteristics is possible, so potential users should seek the manufacturer's advice.

(C) **Deposition efficiency**:The deposition efficiency of electrode shall be calculated by using formula:

$$\textbf{Deposition efficiency \%} = \frac{\text{Wt. of weld metal deposit}}{\text{Wt. of core wire used}} \times 100$$

Advantages of high deposition efficiency

(i) Improve arc stability.
(ii) Increase productivity.
(iii) Spatter will be reduced.
(iv) Slag removal is easy.
(v) Appearance of bead will be good
(vi) Economy in power consumption.
(vii) Reduce the welding/repair cost.

Limitations

It may create problem in positional welding.

Cost benefit:

Let weight of 20 meter of core wire of 4mm diameter = 1kg

Let an electrode A of diameter 4.0 mm has deposition efficiency = 120%, and

B electrode of same size has deposition efficiency = 130%

Net cost of electrode A (20 meter length 4.0 mm diameter) = Rs.40/-

Net cost of electrode B (-do-) = Rs.42/-

Weld deposit of electrode A = 1.2 kg

Cost of weld deposit per Kg = $\frac{1x40}{1.2} = 33.3$

Weld deposit of electrode B = 1.3 kg

Cost of weld deposit per kg = $\frac{1x42}{1.3} = 32.3$

Hence cost of per kg of weld deposit in case of electrode B is less although its cost per meter length of core wire is higher.

Other General information:

1. The electrode must be purchased on the basis of length of core wire only.

2. (a) Amongst five classes A, B1, B2, C1 and C2 class A is meant for the lowest quality followed by B1, B2 etc. While class C2 is for highest quality of work. Class C2 electrodes can be used in lieu of C1, B2, B1 and A electrodes. Similarly, Class C1 can be used where classes B1, B2 is required and so on. The reverse, however, is not permissible.

   (b) Electrodes approved under IRS class H3A can be used in lieu of Class H3 electrodes. Reverse, however, is not permissible.

   (c) On the basis of hydrogen content on weld metal covering having H3 in its code is superior and can be used in lieu of covering having H2 & H1 in code but reverse, however, is not permissible.

   (d) The consignee is advised that besides the IRS class, they should also stipulate diameter of electrode, type of covering, deposition efficiency percentage in case of coating in all varieties of electrodes depending upon the specific applications for which the electrodes are being procured as explained earlier.

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Weldability of Stainless Steel:

The Thermal & Electrical Conductivity of stainless steel is much less than carbon steel & co-efficient of expansion is also higher. Low thermal conductivity tends to higher temperature rise in the vicinity of weld and that coupled with high coefficient of expansion leads to warpage & higher incidence of weld cracking under restrained condition. The low electrical conductivity

Comparative Physical Properties of Stainless Steel & Carbon Steel

Property	Martensitic	Ferritic	Austenitic	Carbon Steel
Thermal Conductivity Cal/sec.cm² ºC/cm	0.059	0.049	0.033	0.104
Coefficient of Expansion µ m/m/ºC	11.2	11.2	18.2	13.2
Electrical Resistivity µ Ώ/cm	58	60	70	15
Melting Range ºC	1483-1532	1427-1510	1398-1454	1538

We will discuss the relative weldability of three types of stainless steels.

Ferritic stainless steel:

Ferritic stainless steel is less weldable than austenitic stainless steel. Following are the common problems encountered in welding ferritic stainless steel:

- Martensite formation
- Excessive grain growth
- Sigma phase formation
- 475 embrittlement
- Sensitization

In general, the most of the Ferritic grades have balanced chemistry to have ferrite structure at all temperature, but some grades with high carbon & low chromium composition , when heated above critical temperature form some austenite which transform to martensite on cooling resulting reduced toughness & ductility.

The steel has a tendency towards excessive grain growth when heated above 950^{0}C. This coarse grain coupled with small amount of martensite results in brittle HAZ.

When Ferritic stainless steel containing more than 20% chromium is subjected to slow heating/cooling in the range of 500-900^{0}C, there is formation of sigma phase, an Iron-Chromium inter-metallic compound which is hard & brittle.

It also suffers from '475 embrittlement' on heating in the range of 400-540^{0}C due to formation of chromium rich zone along certain crystallographic plane.

When ferritic stainless steels are air cooled in the temperature range of 900^{0}C - 700^{0}C, chromium rich carbide & nitride precipitates at the grain boundaries from solid solution. Adjacent to the precipitate, the zone becomes depleted in chromium level and more prone to intergranular corrosion. This zone is called sensitised zone. This phenomenon when takes place welding because of heating & cooling cycle is known as Weld decay or Knife edge cracking.

Corrosion resistance of sensitised zone can be restored by annealing at 1050^{0}C followed by rapid cooling.

To minimise grain growth, heat input should be as low as possible. Inter pass temperature should not be more than 150^{0}C.

Grain coarsening & sigma phase formation can be avoided by avoiding slow cooling. A post weld treatment at 790^{0}C i.e. below the grain coarsening temperature, followed by furnace cooling to 650^0 C, then rapid cooling to 400^0 C is beneficial to avoid '475 embrittlement'.

Matching filler wire or fully austenitic filler wire (25/20 type) may be used. Smaller diameter electrode, low current & stringer beads are helpful.

However, for welding thin sheet using ductile Austenitic SS filler metal, preheating & post weld heat treatment is not generally required.

Martensitic stainless steel:

Martensitic stainless steel is least weld able among all stainless steels because of hardened HAZ which is susceptible to crack formation. Preheating of 150-250^{0}C & post weld heat treatment at 750-800^{0}C, furnace cooling to 590^{0}C then rapid cooling is beneficial. Matching filler wire (13Cr type) or austenitic filler wire (23/12, 25/20 type) may be used.

Austenitic stainless steel:

Austenitic stainless steels are by far the most important group among all stainless steels. These types of steels are readily weldable. No pre-heat or post weld heat treatments are generally required. However, the following problems are encountered.

- Micro fissuring or Solidification cracking.
- Sigma phase formation.
- Weld decay.

Solidification cracking:

A fully austenitic stainless steel weld metal is prone to hot cracking. The impurities like phosphorus, sulphur, boron, selenium, silicon etc, due to poor solubility in the austenite weld metal, segregate along grain boundary between two austenitic grains giving rise to a tendency to develop cracks. This problem is overcome by producing some ferrite (4-5%) in the weld metal because of its ability to dissolve impurities. Composition is balanced in such a way that there is some delta ferrite in the structure.

Sigma phase formation:

Similar to ferritic steel but significant as chromium content is high. The problem aggravates if ferrite content in the weld metal is too high & weld metal contains Mo, Si, Cb, Ti, Al.
Weld decay: Same problem as described in Ferritic SS. The remedial measures are:

- To use extra low carbon base metal.
- To use stabilised base metal & electrode.
- Solution treatment.

Various grades of austenitic stainless steel filler metal are used & available. Arc length is also a significant factor for austenitic stainless steel welding especially when rutile coated electrode is used as sealing is not as good as basic coated one. Longer arc means more chance of chromium loss resulting tendency towards austenitic weld deposit & more nitrogen pick up. Both the phenomena result in Austenite formation. Shorter arc results in little Cr. loss favouring formation of delta ferrite in the weld metal. Again stringer bead leads to fast cooling and promotes ferrite formation in the weld metal. Dilution is also less. That is why welding technique has great influence in SS welding.

Welding Processes:

Following process are used extensively for welding Stainless Steels:

- Shielded metal arc welding
- Gas tungsten arc welding
- Gas metal arc welding
- Submerged arc welding
- Resistance welding (Spot, seam & projection)

SMAW:

A great variety of covered electrode is available for welding of stainless steel. These are covered by specification IS 5206, AWS A-5.4. IRS M-28 contains class M1-M6 for various applications. The covering is generally basic or rutile-basic. The welding is better with DC(+ve) polarity using a rectifier. However, certain electrodes are operable in AC also. The OCV of the equipment should be 70V minimum. Short arc, stringer bead technique should be used to avoid chromium loss & nitrogen pick up and dilution. Welding can be done almost in all position.

GMAW:

This process uses DC reverse polarity using Argon or Argon/Helium shielding gas. Sometimes, Oxygen and/or CO_2 are added to shielding gas improve the arc & penetration. A variety of filler metal is available. These are covered in AWS A5.9. IRS-M-46, Class 6 & 7 covers MIG solid filler wire for Railway use.
The proprietary shielding gas being used in RCF contains 90% Argon, 5% CO_2 & 5% Oxygen.

FCAW (Fluxcored Arc Welding):

This process is also used for welding of Stainless Steel. The process is similar to GMAW. Deposition rate is higher & superior weld metal quality is obtained. Filler wire is covered in AWS A5.22. IRS-M-46, Class 6 & 7 covers MIG flux cored filler wire for Railway use.

GTAW (Gas Tungsten Arc Welding):

This is similar to GMAW & suitable for welding stainless steel upto 6mm thick. Above that thickness the process is uneconomical. The only difference is that here non consumable Tungsten or Thoriated Tungsten electrode is used.

For welding of stainless steel upto 2mm no joint preparation is required and no filler metal is used. Above that, beveling of the face may be required. Filler metal is used manually from outside like gas welding.

For lower thickness gas may be Argon, above that thickness and for machine /automatic application Argon Helium mixture is used to obtain increased weld penetration.

For low thickness AC power can also be used. Other improved power source like Pulsed power source, Square Wave power source etc. was used. Potential problem during welding is Tungsten inclusion and porosity in the weld metal.

LASER Welding:

This technology, developed quite recently, is highly suitable for stainless steel welding. As already discussed, restricted heat input and temperature rise is key to successful SS welding and that precisely is the speciality of this process.

The term LASER stands for **L**ight **A**mplification of **S**timulated **E**mission of **R**adiation. Phased monochromatic light beam is concentrated over a very small area, say 0.01 inch diameter, which produces large amount of heat over the small area. The total heat energy remains quite low, in the range of 2000Wfor SS sheet welding of 3mm thickness, but the temperature rise in that localised spot is very high, sufficient to melt or even vaporise the metal. It is somewhat akin to concentrating sun rays through a magnifying glass to produce enough heat to ignite a paper. The beauty of the process is that due to extremely low range of heat input, HAZ is near absent in this process. So, we get a very narrow band of Weld Metal zone and HAZ. The property modification of SS at different temperature level also is absent due to very small stay at that temperature.

In ICF & RCF, LASER Welding and cutting is being used to for SS sheet joining and cutting. In ICF, one LASER unit of capacity 3mm of SS is being used for both cutting and welding. 2000 Watt for power is used for main welding and 700 Watt for tacking purpose. Nitrogen Gas is used for shielding at the rate of 40l/min.

Two sheets, cut by shearing M/C are placed side by side. The laser head cuts 2mm from each plate to eliminate any undulation or distortion produced during shearing. Then they are again brought side by side with perfect match, tack welded to hold in place and then final weld is carried out. In the next step, window block is cut.

Resistance Welding:

Spot, Seam & Projection welding falls in this category & extensively used for sheet metal welding normally up to 3mm as an alternative to other means of fastening i.e. screwing or bolting.

In resistance welding process in which coalescence of metals is produced at the faying surface by the heat generated at the point of contact of two pieces to be welded by the resistance at the interface to the flow of electric current. Forces are applied before, during & after the application of current to effect proper holding and joining.

In spot welding a nugget of weld metal is produced at the electrode site & used where leak tightness is not required.

Seam welding is a variation of spot welding in which a series of overlapping nuggets are produced to obtain a continuous gas tight seam.

Projection welding is similar to spot welding except the location is pre determined by a projection or embossment on one faying surface

The major variables in resistance welding are current, time & applied pressure. A proper balance of time, current & pressure should be made to ensure proper fusion & avoid 'spitting'. Surface preparation is not generally required for SS sheet except for removal of oil & grease.

As welding is completed in a very short time, heat affected zone is very less and defects such as sigma phase & carbide precipitation etc. are not significant. Spot welding is being used extensively in RCF for fabrication of LHB coach.

Post-Weld Heat Treatment (PWHT):

For preserving corrosion resistance of weldments, unstabilized Austenetic stainless steels (viz.AISI 304, 308 etc.) are solution-treated to dissolve the grain boundary chromium-based carbides and to redistribute 'Cr' uniformly into the matrix. Local solution annealing is not recommended since it can produce a sensitised band slightly away from the PWHT region. Short soaking times are used to avoid grain growth. Recommended solution anneal temperatures for stainless steels are given below:

Recommended Solution Anneal Temperatures For Stainless Steel

Grade	Temperature
301, 302, 303, 304, 304L, 305, 308	1010 – 1120°C
309, 309 S, 316	1035-1120°C
316 L, 317 L	1035-1107°C
317	1065-1120°C
321 (for service temp. below about 450°C)	955-1065°C
347, 348	982-1065°C

The weldment must be cooled fast (quenching for thick sections) after soaking to avoid slow cooling through temperature range of 450-750°C and resultant sensitisation. Care is to be exercised during PWHT to avoid excessive oxidation, scaling sagging or warping.

The recommended stress-relief temperature for austenitic stainless steels is 950^oC, which is above the sensitisation temperature range. This temperature can significantly reduce residual stress in welds eliminating SCC problems. Lower temperature stress relief at 200-430^oC has been found to improve dimensional stability by reduction of high peak stresses and reduce susceptibility to certain corrosion mechanisms.

Corrosion resistance of grade AISI 405 & 409 and low interstitial grade AISI 444 is not significantly affected by welding, and hence, can be used under 'as welded' condition. For other grades, depending on the grade and problem associated with it heat treatment cycle is decided.

Cutting of Stainless Steel:

Cutting is generally required for the following purpose:

- Cutting designed dimensions & shapes of metal pieces.
- Cutting for preparing edges for welding
- Cutting during maintenance

Mechanical cutting i.e. shearing, machining etc. can be adopted during fabrication, but the process may not be suitable for cutting during maintenance. Then thermal cutting may be required.

Ordinary Oxy-Acetylene Cutting is not useful for cutting SS plate because of formation of Chromium Oxide, which has very high MP (1800^oC higher than steel parent metal). Therefore, Oxy Acetylene cutting which operates on principle of oxidation fails to cut stainless steel. Other means of thermal cutting i.e. Plasma Cutting & Metal Arc Cutting may be resorted to. Plasma cutting is economical and a smooth cut face is obtained. The process can be manually operated or machine operated. That is why this process is used for cutting during fabrication also. Metal arc cutting gives a comparatively uneven edge, which requires grinding. There are many cutting electrodes approved under class N1 of IRS-M-28. LASER cutting also is a very effective process for manufacturing units. In ICF, both LASER Cutting & Welding is being used extensively for SS sheet fabrication work. The principle of both cutting & welding is same which has been explained above. For cutting 2500 Watt output power is employed and high pressure Nitrogen gas at 14 bar is used to drive away the molten metal.

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