Lecture: 1

Introduction: Joining

This chapter presents the fundamental approaches used in manufacturing namely casting, forming, welding and machining. Further, common methods of developing joint and selection of suitable methods have been described. Applications, advantages and limitations of welding as a fabrication technique have also been covered.

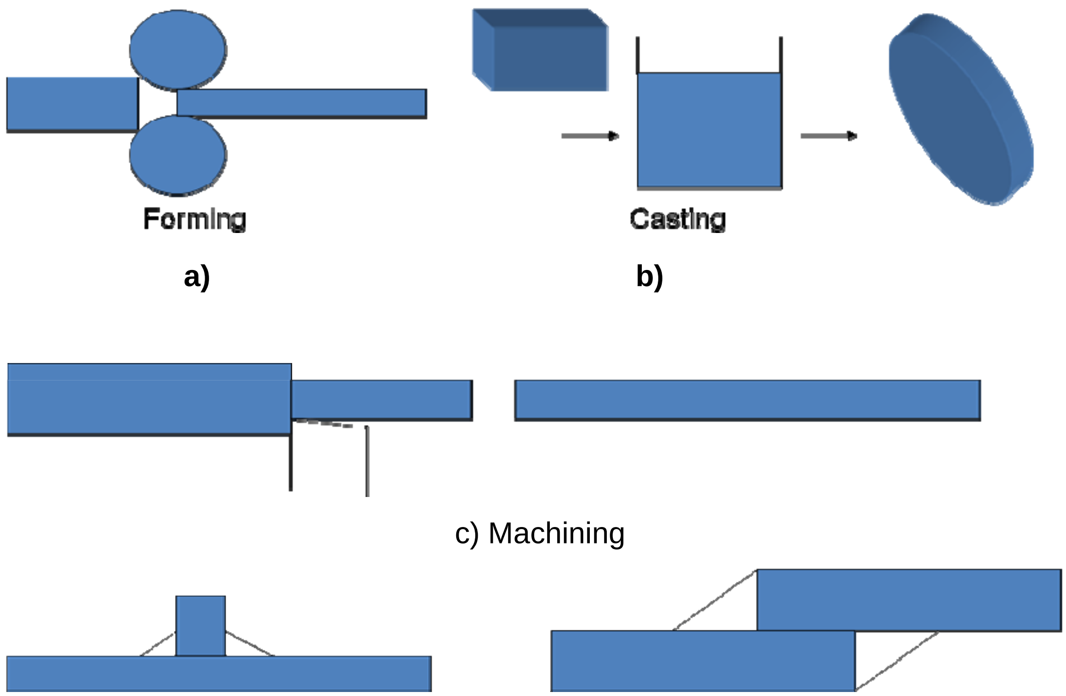
Keywords: Manufacturing process, selection of joint, welding vs. manufacturing processes, selection of welding process, advantages, application and limitation of welding processes

1.1 Introduction

The manufacturing technology primarily involves sizing, shaping and imparting desired combination of the properties to the material so that the component or engineering system being produced to perform indented function for design life. A wide range of manufacturing processes have been developed in order to produce the engineering components ranging from simple to complex geometries using materials of different physical, chemical, mechanical and dimensional properties. There are four chief manufacturing processes i.e. casting, forming, machining and welding. Selection of suitable manufacturing process for a produce/component is dictated by complexity of geometry of the component, number of units to be produced, properties of the materials (physical, chemical, mechanical and dimensional properties) to be processed and economics. Based on the approach used for obtaining desired size and shape by different manufacturing processes; these can be termed as positive, negative and or zero processes.

- Casting: zero process
- Forming: zero process
- Machining: negative process
- Joining (welding): positive process

Casting and forming are categorized as zero processes as they involve only shifting of metal in controlled (using heat and pressure singly or in combination) way from one region to another to get the required size and shape of product. Machining is considered as a negative process because unwanted material from the stock is removed in the form of small chips during machining for the shaping and sizing of a product purpose. During manufacturing, it is frequently required to join the simple shape components to get desired product. Since simple shape components are brought together by joining in order to obtain desired shape of end useable product therefore joining is categorized as a positive process. Schematic diagrams of few typical manufacturing processes are shown in Fig. 1.1.



d) Joining

Fig. 1.1 Schematic diagram showing shaping approaches using different manufacturing processes a) forming, b) casting, c) machining and d) joining

1.2 Selection of Joint

The fabrication of engineering systems frequently needs joining of simple components and parts. Three types of joining methods namely mechanical joining (nuts & bolts, clamps, rivets), adhesive joining (epoxy resins, fevicol), welding (welding, brazing and soldering) are commonly used for manufacturing variety of engineering product/component. Each type of joint offers different load carrying capacity, reliability, compatibility in joining of similar or dissimilar materials besides their fitness for use in different environments and cost. It will be appropriate to consider following aspects while selecting type of joints for an application:

a) type of joint required for an application is temporary or permanent

b) Whether similar or dissimilar materials are to be joined in order to take care of the compatibility aspect as metallurgical incompatibility can be disastrous for performance of the joints
c) Physical, chemical metallurgical properties of materials to be joined
d) requirements of the service from the joint under special conditions of temperature, corrosion, environment, and reliability
e) type and nature of loading conditions (static and dynamic loading under tension, shear, compression, bending etc.)
f) economy or cost effectiveness is one most important factors influencing the selection of joint for manufacturing an engineering component

1.3 Welding and its comparison with other manufacturing processes

Welding is one of the most commonly used fabrication techniques for manufacturing engineering components for power, fertilizer, petro-chemical, automotive, food processing, and many other sectors. Welding generally uses localized heating during common fusion welding processes (shielded metal arc, submerged arc, gas metal arc welding etc.) for melting the faying surfaces and filler metal. However, localized and differential heating & cooling experienced by the metal during welding makes it significantly different from other manufacturing techniques:

- Residual stresses are induced in welded components (development of tensile residual stresses adversely affects the tensile and fatigue properties of work piece)
- Simple shape components to be joined are partially melted
- Temperature of the base metal during welding in and around the weld varies as function of time (weld thermal cycle)
- Chemical, metallurgical and mechanical properties of the weld are generally anisotropic
- Reliability of weld joint is poor.
- Little amount of metal is wasted in the form of spatter, run in and run off
- Process capabilities of the welding in terms of dimensional accuracy, precision and finish are poor.
- Weld joints for critical applications generally need post weld treatment such as heat treatment or mechanical working to get desired properties or reline residual stress.

- Problem related with ductile to brittle transition behaviour of steel is more severe with weld joints under low temperature conditions.

1.4 **Selection of welding process**

A wide range of welding processes are available to choose. These were developed over a long period of time. Each process differs in respect of their ability to apply heat for fusion, protection of the weld pool and soundmen of welds joint the so performance of the weld joint. However, selection of a particular process for producing a weld joint is dictated by the size and shape of the component to be manufactured, the metal system to be welded, availability of consumables and machines, precision required and economy. Whatever process is selected for developing weld joint it must be able to perform the intended function for designed life. Welding processes with their field of applications are given below:

- Resistance welding: Automobile
- Thermite welding: Rail joints in railways
- Tungsten inert gas welding: Aerospace and nuclear reactors
- Submerged arc welding: Heavy engineering, ship building
- Gas metal arc welding: Joining of metals (stainless steel, aluminium and magnesium) sensitive to atmospheric gases

1.5 Advantages and Limitation of Welding as a Fabrication Technique

Welding is mainly used for the production of comparatively simple shape components. It is the process of joining the metallic components with or without application of heat, pressure and filler metal. Application of welding in fabrication offers many advantages, however; it suffers from few limitations also. Some of the advantage and limitations are given below.

Advantages of welding are enlisted below:

1. Permanent joint is produced, which becomes an integral part of work piece.
2. Joints can be stronger than the base metal if good quality filler metal is used.
3. Economical method of joining.
4. It is not restricted to the factory environment.

Disadvantages of welding are enlisted also below:

1. Labour cost is high as only skilled welder can produce sound and quality weld joint.

2. It produces a permanent joint which in turn creates the problem in dissembling if of sub-component required.
3. Hazardous fumes and vapours are generated during welding. This demands proper ventilation of welding area.
4. Weld joint itself is considered as a discontinuity owing to variation in its structure, composition and mechanical properties; therefore welding is not commonly recommended for critical application where there is a danger of life.

1.6 Applications of welding

General applications

- The welding is widely used for fabrication of pressure vessels, bridges, building structures, aircraft and space crafts, railway coaches and general applications besides shipbuilding, automobile, electrical, electronic and defense industries, laying of pipe lines and railway tracks and nuclear installations.
- Specific components need welding for fabrication includes

1. Transport tankers for transporting oil, water, milk etc.
2. Welding of tubes and pipes, chains, LPG cylinders and other items.
3. Fabrication of Steel furniture, gates, doors and door frames, and body
4. Manufacturing white goods such as refrigerators, washing machines, microwave ovens and many other items of general applications

The requirement of the welding for specific area of the industry is given in following section.

Oil & Gas

1. Welding is used for joining of pipes, during laying of crude oil and gas pipelines, construction of tankers for their storage and transportation. Offshore structures, dockyards, loading and unloading cranes are also produced by welding.

Nuclear Industry

2. Spheres for nuclear reactor, pipe line bends, joining of pipes carrying heavy water require welding for safe and reliable operations.

Defense industry

3. Tank body fabrication, joining of turret mounting to main body of tanks are typical examples of applications of welding in defense industry.

Electronic industry

4. Electronic industry uses welding to limited extent e.g. joining leads of special transistors but other joining processes such as brazing and soldering are widely used.
5. Soldering is used for joining electronic components to printed circuit boards (PCBs).
6. Robotic soldering is very common for joining of parts to printed circuit boards of computers, television, communication equipment and other control equipment etc.

Electrical Industry

7. Components of both hydro and steam power generation system, such as penstocks, water control gates, condensers, electrical transmission towers and distribution system equipment are fabricated by welding. Turbine blades and cooling fins are also joined by welding.

Surface transport

8. Railway: Railway uses welding extensively for fabrication of coaches and wagons, repair of wheel, laying of new railway tracks by mobile flash butt welding machines and repair of cracked/damaged tracks by thermite welding.
9. Automobiles: Production of automobile components like chassis, body and its structure, fuel tanks and joining of door hinges require welding.

Aerospace Industry

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

Ship Industry

12. Ships were produced earlier by riveting. Welding found its place in ship building around 1920 and presently all welded ships are widely used. Similarly submarines are also produced by welding.

Construction industry

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

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Lecture - 2

Classification of Welding Processes I

Welding is a process of joining metallic components with or without application of heat, with or without pressure and with or without filler metal. A range of welding processes have been developed so far using single or a combination above factors namely heat, pressure and filler. Welding processes can be classified on the basis of following techological criteria:

- Welding with or without filler material
- Source of energy for welding
- Arc and non-arc welding
- Fusion and pressure welding

Keywords: Classification of welding process, autogenous weld, fusion vs. pressure welding

2.1 Classification of welding processes on the basis of technical factors

2.1.1 Welding with or without filler material

A weld joint can be developed just by melting of edges (faying surfaces) of plates or sheets to be welded especially when thickness is lesser than 5 mm thickness. A weld joint developed by melting the fating surfaces and subsequently solidification only (without using any filler metal) is called “autogenous weld”. Thus, the composition of the autogenous weld metal corresponds to the base metal only. However, autogenous weld can be crack sensitive when solidification temperature range of the base metal to be welded is significantly high (750^{o} - 100^{o}C). Following are typical welding processes in which filler metal is generally not used to produce a weld joint.

- Laser beam welding
- Electron beam welding
- Resistance welding,
- Friction stir welding

However, for welding of thick plates/sheets using any of the following processes filler metal can be used as per needs according to thickness of plates. Application of autogenous fusion weld in case of thick plates may result in concave weld or under fill like discontinuity in weld joint. The composition of the filler metal can be similar to that of base metal or different one accordingly weld joints are categorized as homogeneous or heterogeneous weld, respecting.

In case of autogenous and homogeneous welds, solidification occurs directly by growth mechanism without nucleation stage. This type of solidification is called epitaxial solidification. The autogenous and homogeneous welds are considered to be of lesser prone to the development of weld discontinuities than heterogeneous weld because of a uniformity in composition and (b) if solidification largely occurs at a constant temperature. Metal systems having wider solidification temperature range show issues related with solidification cracking and partial melting tendency. The solidification in heterogeneous welds takes place in conventional manner in two stages i.e. nucleation and growth. Following are few fusion welding processes where filler may or may not be used for developing weld joints:

- Plasma arc welding
- Gas tungsten arc welding
- Gas welding

Some of the welding processes are inherently designed to produce a weld joint by applying heat for melting base metal and filler metal both. These processes are mostly used for welding of thick plates (usually > 5mm) with comparatively higher deposition rate.

- Metal inert gas welding: (with filler)
- Submerged arc welding: (with filler)
- Flux cored arc welding: (with filler)
- Electro gas/slag welding: (with filler)

Comments on classification of welding processes based on with/without filler

The gas welding process was the only fusion welding process earlier using which joining could be achieved with or without filler material. The gas welding performed without filler material was termed as autogenous welding. However, with the development of tungsten inert gas welding, electron beam, laser beam and many other welding processes, such classification created confusion as many processes were falling in both the categories.

2.1.2 Source of energy for welding

Almost all weld joints are produced by applying energy in one or other form to develop atomic/metallic bond between metals being joined and the same is achieved either by melting the faying surfaces using heat or applying pressure either at room temperature or high temperature (0.5^o to 0.9^o Tm). Based on the type of energy being used for creating metallic bonds between the components to be welded, welding processes can be grouped as under:

- Chemical energy: Gas welding, explosive welding, thermite welding
- Mechanical energy: Friction welding, ultrasonic welding
- Electrical energy: Arc welding, resistance welding
- Radiation energy: Laser beam welding, electron beam welding

Comments on classification of welding processes based on source of energy
Energy in various forms such as chemical, electrical, light, sound, mechanical energies etc. are used for developing weld joints. However, except chemical energy all other forms of energies are generated from electrical energy for welding. Hence, categorization of the welding processes based on the source of energy criterion also does not justify classification properly.

2.1.3 Arc or Non-arc welding

Metallic bond between the plates to be welded can be developed either by using heat for complete melting of the faying surfaces then allowing it to solidify or by apply pressure on the components to be joined for mechanical interlocking. All those welding processes in which heat for melting the faying surfaces is provided after establishing an arc either between the base plate and an electrode or between electrode & nozzle are grouped under arc welding processes. Another set of welding processes in which metallic bond is produced using pressure or heat generated from sources other than arc namely chemical reactions or frictional effect etc., are grouped as non-arc based welding processes. Welding processes corresponding to each group are given below.

- Arc based welding processes
  - Shielded Metal Arc Welding: Arc between base metal and covered electrode
  - Gas Tungsten Arc Welding: Arc between base metal and tungsten electrode
  - Plasma Arc Welding: Arc between base metal and tungsten electrode
  - Gas Metal Arc Welding: Arc between base metal and consumable electrode
  - Flux Cored Arc Welding: Arc between base metal and consumable electrode
  - Submerged Arc Welding: Arc between base metal and consumable electrode

- Non-arc based welding processes
  - Resistance welding processes: uses electric resistance heating
  - Gas welding: uses heat from exothermic chemical reactions
  - Thermit welding: uses heat from exothermic chemical reactions
  - Ultrasonic welding: uses both pressure and frictional heat
  - Diffusion welding: uses electric resistance/induction heating to facilitate diffusion
  - Explosive welding: involves pressure

Comments on classification of welding processes based on arc or non arc based process

Arc and non-arc welding processes classification leads to grouping of all the arc welding processes in one class and all other processes in non-arc welding processes. However, welding processes such as electro slag welding (ESW) and flash butt welding were found difficult to classify in either of the two classes as ESW process starts with arcing and subsequently on melting of sufficient amount flux, the arc extinguishes and heat for melting of base metal is generated by electrical resistance heating by flow of current through molten flux/metal. In flash butt welding, tiny arcs i.e. sparks are established during initial stage of the welding followed by pressing of components against each other. Therefore, such classification is also found not perfect.

2.1.4 Pressure or Fusion welding

Welding processes in which heat is primarily applied for melting of the faying surfaces are called fusion welding processes while other processes in which pressure is primarily applied (with little or no application of heat for softening of metal up to plastic state) for developing metallic bonds are termed as solid state welding processes.

- Pressure welding
    - Resistance welding processes (spot, seam, projection, flash butt, arc stud welding)
    - Ultrasonic welding
    - Diffusion welding
    - Explosive welding
- Fusion welding process
    - Gas Welding
    - Shielded Metal Arc Welding
    - Gas Metal Arc Welding
    - Gas Tungsten Arc Welding
    - Submerged Arc Welding
    - Electro Slag/Electro Gas Welding

Comments on classification of welding processes based on Fusion and pressure welding

Fusion welding and pressure welding is most widely used classification as it covers all processes in both the categories irrespective of heat source and welding with or without filler material. In fusion welding, all those processes are included in which molten metal solidifies freely while in pressure welding, molten metal if any is retained in confined space (as in case of resistance spot welding or arc stud welding) and solidifies under pressure or semisolid metal cools under pressure. This type of classification poses no problems and therefore it is considered as the best criterion.

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Lecture: 3

Classification of Welding Processes II

Apart from technical factors, welding processes can also be classified on the fundamental approaches used for deposition of materials for developing a joint. This chapter presents the classification of welding processes as welding processes and allied process used for developing a joint

Keywords: Welding and allied processes, approach of classification, cast weld, resistance weld, fusion weld, solid state weld

3.1 Classification of welding processes

There is another way of classifying welding and allied processes which is commonly reported in literature. Various positive processes involving addition or deposition of metal are first broadly grouped as welding process and allied welding processes as under:

1. Welding processes
    1. Cast weld processes
    2. Fusion weld processes
    3. Resistance weld processes
    4. Solid state weld processes
2. Allied welding processes
    1. Metal depositing processes
    2. Soldering
    3. Brazing
    4. Adhesive bonding
    5. Weld surfacing
    6. Metal spraying

This approach of classifying the welding process is primarily based on the way metallic pieces are united together during welding such as

- Availability and solidification of molten weld metal between components being joined are similar to that of casting: Cast weld process.

- Fusion of faying surfaces for developing a weld: Fusion weld process
- Heating of metal only to plasticize then applying pressure to forge them together: Resistance weld process
- Use pressure to produce a weld joint in solid state only: Solid state weld process

3.2 Cast welding process

Those welding processes in which either molten weld metal is supplied from external source or melted and solidified at very low rate during solidification like castings. Following are two common welding processes that are grouped under cast welding processes:

- o Cast weld processes
    - Thermite welding
    - Electroslag welding

In case of thermite welding, weld metal is melted externally using exothermic heat generated by chemical reactions and the melt is supplied between the components to be joined while in electroslag welding weld metal is melted by electrical resistance heating and then it is allowed to cool very slowly for solidification similar to that of casting.

Comments on classification based on cast weld processes

This classification is true for thermite welding where like casting melt is supplied from external source but in case of electroslag welding, weld metal obtained by melting of both electrode and base metal and is not supplied from the external source. Therefore, this classification is not perfect.

3.3 Fusion Weld Processes

Those welding processes in which faying surfaces of plates to be welded are brought to the molten state by applying heat and cooling rate experienced by weld metal in these processes are much higher than that of casting. The heat required for melting can be produced using electric arc, plasma, laser and electron beam and combustion of fuel gases. Probably this is un-disputed way of classifying few welding processes. Common fusion welding processes are given below:

- Fusion Weld Processes
  - Carbon arc welding
  - Shielded metal arc welding
  - Submerged arc welding
  - Gas metal arc welding
  - Gas tungsten arc welding
  - Plasma arc welding
  - Electrogas welding
  - Laser beam welding
  - Electron beam welding
  - Oxy-fuel gas welding

3.4Resistance welding processes

Welding processes in which heat required for softening or partial melting of base metal is generated by electrical resistance heating followed by application of pressure for developing a weld joint. However, flash butt welding begins with sparks between components during welding instead of heat generation by resistance heating.

- Resistance welding processes
  - Spot welding
  - Projection welding
  - Seam welding
  - High frequency resistance welding
  - High frequency induction welding
  - Resistance butt welding
  - Flash butt welding
  - Stud welding

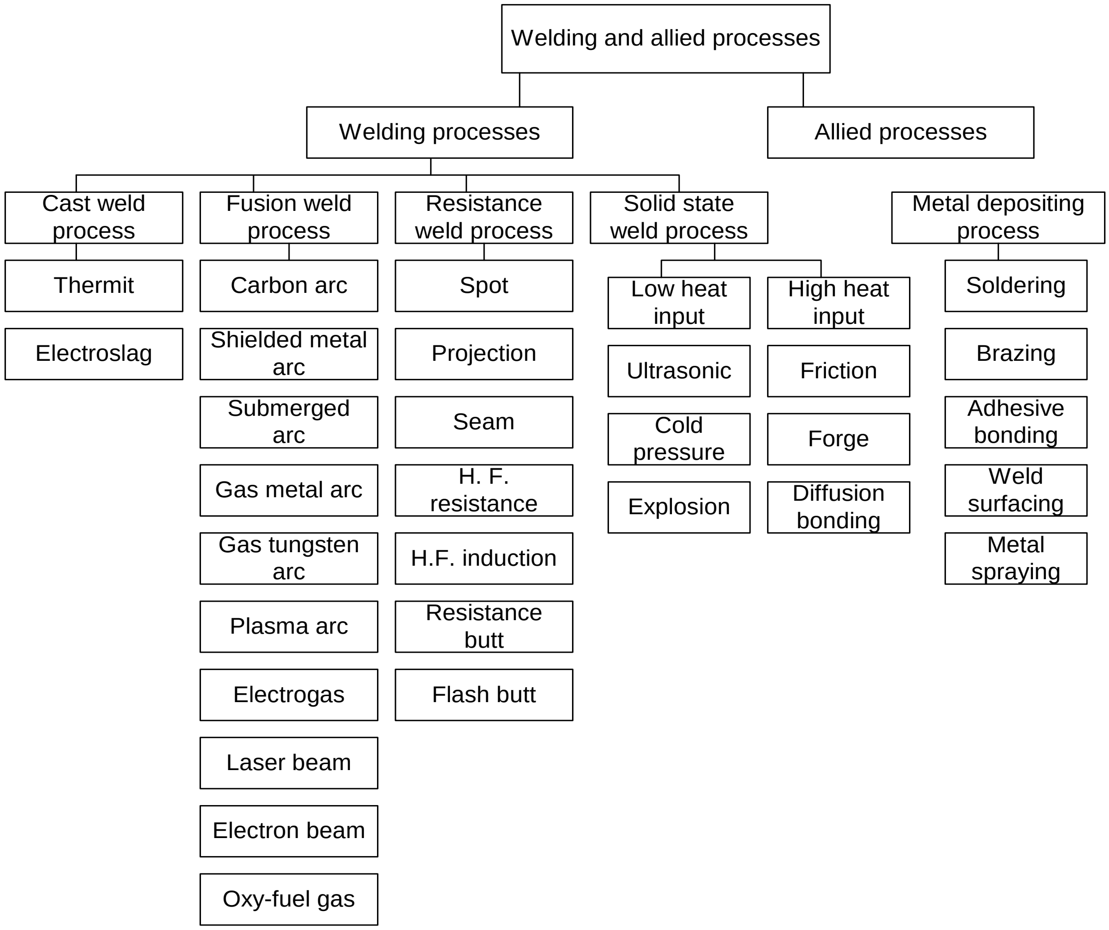
3.5 Solid state welding process

Welding processes in which weld joint is developed mainly by application of pressure and heat through various mechanism such as mechanical interacting, large scale interfacial plastic deformation and diffusion etc.. Depending up on the amount of heat generated during welding these are further categorized as under:

- Solid state welding process
  - Low heat input processes
    - Ultrasonic welding
    - Cold pressure welding
    - Explosion welding
  - High heat input processes
    - Friction welding
    - Forge welding
    - Diffusion welding

There are many ways to classify the welding processes however, fusion welding and pressure welding criterion is the best and most accepted way to classify all the welding processes. The flow chart is showing classification of welding and allied processes for better understanding of nature of a specific process (Chart 3.1).

Chart 3.1 Classification of Welding and Allied Processes



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Lecture: 4

Power density and welding process

In this chapter, energy density and temperature associated with different welding processes have been presented. Further, the influence of energy density on the performance parameters of the weld joints has also been described.

Keywords: Power density, temperature of heat source, heat input, distortion, mechanical properties

4.1 Introduction

Fusion welding processes can be looked into on the basis of range of energy density which they can apply for melting the faying surfaces of base metal for joining. Heat required for fusion of faying surfaces of components being welded comes from different sources in different fusion welding processes (gas, arc and high energy beam). Each type of heat source has capability to supply heat at different energy densities (kW/mm^2). Even for a given arc power (arc current I X arc voltage V), different welding processes provide heat at different energy densities due to the fact that it is applied over different areas on the surface of base metal in case of different processes. Energy density (kW/mm^2) is directly governed by the area over which heat is applied by a particular process besides welding parameters. Power density in ascending order from gas welding to arc welding to energy beam based welding processes is shown in table 4.1. Typical values of energy densities and approximate maximum temperature generated during welding by different processes are shown in Table 4.1.

Table 4.1 Heat intensity and maximum temperature related with different welding processes

Sr. No.	Welding process	Heat density (W/cm^2)	Temperature (^{0}C)
1	Gas welding	10^2 -10^3	2500-3500
2	Shielded meta arc welding	10^4	>6000
	Gas metal arc welding	10^5	8000-10000
3	Plasma arc welding	10^6	15000-30000
4	Electron beam welding	10^7 -10^8	20,000-30000
5	Laser beam welding	>10^8	>30,000

4.2 Effect of power density

Energy density associated with a particular welding process directly affects amount of heat required to be supplied for fusion of the faying surfaces. An increase in power density decreases the heat input required for melting and welding of work pieces because it decreases time over which heat is to be applied during welding for melting. The decrease in heat application time in turn lowers the amount of heat dissipated away from the faying surfaces to the base metal so the most of the heat applied on the faying surfaces is used for their fusion only. However, it is important to note that heat required for melting the unit quantity of a given metal is constant and is a property of material. Heat for melting comprises sensible heat and latent heat. Latent heat for steel is 2 kJ/mm^3.

Fusion welding processes are based on localized melting using high-density heat energy. To ensure melting of base metal in short time it is necessary that energy density of welding process is high enough (Fig. 4.1). Time to melt the base metal is found inversely proportional to the power density of heat source i.e. power of (arc or flame) / area of work piece over which it is applied (W/cm^2). Lower the energy density of heat source greater will be the heat input needed for fusion of faying surface welding as a large amount of heat is dissipated to colder base material of work piece away from the faying surface by thermal conduction (Fig. 4.2).

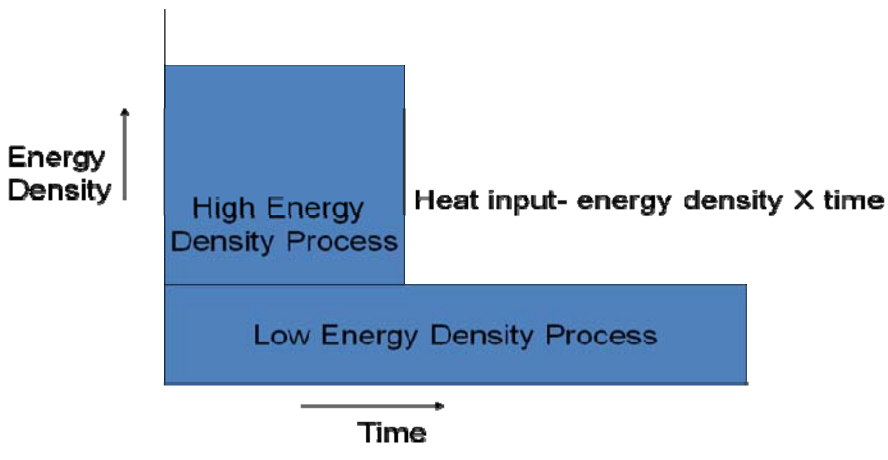

Fig. 4.1 Effect of energy density and time on energy input

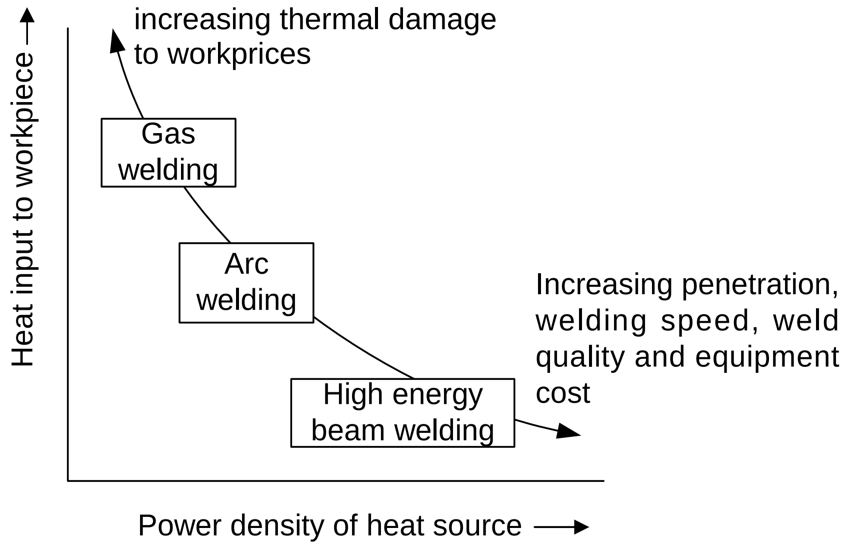

Fig. 4.2 Effect of power density of heat source on heat input required for welding [Kou S, 2003]

4.3 Need of optimum power density of welding process

As stated, low power density processes need higher heat input than high power density processes. Neither too low nor too high heat input is considered good for developing a sound weld joint. As low heat input can lead to lack of penetration and poor fusion of faying surfaces during welding while excessive heat input may cause damage to the base metal in terms of distortion, softening of HAZ and reduced mechanical properties (Fig. 4.3). High heat input has been reported to lower the tensile strength of many aluminium alloys of commercial importance due to thermal softening of HAZ and development of undesirable metallurgical properties of the weldment (Fig. 4.4). Moreover, use of high power density offers many advantages such as deep penetration, high welding speed and improved quality of welding joints. Welding process (where melting is required) should have power density approximately 10(W/mm^2). Vaporization of metal takes place at about 10,000W/mm^2 power-density. Processes (electron and laser beam) with such high energy density are used in controlled removal of metal for shaping of difficult to machine metals. Welding processes with power density in ascending order are shown in Fig. 4.5.

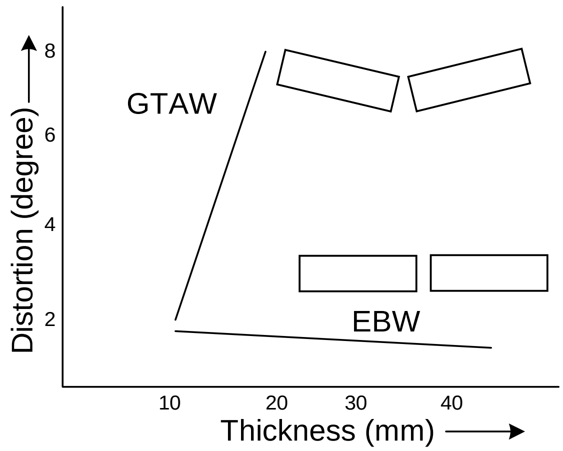

Fig. 4.3 Effect of welding process on angular distortion of weld joint as a function of plate thickness[Kou S, 2003]

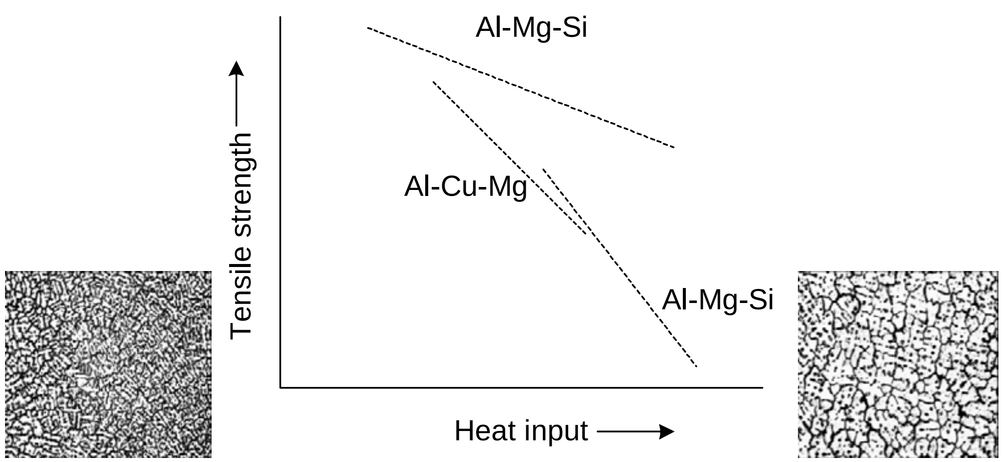

Fig. 4.4 Schematic diagram showing effect of heat input on tensile strength of aluminium alloy weld joints (magnfication of micrograph in figure is 200 X) [Kou S, 2003]

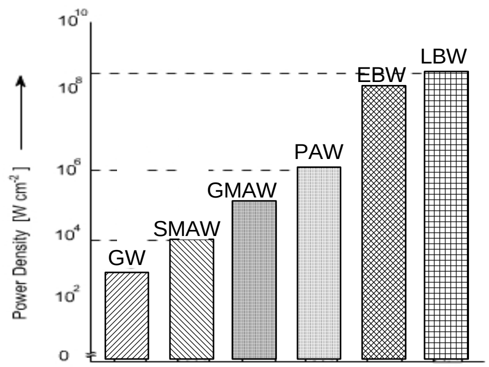

Fig. 4.5 Power densities of different welding processes

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Lecture 5

Physics of Welding Arc I

This chapter presents fundamentals of welding arc, mechanisms of electron emission, different zones in welding arc, electrical aspects related with welding arc and their significance in welding.

Keywords: Welding arc, electron emission, thermo-ionic emission, field emission, cathode and anode spot, arc power

5.1 Introduction

A welding arc is an electric discharge that develops primarily due to flow of current from cathode to anode. Flow of current through the gap between electrode and work piece needs column of charged particles for having reasonably good electrical-conductivity. These charged particles are generated by various mechanisms such as thermal emission, field emission secondary emission etc. Density of charged particles in gap governs the electrical conductivity of gaseous column. In an electric arc, electrons released from cathode (due to electric field or thermo-ionic emission) are accelerated towards the anode because of potential difference between work piece and electrode. These high velocity electrons moving from cathode toward anode collide with gaseous molecules and decompose them into charged particles i.e. electrons and ions. These charged particles move towards electrode and work piece as per polarity and form a part of welding current. Ion current becomes only about 1% of electron current as ions become heavier than the electrons so they move slowly. Eventually electrons merge into anode. Arc gap between electrode and work piece acts as pure resistance load. Heat generated in a welding arc depends on arc voltage and welding current.

5.2 Emission of Free electrons

Free electrons and charged particles are needed between the electrode and work for initiating the arc and their maintenance. Ease of emitting electrons by a material assessed on the basis of two parameters work function and ionization potential. Emission of electrons from the cathode metal depends on the work function. The work function is the energy (ev or J) required to get one electron released from the surface of material. Ionization potential is another measure of ability of a metal to emit the electrons and is defined as energy/unit charge (v) required for removing an electron from an atom. Ionization potential is found different for different metal. For example, Ca, K, and Na have very low ionization potential (2.1-2.3ev), while that for Al and Fe is on the higher side with values of 4 and 4.5 ev respectively. Common mechanisms through which free electrons are emitted during arc welding are described below:

5.2.1 Thermo-ionic emission

Increase in temperature of metal increases the kinetic energy of free electrons and as it goes beyond certain limit, electrons are ejected from the metal surface. This mechanism of emission of electron due to heating of metal is called thermo ionic emission. The temperature at which thermo-ionic emission takes place, most of the metals melt. Hence, refractory materials like tungsten and carbon, having high melting point exhibit thermo ionic electron emission tendency.

5.2.2 Field emission:

In this approach, free electrons are pulled out of the metal surface by developing high strength electro-magnetic field. High potential difference (10^7 V/cm) between the work piece and electrode is established for the field emission purpose.

5.2.3 Secondary emission

High velocity electrons moving from cathode to anode in the arc gap collide with other gaseous molecules. This collision results in decomposition of gaseuous molecules into atoms and charged particles (electrons and ions).

5.3 Zones in Arc Gap

On establishing the welding arc, drop in arc voltage is observed across the arc gap. However, rate of drop in arc voltage varies with distance from the electrode tip to the weld pool (Fig. 5.1). Generally, five different zones are observed in the arc gap namely cathode spot, cathode drop zone, plasma, anode drop zone and anode spot (Fig. 5.2).

5.3.1 Cathode spot

This is a region of cathode wherefrom electrons are emitted. Three types of cathode spots are generally found namely mobile, pointed, and normal. There can be one or more than one cathode spots moving at high speed ranging from 5-10 m/sec. Mobile cathode spot is usually produced at current density 100-1000 A/mm^2. Mobile cathode spot is generally found during the welding of aluminium and magnesium. This type of cathode spot loosens the oxide layer on reactive metal like aluminium, Mg and stainless steel. Therefore, mobile cathode spot helps in cleaning action when reverse polarity is used i.e. work piece is cathode. Pointed cathode spot is formed at a point only mostly in case of tungsten inert gas welding at about 100A/mm^2. Pointed tungsten electrode forms the pointed cathode-spot. Ball shaped tip of coated steel electrode forms normal cathode spot.

5.3.2 Cathode drop region:

This region is very close to the cathode and a very sharp drop of voltage takes place in this zone due to cooling effect of cathode. Voltage drop in this region directly affects the heat generation near the cathode which in turn governs melting rate of the electrode in case of the consumable arc welding process with straight polarity (electrode is cathode).

5.3.3 Plasma:

Plasma is the region between electrode and work where mostly flow of charged particles namely free electrons and positive ions takes place. In this region, uniform voltage drop takes place. Heat generated in this region has minor effect on melting of the work piece and electrode.

5.3.4 Anode drop region:

Like cathode drop region, anode drop region is also very close to the anode and a very sharp drop in voltage takes place in this region due to cooling effect of the anode. Voltage drop in this region affects the heat generation near the anode & so melting of anode. In case of direct current electrode negative (DCEN), voltage drop in this zone affects melting of the work piece.

5.3.5 Anode spot:

Anode spot is the region of a anode where electrons get merged and their impact generates heat for melting. However, no fixed anode spot is generally noticed on the anode like cathode spot.

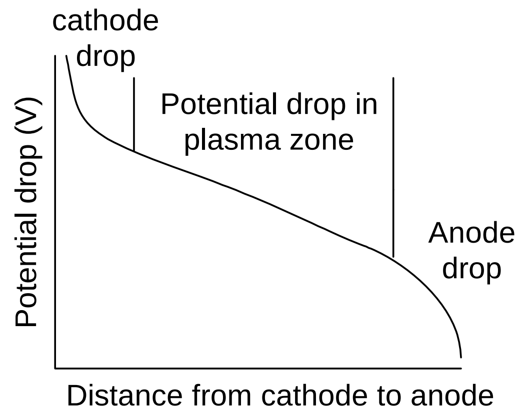

Fig. 5.1 Potential drop as function of distance form the cathode to anode

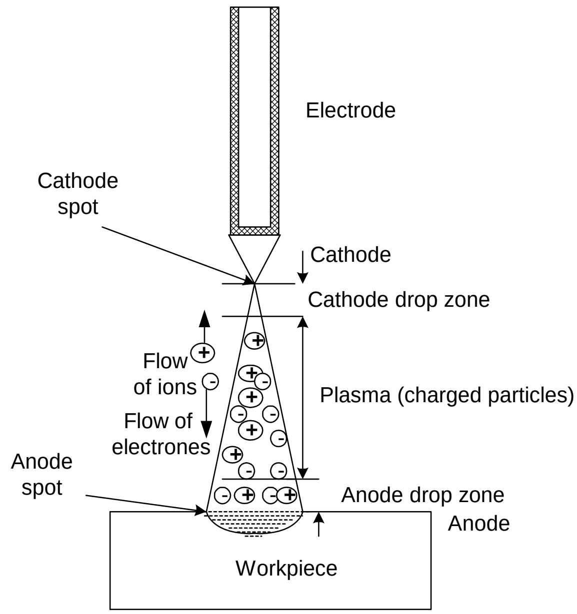

Fig. 5.2 Zones in arc gap of a welding arc

5.4 Electrical Fundamentals of Welding Arc

The welding arc acts as impedance for flow of current like an electric conductor. The impedance of arc is usually found a function of temperature and becomes inversely proportional to the density of charge particles and their mobility. Therefore, distribution of charged particles in radial and axial direction in the arc affects the total impedance of the arc. Three major regions have been noticed in arc gap that accounts for total potential drop in the arc i.e. cathode drop region, plasma and anode drop region. Product of potential difference across the arc (V) and current (I) gives the power of the arc indicating the heat generation per unit time. Arc voltage (V) is taken as sum of potential drop across the cathode drop region (V_c), potential drop across the plasma region (V_p), and potential drop across the anode drop region (V_a) as shown in Fig. 5.3.

Power of the arc (P) = $(V_c + V_p + V_a)$ I……………………….(5.1)

Potential drop in different zones is expressed in terms of volt (V), welding current in ampere (A) and power of arc P is in watt (W). Equation 5.1 suggests that the distribution of heat in three zones namely cathode, anode and arc plasma can be changed. Variation of arc length mainly affects plasma heat while shielding gas influences the heat generation in the cathode and anode drop zones. Addition of low ionization potential materials (namely potassium and sodium) reduces the arc voltage because of increased ionization in arc gap so increased electrical conductivity which in turn reduces the heat generation in plasma region. Heat generation at the anode and cathode drop zones is primarily governed by type of welding process and polarity associated with welding arc. In case of direct current (DC) welding, when electrode is connected to the negative terminal and workpiece is connected with positive terminal of the power source then it is termed as direct current electrode negative polarity (DCEN) or straight polarity and when electrode is connected to the positive terminal of the power source and workpiece is connected with negative terminal then it is termed as direct current electrode positive polarity (DCEP) or reverse polarity. TIG welding with argon as shielding gas shows 8-10 time higher current carrying capacity (without melting) than DCEP. The submerged arc welding with DCEP generates larger amount of heat at cathode than anode as indicated by high melting rate of consumable electrode.

Increase in spacing between the electrode and work-piece generally increases the potential of the arc because of increased losses of the charge carriers by radial migration to cool boundary of the plasma. Increase in the length of the arc column (by bulging) exposes more surface area of arc column to the low temperature atmospheric gas which in turn imposes the requirement of more number of charge carriers to maintain the flow of current. Therefore, these losses of charged particles must be accommodated to stabilize the arc by increasing the applied voltage. The most of the heat generated in consumable arc welding process goes to weld pool which in turn results in higher thermal efficiencies. This is more evident from the fact that the thermal efficiency of metal arc welding processes is found in range of 70-80% whereas that for non-consumable arc welding processes is found in range of 40-60%.

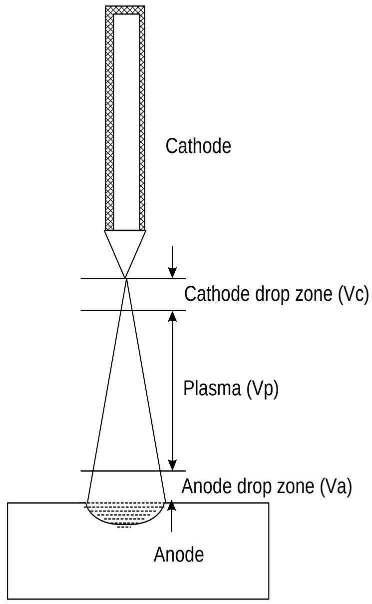

Fig. 5.3 Three different zone in which voltage drop takes place

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Lecture 6

Physics of Welding Arc II

This chapter presents methods of initiating and maintenance of the welding arc besides the arc characteristics and temperature distribution in welding arc. Further, factors affecting the arc characteristics and temperature distribution of welding arc have also been described.

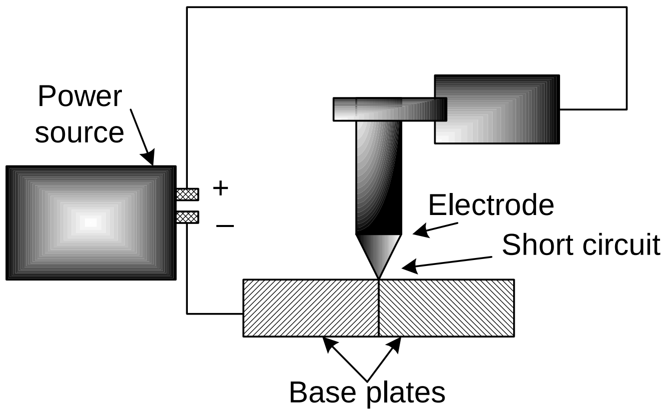
Keywords: Arc initiation, touch start, field start, ionization potential, power factor, arc characteristics, arc temperature

6.1 Arc Initiation

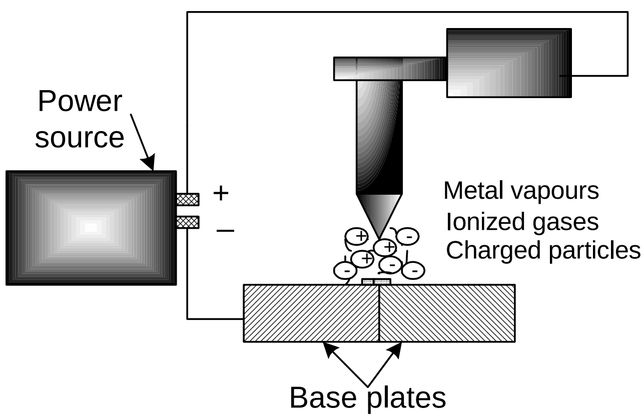
There are two most commonly used methods to initiate an electric arc in welding processes namely touch start and field start. The touch start method is used in case of all common welding processes while the later one is preferred in case of automatic welding operations and in the processes where electrode has tendency to form inclusion in the weld metal like in TIG welding or electrode remains inside the nozzle.

6.1.1 Touch Start

In this method, the electrode is brought in contact with the work piece and then pulled apart to create a very small gap. Touching of the electrode to the workpiece causes short-circuiting resulting in flow of heavy current which in turn leads to heating, partial melting and even slight evaporation of the metal at the electrode tip. All these events happen in very short time usually within few seconds (Fig. 6.1 a, b). Heating of electrode produces few free electrons due to thermal ionization; additionally dissociation of metal vapours (owing to lower ionization potential of the metal vapours than the atmospheric gases) also produces charged particles (electron and positively charged ions). On pulling up of the electrode apart from the work piece, flow of current starts through these charged particles and for a moment arc is developed. To use the heat of electric arc for welding purpose it is necessary that after initiation of arc it must be maintained and stabilized.



a)



b)

Fig. 6.1 Schematic diagram showing mechanism of arc initiation by touch start method a) when circuit closed by touching electrode with work piece b) emission of electrode on putting them apart

6.1.2 Field Start

In this method, high strength electric field (10^7 V) is applied between electrode and work piece so that electrons are released from cathode electro-magnetic field emission (Fig. 6.2). Development of high strength field leads to ejection of electron from cathode spots. Once the free electrons are available in arc gap, normal potential difference between electrode and work piece ensures flow of charged particles to maintain a welding arc. This method is commonly used in mechanized welding processes such as plasma arc and GTAW process where direct contact between electrode and work piece is not preferred.

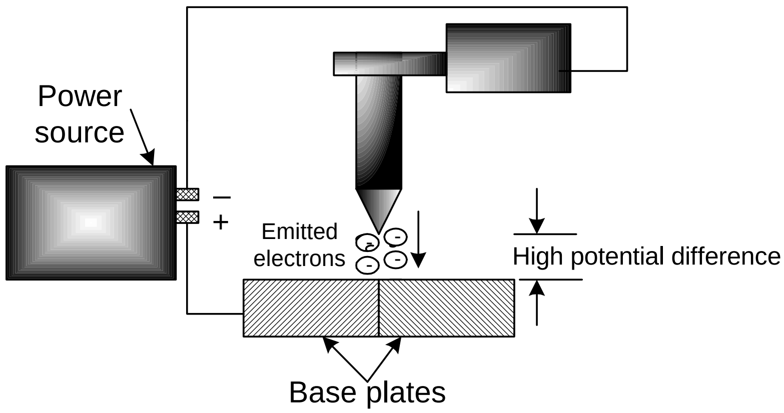


Fig. 6.2 Schematic diagram showing the field-start method of arc initiation

6.2 Maintenance of Arc

Once electric arc is initiated, next step is to maintain it to use the heat generated for welding purpose. For maintaining of the arc two conditions must be fulfilled (1) heat dissipation rate from the arc, region should be equal to that of heat generated to maintain the temperature of the arc and (2) number of electrons produced should be equal to that of electrons lost to the work piece and surroundings.

An electric arc primarily involves flow of current through the gap between the work piece and electrode hence there must be sufficient number of charged particles namely electrons and ions. However, some of the electrons are lost from the arc surface, to the weld pool and surroundings and few electrons reunite with ions. Loss of these electrons must be compensated by generation of new free electrons. In case of direct current, magnitude and direction of current does not change with time hence maintaining the flow of electrons and so the arc becomes easy while in case of alternating current (A. C.) both magnitude and direction change with time and for a moment flow of current becomes zero. This makes re-ignition of an electric arc with AC somewhat difficult and therefore it needs extra precautions and provisions. There are two commonly used methods for maintaining the arc in A.C. welding: (1) use of low ionization potential elements in coatings flux and (b) use of low power factor power source.

6.2.1 Low Ionization Potential Elements

In this method, low ionization potential elements such as potassium, calcium and sodium are added in the flux covering of the electrode (coating). These elements release free electrons needed to have reasonably good electrical conductivity for maintaining welding arc even with small potential difference between electrode and work piece (Fig. 6.3).

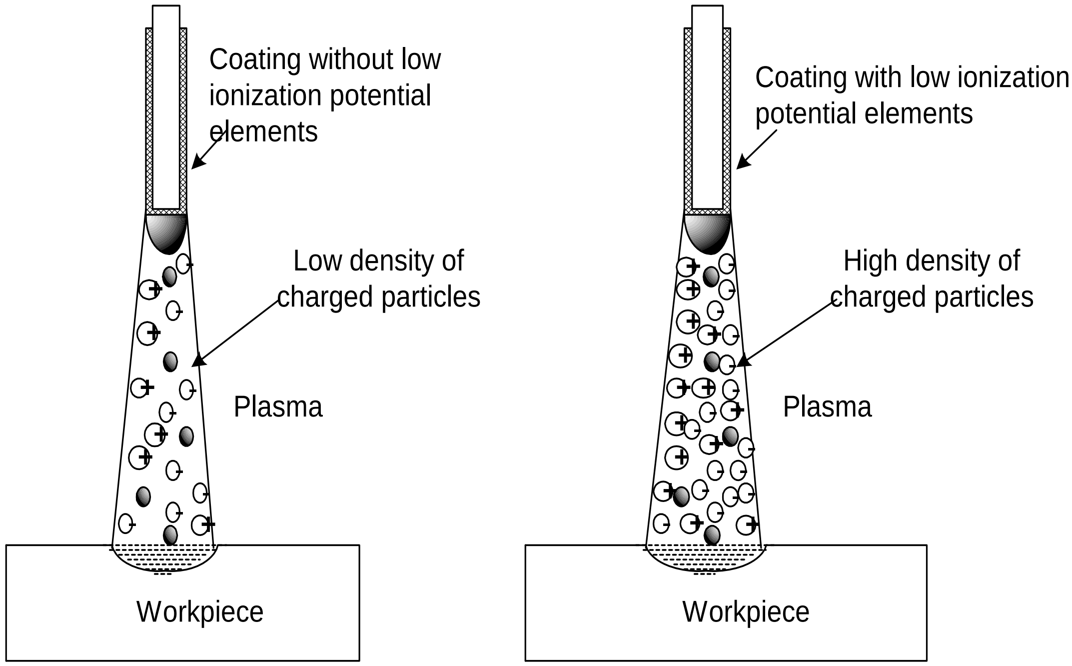


Fig. 6.3 Schematic representation of effect of low ionization potential elements on density of charged particles

6.2.2 Low Power Factor

Power factor of a system indicates how effectively power is being utilized and it is generally preferred to have high power factor of machine or system. Power factor is defined as ratio of actual power drawn from the power source to perform the welding and apparent power drawn into the welding circuit line. Welding transformer operates at high power factor (>0.9).

However, in welding usually low power factor is intentionally used to improve the arc stability and maintenance of welding arc. In this method, current and voltage are made out of phase by using proper low power factor (0.3) so that when current is zero, full open circuit voltage is available between electrode and work piece (Fig. 6.4). Full open circuit voltage across the electrode and work helps in release of free electrons to maintain flow of already existing electrons which is a perquisite for maintenance of the arc.

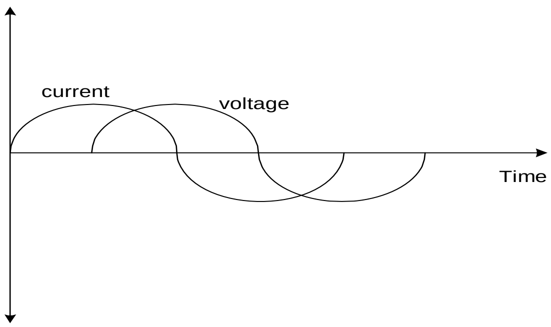


Fig. 6.4 setting proper power factor to have current and voltage out of phase

6.3 Arc Characteristic

Welding arc characteristic shows variation in the arc voltage with welding current. There are three different regions on the arc characteristic curve namely dropping, flat and rising characteristics zones (Fig. 6.5). Initially at low current when arc is thin, an increase in welding current increases the temperature of arc zone which in turn enhances the number of charged particles in plasma zone of the arc due to thermal ionization and thermo-ionic emission of electrons. As a result, electrical conductivity of arc zone increases which in turn decrease arc voltage decreases with initial increase in welding current in this zone. Arc tends to be stable in this region. This trend continues up to certain level of current and beyond that increase in current increases the diameter of cylindrical arc that increases the surface area of the arc. Increase in surface area of the arc in turn increases loss of heat from the arc surface. Therefore, no significant rise in arc temperature takes place with increase of current hence arc voltage is not affected appreciably over a range of current in flat zone of the curve. Further, increase in current bulges the arc, which in turn increases the resistance to flow of current (due to increased losses of charge carriers and heat from arc) so arc voltage increases with increase in welding current in rising characteristic zone . These three zones of arc characteristic curve are called drooping, flat and rising characteristics. Increase in arc length in general increases arc voltage during welding. However, the extent of increase in arc voltage with increase in arc length varies with process as shown in Fig. 6.6. In general, arc voltage increases almost lineally with increase in arc length (within reasonable limits) and the same is attributed to increase in resistance to the flow of current due to reduction in charged particle density in arc zones with increase in arc length.

Variation in charged particle density in arc zones associated different arc welding processes such as SMAW, GMAW and GTAW is attributed to appreciable difference in arc voltage vs. arc length relationship (Fig. 6.6). For example, GTAW process due to tungsten electrode (having high electron emitting capability) results in higher charged particle density in arc region than GMAW and SMAW which in turn leads to lower arc voltage/arc length ratio for GTAW than LMAW & SMAW process.

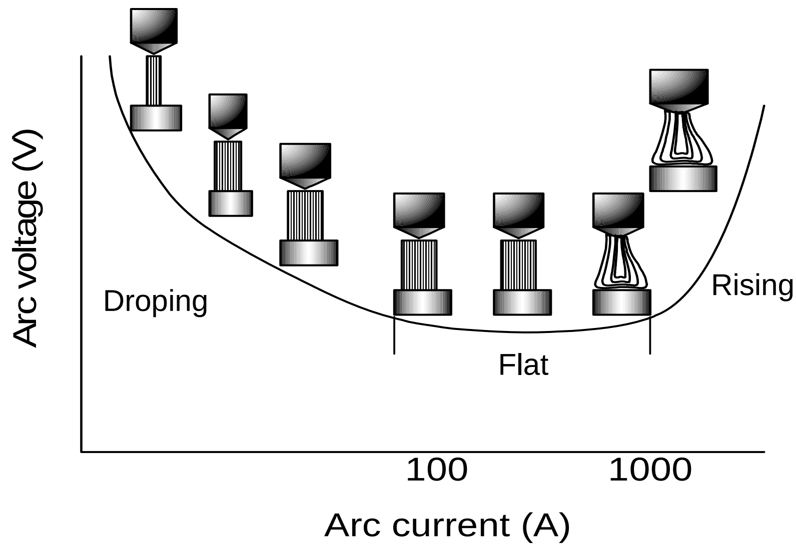


Fig. 6.5 Schematic diagram showing welding arc characteristic curve

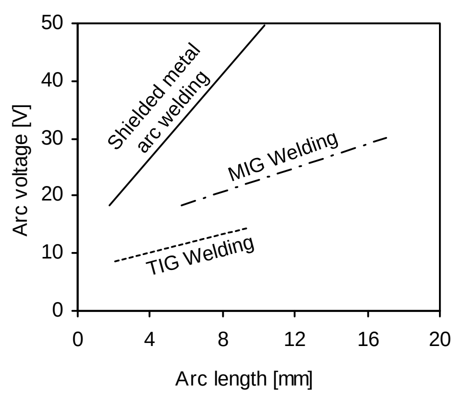


Fig. 6.6 Variation in arc voltage as function of arc length for different arc welding processes

6.4 Temperature of the Arc

In addition to arc voltage and current parameters (governing the power of arc), thermal properties (thermal conductivity) of shielding gases present in arc zone predominantly affect the temperature and its distribution in the arc region. Thermal conductivity of most of the gases (He, N, Ar) increases with rise in temperature however, this increase is not continuous for some of the gases such as Helium. Thermal conductivity of base metal/shielding gas governs temperature gradient in the arc region. Reduction in thermal conductivity increases the temperature gradient. Therefore, a very rapid decrease in temperature of arc is observed with increase in distance from the axis (center) of the arc (Fig. 6.7). Maximum temperature is observed at core (along the axis of electrode) of the arc and it decreases rapidly with increase in distance away from the core. Temperatures in anode and cathode drop zones are generally lower than the plasma region due to cooling effect of electrode/work piece. Temperature of arc can vary from 5000-30,000K depending upon the current voltage shielding gas and plasma gas. For example, in case of SMAW, temperature of arc is about 6000K while that for TIG/MIG welding arc it is found in range of 20000-25000K.

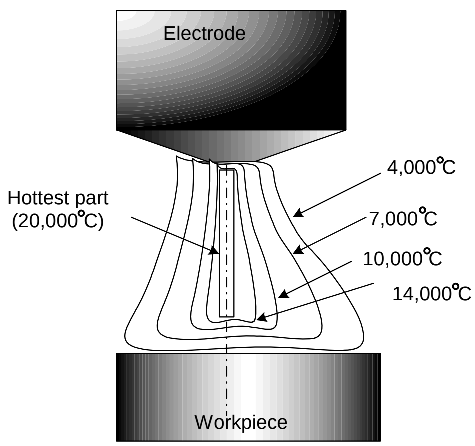


Fig. 6.7 Schematic diagram showing typical temperature distribution in the arc

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Lecture 7

Physics of Welding Arc III

This chapter presents the different forces acting in a typical welding arc zone and their effect on welding. Further, influence of electrode polarity in welding has been described in respect of arc stability, heat generation and cleaning action on weld metal. Mechanism of arc blow and methods to overcome the same have also been discussed.

Keywords: Arc forces, pinch force, electrode polarity, heat generation, arc stability, cleanliness of weld, arc blow, electromagnetic forces,

7.1 Arc Forces and Their significance on Welding

All the forces acting in arc zone are termed as arc forces. In respect of welding, influence of these forces on resisting or facilitating the detachment of molten metal drop hanging at the electrode tip is important which in turn affect the mode of metal transfer and weld metal disposition efficiencies (Fig. 7.1 a-f). Metal transfer is basically detachment and movement of molten metal drops from tip of the electrode to the weld pool in work piece and is of great practical importance because two reasons (a) flight duration of molten metal drop in arc region affects the quality of weld metal and element transfer efficiency, and (b) arc forces affect the deposition efficiency.

7.1.1 Gravity Force

This is due to gravitational force acting on molten metal drop hanging at the tip of electrode. Gravitational force depends on the volume of the drop and density of metal. In case of down hand welding, gravitational force helps in detachment/transfer of molten metal drop from electrode tip (Fig. 7.1a). While in case of overhead welding it prevents the detachment.

Gravitational force (F_g)=ρVg ...7.1

Where ρ (kg/m)^{3}is the density of metal, V is volume of drop (m^3) and g is gravitational constant (m/s^2).

7.1.2 Surface Tension Force

This force is experienced by drop of the liquid metal hanging at the tip of electrode due to surface tension effect. Magnitude of the surface tension force (Equation 7.2) is influenced by the size of droplet, electrode diameter and surface tension coefficient. This force tends to resist the detachment of molten metal drop from electrode tip and usually acts against gravitational force. In case of vertical and overhead welding positions, high surface tension force helps in placing the molten weld metal at required position more effectively by reducing tendency of falling down of molten weld metal (Fig. 7.1b). Accordingly, flux/electrode composition for odd-position welding purpose must be designed to have viscous and high surface tension weld metal/slag.

Surface tension (F_s) = $(2\sigma \, X \pi R_e^2)/4R$ ...(7.3)

Where σ is the surface tension coefficient, R is drop radius and R_e is the radius of electrode tip. An Increase in temperature of the molten weld metal reduces the surface tension coefficient (σ), hence this will reduce hindering effect of the surface tension force on detachment of the drop and so it will facilitate the detachment of drop from electrode tip.

7.1.3 **Force Due to Impact of Charge Carriers**

As per polarity charged particles (ions & electrons), move towards anode or cathode and eventually impact/collide with them. Force generated owing to impact of charged particles on to the molten metal drop hanging at the tip of electrode tends to hinder the detachment (Fig. 7.1c). This force is given by equation 7.4

Force due to impact of charged particles $F_m = m(dV/dt)$ ...(7.4)

Where m is the mass of charge particles, V is the velocity and t is the time.

7.1.4 Force Due to Metal Vapours

Molten metal evaporating from bottom of drop and weld pool move in upward direction. Forces generated due to upward movement of metal vapours act against the molten metal drop hanging at the tip of the electrode. Thus, this force tends to hinder the detachment of droplet (Fig. 7.1d).

7.1.5 Force Due to Gas Eruption

Gases present in molten metal such as oxygen, hydrogen etc. may react with some of the elements (such as carbon) present in molten metal drop and form gaseous molecules (carbon dioxide). The growth of these gases in molten metal drop as a function of time ultimately leads to bursting of metal drops which in turn increases the spattering and reduces the control over handling of molten weld metal (Fig. 7.1 e1-e4).

7.1.6 Force Due to Electro Magnetic Field

Flow of current through the arc gap develops the electromagnetic field. Interaction of this electromagnetic field with that of charge carriers produces a force which tends to pinch the drop hanging at the tip of the electrode also called pinch force. The pinch force reduces the cross section for molten metal drop near the tip of the electrode and thus helps in detachment of the droplet from the electrode tip (Fig. 7.1 f1-f2). A component of pinch force acting in downward direction is generally held responsible for detachment of droplet and is given by:

Pinch force $(F_p) = (\mu \text{ X } I^2)/8\pi$ ...(7.4)

Where μ is the magnetic permeability of metal, I is the welding current flowing through the arc gap.

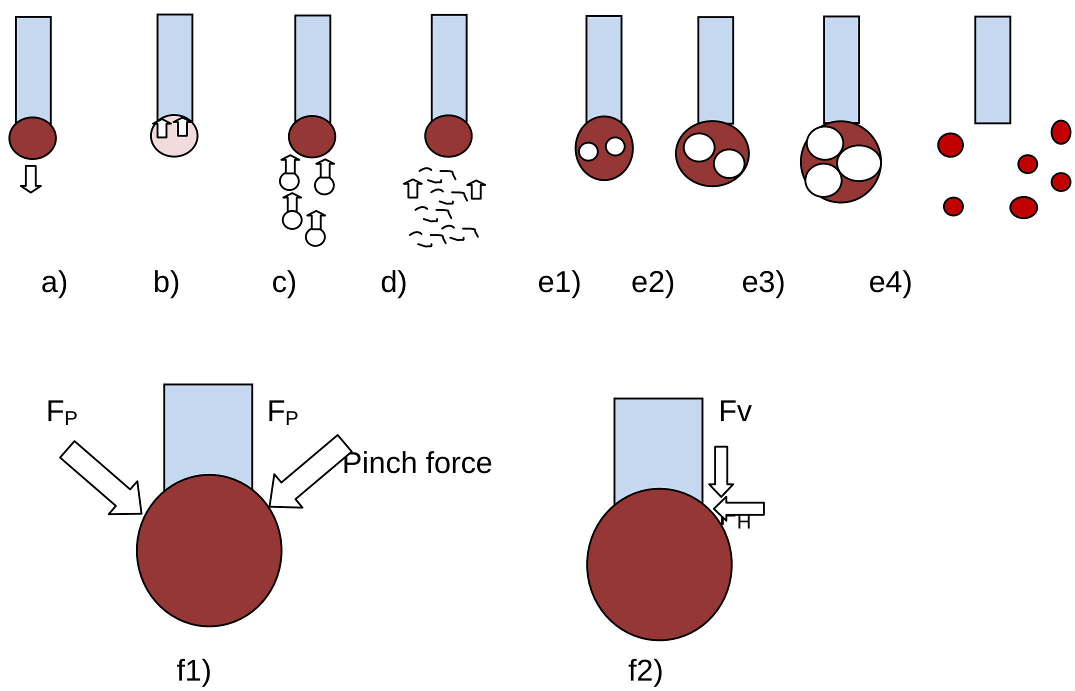


Fig. 7.1 Schematic diagram showing different arc forces a) gravitational force, b) surface tension force, c) force due to impact of charge particles, d) force due to metal vapours, e1 to e5) stages in force generation due to gas eruption and f1&f2) electromagnetic pinch force

7.2 Effect of Electrode Polarity

In case of D. C. welding, polarity depends on the way electrode is connected to the power source i.e. whether electrode is connected to positive or negative terminal of the power source. If electrode is connected to negative terminal of the power source, then it is called direct current electrode negative (DCEN) or straight polarity and if electrode is connected to positive terminal of the power source then it is called direct current electrode positive (DCEP) or reverse polarity. Polarity in case of A. C. welding doesn't remain constant as it changes in every half cycle of current. Selection of appropriate polarity is important for successful welding as it affects (Table 7.1):

1. distribution of heat generated by welding arc at anode and cathode,
2. stability of the arc and
3. cleanliness of weld

7.2.1 Heat Generation

In general, more heat is generated at the anode than the cathode. Of total DC welding arc heat, about two-third of heat is generated at the anode and one third at the cathode. The differential heat generation at the anode and cathode is due to the fact that impact of high velocity electrons with anode generates more heat than that of ions with cathode as electrons possess higher kinetic energy than the ions. Ion being heavier than electrons do not get accelerated much so move at low velocity in the arc region. Therefore, DCEN polarity is commonly used with non-consumable electrode welding processes so as to reduce the thermal degradation of the electrodes. Moreover, DCEP polarity facilitates higher melting rate deposition rate in case of consumable electrode welding process such as SAW and MIG etc.

7.2.2 Stability of Arc

All those welding processes (SMAW, PAW, GTAW) in which electrode is expected to emit free electrons required for easy arc initiation and their stability, selection of polarity affects the arc stability. Shielded metal arc welding using covered electrode having low ionization potential elements provide better stable arc stability with DCEN than DCEP. However, SMA welding with DCEP gives smoother metal transfer. Similarly, in case of GTAW welding, tungsten electrode is expected to emit electrons for providing stable arc and therefore DCEN is commonly used except when clearing action is receded in case of reactive metals e.g. Al, Mg, Ti.

7.3.3 Cleaning action

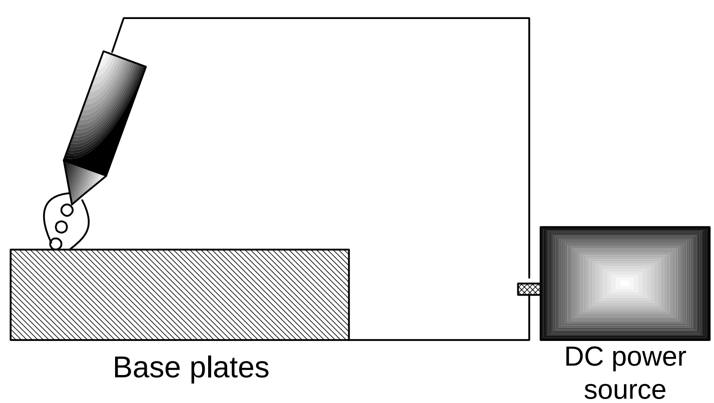
Good cleaning action is provided by mobile cathode spot because it loosens the tenacious refractory oxide layer during welding of aluminium and magnesium. Therefore, work piece is intentionally made cathode and electrode is connected to positive terminal of the power source. Thus, use of DCEP results in required cleaning action. Further, during TIG welding, a compromise is made between the electrode life and cleaning action by selecting the A.C..

Table 7.1 Comparison of AC and DC welding power sources

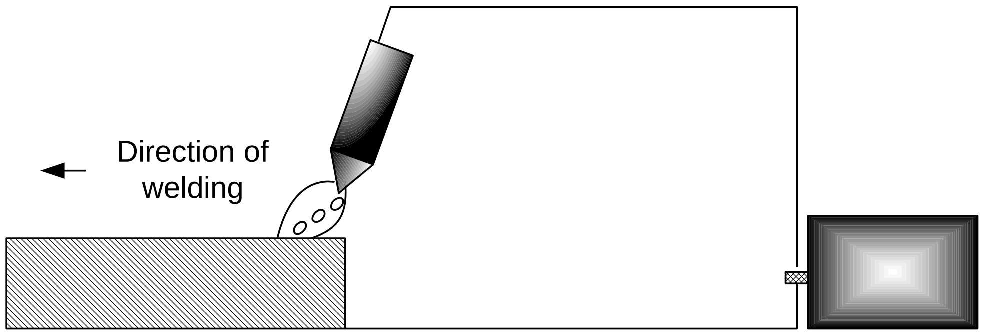
S. No.	Parameter	AC	DC
1	Arc stability	Poor	Good
2	Distribution of arc heat	Uniform	Provide better control of heat distribution
3	Efficiency	High	Low
4	Power factor	Low	High
5	Cleaning action	Good	Depends on polarity
6	Maintenance	Less	More
7	Cost	Less	More

7.3 Arc Blow

Arc blow is basically a deflection of a welding arc from its intended path i.e. axis of the electrode. Deflection of arc during welding reduces the control over the handling of molten metal by making it difficult to apply the molten metal at right place. A severe arc blow increases the spattering which in turn decreases the deposition efficiency of the welding process. According to the direction of deflection of arc with respect to welding direction, an arc blow may termed as be forward or backward arc blow. Deflection of arc ahead of the weld pool in direction of the welding is called forward arc blow and that in reverse direction is called backward arc blow (Fig. 7.2 a-c).



a)



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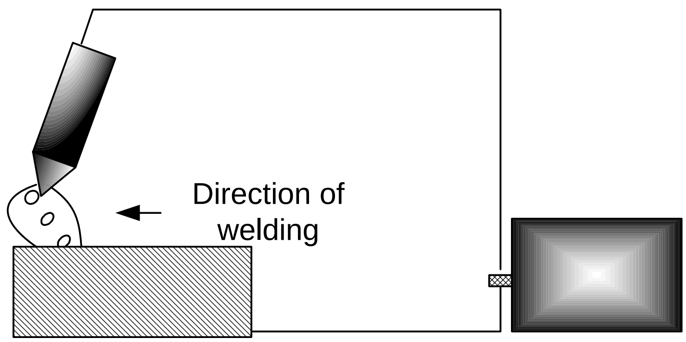

c)

Fig. 7.2 Schematic diagram showing welding a) without arc blow, b) with forward arc blow and c) with backward arc blow

7.3.1 Causes of arc blow

Arc blow is mainly encountered during DC arc welding due to interaction between different electromagnetic fields in and around the welding arc. Incidences of interaction between electromagnetic fields mainly occur in areas where these fields are localized. There are two common situations of interaction between electromagnetic fields that can lead to arc blow:

- interaction between electromagnetic field due to flow of current through the arc gap and that due to flow of current through plates being welded. Electromagnetic field is generated around the arc in arc gap. Any kind of interaction of this field with other electromagnetic fields leads to deflection of the arc from its intended path (Fig. 7.3a).
- interaction between electromagnetic field due to flow of current through the arc gap and that is localized while welding near the edge of the plates. The lines of electromagnetic fields are localized near the egde of the plates as these can flow easily through the metal than the air therefore distribution of lines of electromagnetic forces does not remain

uniform around the arc. These lines get concentrated near the edge of the plate (Fig. 7.3b).

7.3.2 Mechanism of arc blow

Electromagnetic field is generated in a plane perpendicular to the direction of current flow through a wire. Intensity of self induced magnetic field ($H = i/2\pi r$) due to flow of current depends upon the distance of point of interest from center of wire (r) and magnitude of current (i). In general, increase in current and decrease the distance of from the wire increase the intensity of electromagnetic field. Depending upon the direction of current flow through two wires, there can be two types of polarities namely like and unlike polarity, accordingly electromagnetic fields due to current flow interacts with each other (Fig. 7.3 a). In case of like polarity, the direction of flow of current is same in two conductors. Electromagnetic fields in case of like polarities repel each other while those of unlike polarities attract each other.

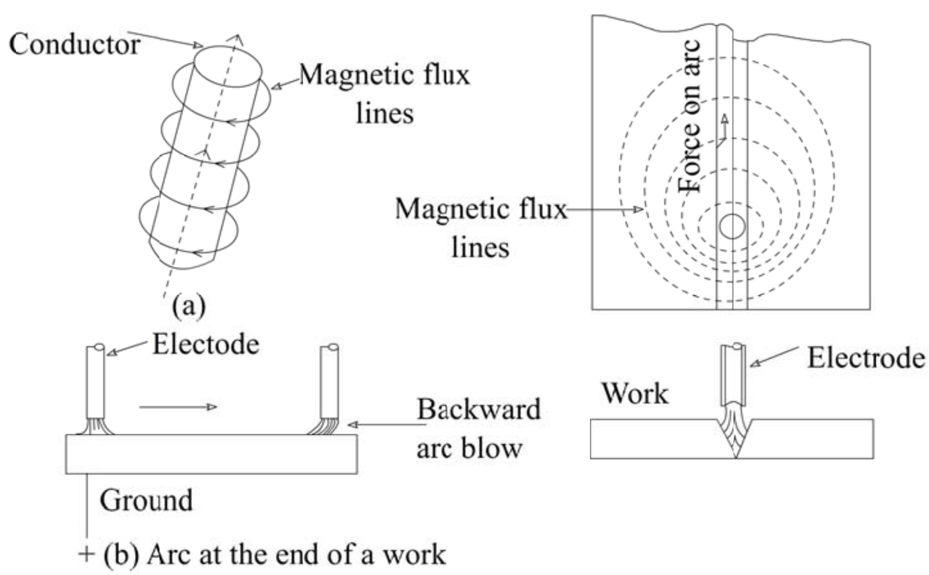

Fig. 7.3 Schematic diagrams showing generation of electromagnetic force around the welding arc & electrode causing arc blow

The welding arc tends to deflect away from area where electro-magnetic flux concentration exit. In practice, such kind of localization of electromagnetic fields and so deflection of arc depends on the position of ground connection as it affects the direction of current flow and related electro-magnetic field. Arc can blow towards or away from the earthing point depending upon the orientation of electromagnetic field around the welding arc. Effect of ground connection on arc blow is called ground effect. Ground effect may add or reduce the arc blow, depending upon the position of arc and ground connection. In general, ground effect causes the deflection of arc in the direction opposite to the ground connection.

Arc blow occurring due to interaction between electromagnetic field around the arc and that of localized electromagnetic field near the edge of the plates, always tends to deflect the arc away from the edge of the plate (Fig. 7.3 b-c). So the ground connection in opposite side of the edge experiencing deflection can help to reduce the arc blow.

Arc blow can be controlled by:

- Reduction of the arc length so as to reduce the extent of misplacement of molten metal
- Adjust the ground connection as per position of arc so as to use ground effect unfavorable manner from D.C. to
- Shifting to A. C. if possible so as to neutralize the arc blow occurring in each half
- Directing the tip of the electrode in direction opposite to the arc blow.

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- Richard Little, Welding and Welding Technology, McGraw Hill, 2001, 1st edition.
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Lecture 8

Physics of Welding Arc IV

This chapter describes fundamental approach of obtaining the arc efficiency of consumable and non-consumable arc welding process and factors affecting the same besides the modes of metal transfer and their effect on quantity of weld joint. Methods of obtaining the melting rate and factors limiting the melting rate for common welding processes have also been presented.

Keywords: Arc efficiency, heat distribution, metal transfer, globular and spray transfer, transition current, melting rate

8.1 Arc Efficiency

Arc welding basically involves melting of faying surfaces of base metal using heat generated by arc under a given set of welding conditions i.e. welding current and arc voltage. However, only a part of heat generated by the arc is used for melting purpose to produce weld joint and remaining is lost in various ways namely through conduction to base metal, by convention and radiation to surrounding (Fig. 8.1). Moreover, the heat generation on the work piece side depends on the polarity in case of DC welding while it is equally distributed in work piece and electrode side in case of AC welding. Further, it can be recalled that heat generated by arc is dictated by the power of the arc (VI) where V is arc voltage i.e. mainly sum voltage drop in cathode drop (V_C), plasma (V_p) and anode drop regions (V_p) apart from of work function related factor and I is welding current. Product of welding current (I) and voltage drop in particular region governs the heat generated in that zone e.g. near anode, cathode and in plasma region. In case of DCEN polarity, high heat generation at work piece facilitates melting of base metal to develop a weld joint of thick plates.

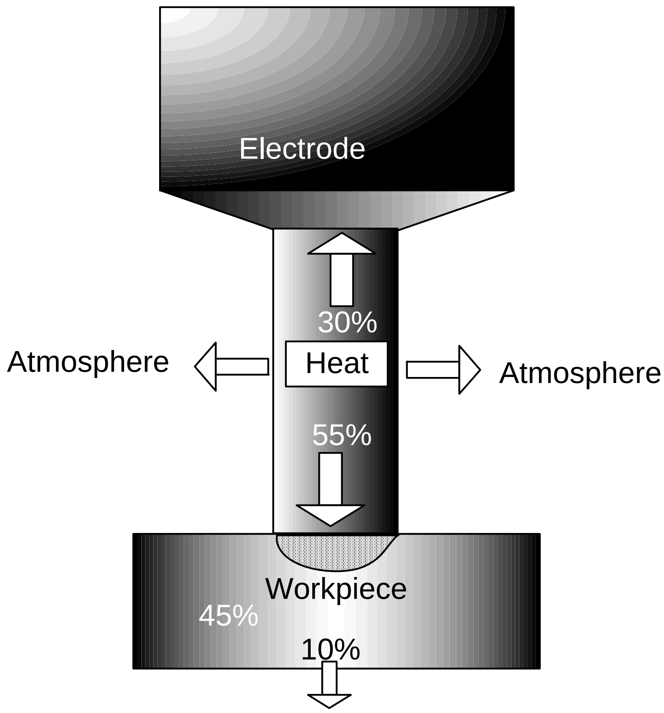

Fig. 8.1 Distribution of heat from the welding arc in DCEN polarity

8.1.1 Rationale behind variation in arc efficiency of different arc welding processes

Under simplified conditions (with DCEN polarity), ratio of the heat generated at anode and total heat generated in the arc is defined as arc efficiency. However, this ratio indicates the arc efficiency only in case of non-consumable arc welding processes such as GTAW, PAW, Laser and electron beam welding processes where filler metal is not commonly used. However, this definition doesn't reflect true arc efficiency for consumable arc welding processes as it is doesn't include use of heat generated in plasma region and cathode side for melting of electrode or filler metal and base metal (Fig. 8.2). Therefore, arc efficiency equation for consumable arc welding processes must include heat used for melting of both work piece and electrode.

Since consumable arc welding processes (SMAW, SAW, GMAW) use heat generated both at cathode and anode for melting of filler and base metal while in case of non-consumable arc welding processes (GTAW, PAW) heat generated at the anode only is used for melting of the base metal, therefore, in general, consumable arc welding processes offer higher arc efficiency than non-consumable arc welding processes. Additionally, in case of consumable arc welding processes

(SMAW, SAW) heat generated is more effectively used because of reduced heat losses to surrounding as weld pool is covered by molten flux and slag.

Welding processes in ascending order of arc efficiency are GTA, GMA, SMA, and SAW. GTAW offer's lower arc efficiency (21-48%) than SMAW/GMAW (66-85%) and SA welding (90-99%).

8.1.2 Determination of arc efficiency

Heat generated at the anode is found from sum of heat generated due to electron emission and that from anode drop zone.

q_a= [ϕ + V_a] I……………………………………………………………(equation 8.1)

whereq_a= is the heat at anode

$\phi$is work function of base metal at temperature T = [(ϕ_0 +1.5 kT) ………(equation 8.2)

ϕ_0 is work function of base metal at temperature OK

k is the Boltzmann constant

T temperature in Kelvin

V_a anode voltage drop

I welding current

Heat generated in plasma region q_p =V_p I……………………………(equation 8.3)

Say it's a fraction m % of the heat generated in plasma region goes to anode/work piece for melting = m (V_p I) ……………………………(equation 8.4)

So arc efficiency = total heat used / total heat generated in arc= [q_a + m (V_p I)]/VI……………………………(equation 8.5)

Where V is arc voltage = V_a + V_p + V_c

Another way is that [{total heat generated in arc- (heat with plasma region + heat of cathode drop zone)}/total heat generated in arc}]

So arc efficiency [{VI-[q_c + (1-m) (V_p I)}/VI}] or [{VI-[V_cI + (1-m) (V_p I)}/VI}]……………………………(equation 8.6)

Where q_c is the heat generated in cathode drop zone.

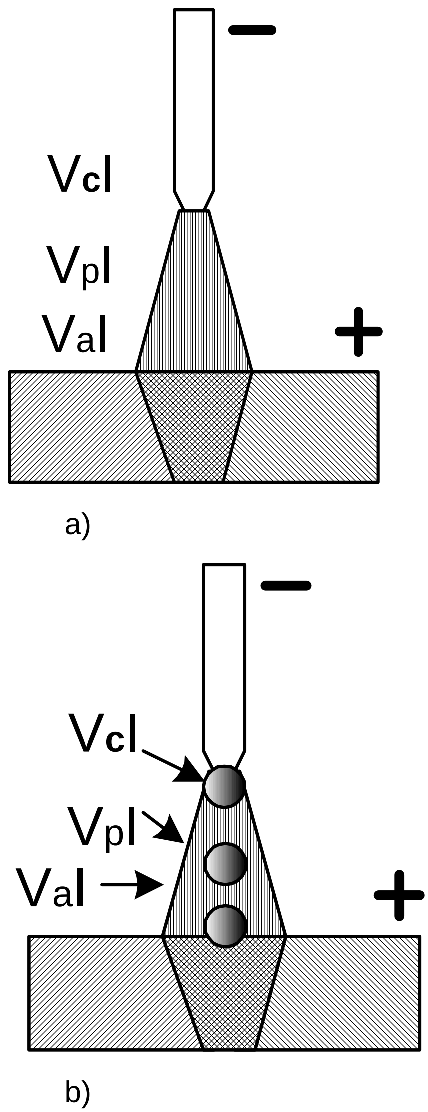

Fig. 8.2 Schematic of heat generation in different zones of the arc of a) non-consumable arc and b) consumable arc welding processes.

8.2 Metal Transfer

Metal transfer refers to the transfer of molten metal from the tip of a consumable electrode to the weld pool and is of great academic and practical importance for consumable electrode welding processes as it directly affects the control over the handling of molten metal, slag and spattering. However, metal transfer is considered to be more of academic importance for GMA and SA welding than practical need. Shielding gas, composition of the electrode, diameter and extension of the electrodes are some of the arc welding related parameters, which affect the mode of metal transfer for a given power setting namely welding current and voltage. Four common modes of metal transfer are generally observed in case of consumable arc welding processes. These have been described in the following sections.

8.2.1 **Short Circuit Transfer**

This kind of metal transfer takes place, when welding current is very low but high enough to have stable arc and arc gap is small. Under these welding conditions, molten metal droplet grows slowly at the tip of the electrode and then as soon as drop touches weld pool, short-circuiting takes place. Due to narrow arc gap, molten drop does not attain a size big enough to fall down on its own (by weight) under gravitational force. On occurrence of short circuit, welding current flowing through the droplet to the weld pool increases abruptly which in turn results in excessive heat generation that makes the molten metal of droplet thinner (low surface tension). Touching of the molten metal drop to weld pool leads to transfer of molten metal into weld pool by surface tension effect. Once molten metal is transferred to the weld pool, an arc gap is established which in turn increases arc voltage abruptly. This increase in arc voltage (due to setting up of the arc-gap) re-ignites arc and flow of current starts. This whole process is repeated at a rate varying from 20 to more than 200 times per second during the welding. Schematically variation in welding current and arc voltage for short circuit metal transfer is shown in Fig. 8.3 (a).

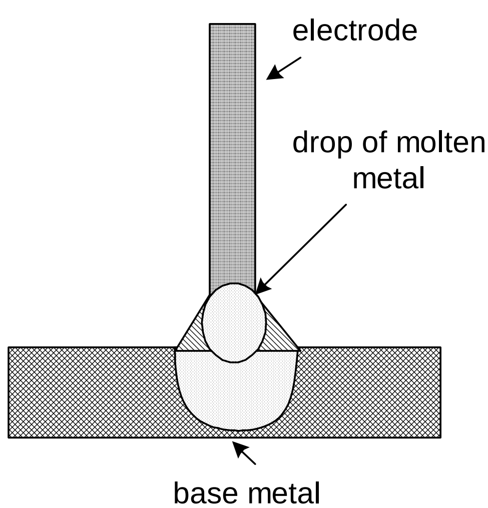

Fig. 8.3 (a) Schematic of short circuiting metal transfer

8.2.2 Globular Transfer

Globular metal transfer takes place when welding current is low (but higher than that for short circuit transfer) and arc gap is large enough so molten metal droplet can grow slowly (at the tip of the electrode) with melting of the electrode tip (Fig. 8.3 b).

Drop continues to grow until gravitational force on drop (due to its own weight) exceeds the surface tension force other forces if any trying to add the drop at the tip of electrode. As soon as drop attains large size enough and so gravitational force becomes more than other drop-holding-forces such as surface tension force, drop detaches from the electrode tip and is transferred to the weld pool. The transfer of molten metal drop normally occurs when it attains size larger than the electrode diameter. No short-circuit takes place in this mode of metal transfer.

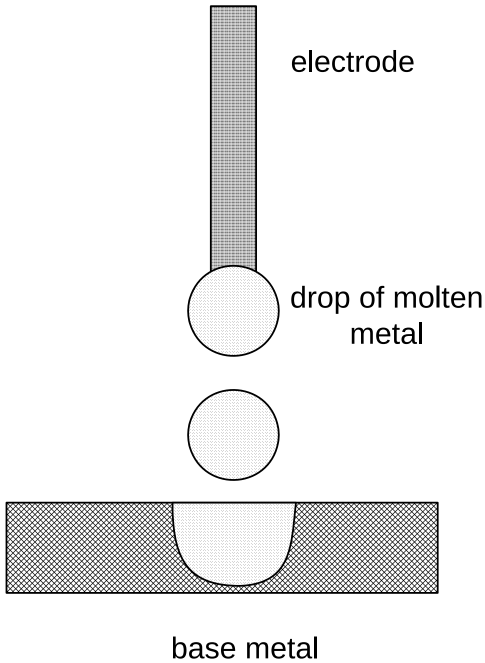

Fig. 8.3 (b) Schematic of globular metal transfer

8.2.3 Spray Transfer

This kind of metal transfer takes place when welding current density is higher than that is required for globular transfer. High welding current density results in high melting rate and greater pinch force as both melting rate and pinch force are directly related with welding current and are found proportional to square of welding current. Therefore, at high welding current density, droplets are formed rapidly and pinched off from the tip of electrode quickly by high pinch force even when they are of very small in size. Another reason for detachment of small droplets is that high welding current increases temperature of arc zone which in turn lowers the surface tension force. Reduction in surface tension force decreases the resistance to detachment of which in turn facilities detachment of drops even when they are of small size enough drop from the electrode tip. The transfer of molten metal from electrode tip appears similar to that of spray in line of axis of the electrode (Fig. 8.3 c). This feature helps to direct the molten metal in proper place where it is required especially in difficult to access areas.

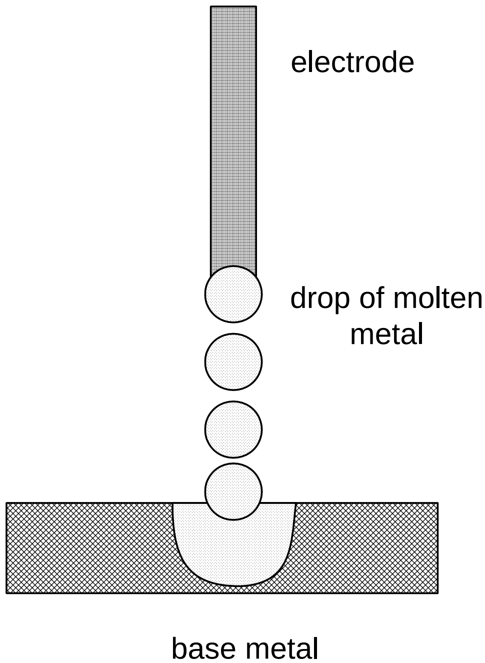

Fig. 8.3 (c) Schematic of spay metal transfer

8.2.4 Dip Transfer

Dip type of metal transfer is observed when welding current is very low and feed rate is high. Under these welding conditions, electrode is short-circuited with weld pool, which leads to the melting of electrode and transfer of molten drop (Fig. 8.3 d). Approach wise dip transfer is similar to that of short circuit metal transfer and many times two are used interchangeably. However, these two differ in respect of welding conditions especially arc gap that lead to these two types of metal transfers. Low welding current and narrow arc gap (at normal feed rate) results in short circuit mode of metal transfer while the dip transfer is primarily caused by abnormally high feed rate even when working with recommended range of welding current and arc gap.

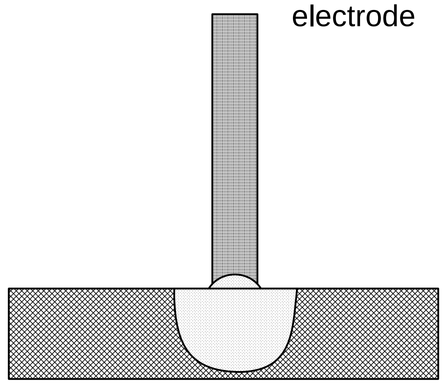

Fig. 8.3 (d) Schematic of dip transfer

8.3 Melting Rate

In consumable arc welding processes, weld metal deposition rate is governed by the rate at which electrode is melted during welding. Melting of the electrode needs the sensible and latent heat, which is supplied by arc through the electrical reactions i.e. heat generated at anode ($I.V_a$), cathode ($I.V_c$) and plasma zone ($I.V_p$). In case of DCEN polarity, heat generated in anode drop region and plasma region do not influence melting of electrode tip appreciably as electrode (cathode) in case of straight polarity (DCEN) gets very negligible heat from these two regions (anode and plasma). Hence, in case of straight polarity (DCEN), melting rate of electrode primarily depends on the heat generated by a) cathode reaction and b) electrical resistance heating. Accordingly, melting rate of electrode for consumable arc welding processes is given by following equation:

Melting Rate = a X I + b X L X I^2……………………………(equation 8.7)

Where a & b are constant {(independent of electrode extension (L) and welding current (I)}

Value of constant “a” depends on ionization potential of electrode material (ability to emit the charge carriers), polarity, composition of electrode and anode/cathode voltage drops while another constant “b” accounts for electrical resistance of electrode (which in turn depends on electrode diameters and resistivity of electrode metal).

Melting rate equation suggests that first factor (a X I) accounts for electrode melting due to heat generated by anode/cathode reaction and second factor (b X L X I^2)

considers the melting rate owing to heat generated by electrical resistance heating. Melting rate is mainly governed by the first factor when welding current is low, electrode diameter is large and extension is small, whereas second factor significantly determines the melting rate of electrode when welding current in high, electrode diameter is small, extension is large and electrical resistivity of electrode metal is high.

8.3.1 Factors Limiting the Melting Rate

Difference in values of constant a and b and welding parameters lead to the variation in melting rate of the electrode in case of different welding processes. To increase the melting rate, welding current for a specific welding process can be increased up to a limit. The upper limit of welding current is influenced by two factors a) extent overheating of electrode caused by electrical resistance heating and so related thermal degradation of the electrode and b) required mode of metal transfer for smooth deposition of weld metal with minimum spatter. For example, in semiautomatic welding process such MIG/SAW, minimum welding current is determined by the current level at which short circuit metal transfer starts and upper level of current is limited by appearance of rotational spray transfer. For a given electrode material and diameter, upper limit of current in case of SMAW is dictated by thermal composition of the electrode coating and that in case of GTAW is determined by thermal damage to tungsten electrode. Lower level of current in general determined is by arc stability (the current at which stable arc is developed) besides other minimum requirement of weld such as penetration, proper placement of the weld metal and control over the weld pool especially in vertical and overhead welding positions and those related with poor accessibility. Depending upon these factors higher and lower limits of welding current melting rate are decided.

Example

A TIG welding process uses DCEN polarity, arc voltage of 30 V and welding current of 120 A for welding of 2 mm thin plate. Assuming a) the voltage drop in anode, cathode and plasma regions is 16 V, 10 V, 4 V respectively and b) 20 % of heat generated in plasma zone is used for melting of base metal and c) all heat generated in anode drop zone is used for welding. Neglecting the voltage drop on account of work function of metal during welding, calculate the arc efficiency.

Solution

Arc efficiency: (Heat generated in anode drop zone + heat generated in plasma used welding) / all heat produced by welding arc

: Va X I + m(Vp XI)/VI ~ (Va + mVp)/V

(16 0.2 X 4)/30~ 16.8/30

Arc efficiency: 0.56~56%

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- Richard Little, Welding and Welding Technology, McGraw Hill, 2001, 1st edition.
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Lecture 9

Arc Welding Power Source I

This chapter presents the need of welding power source and their classification besides the basic characteristics of welding power sources. Selection of suitable type of power source for different welding processes has also been described. Further, the concept of self regulating arc has been elaborated.

Keywords: Welding power source, classification, basic characteristics of power source, OCV, power factor, constant current and constant voltage power source, self regulating arc, operating point

9.1 Introduction

One of the main requirements of a welding power source is to deliver controllable current at a voltage desired according to the demands of the welding process. Each welding process has distinct features from other processes in the form of process controls required. Therefore, arc welding power sources play very important role in successful welding. The conventional welding power sources are:

Power Source	Supply
(i) Welding Transformer	AC
(ii) Welding Rectifier	DC
(iii) Welding Generators	AC/DC
(IV) Inverter type welding power source	DC

Welding transformers, rectifiers and DC generators are used in shops while engine coupled DC and AC generators are used at site where domestic line supply is not available. Rectifiers and transformers are usually preferred because of lower noise, higher efficiency and lower maintenance as compared to generators. The inverter type welding power source first transforms the AC into DC. The DC power is then fed into a step-down transformer to produce the desired welding voltage/current. The pulse of high voltage and high frequency DC is fed to the main step-down transformer and there it is transformed into low voltage and high frequency DC suitable for welding. Finally, low voltage and high frequency DC is passed through filters and for rectification. The switching on and off is performed by solid state switches at frequencies above 10,000. The high switching frequency reduces the volume of the step down transformer. The inverter type of power source provides better features for power control and overload protection. These systems are found more efficient and better in respect of control of welding parameters than other welding system. The invertors with microcontrollers allow changes in electrical characteristics of the welding power by software in real time. This can be done even on a cycle by cycle basis so as to provide features such as pulsing the welding current, variable ratios and current densities, stepped variable frequencies.

Selection of a power source mainly depends on the welding process and welding consumables to be used for arc welding. The open circuit voltage normally ranges between 70-90 V in case of welding transformers while that in case of rectifiers varies from 20-60 V. Moreover, welding arc voltage becomes lower than open circuit voltage of the power source. Welding power sources can be classified based on different parameters related with them as under:

- Type of current: A.C., D.C. or both.
- Cooling medium: Air, water, oil cooled.
- Cooling system: Forced or natural cooling
- Static characteristics: Constant current, constant voltage, rising characteristics.

9.2 Characteristics of power source

Each welding power source has set of characteristics indicating the capability and quality of the power source. These characteristics help in selection of suitable welding power source for a given welding condition. Basic characteristics of a welding power source are given below:

- Open circuit voltage (OCV)
- Power factor (pf)

- Static characteristics
- Dynamic characteristics
- Current rating and duty cycle
- Class of Insulation

9.2.1 Open circuit voltage (OCV)

OCV shows the potential difference between the two terminals of the power source when there is no load. Setting up of correct open circuit voltage is important for stability of welding arc especially when AC is used. The selection of an optimum value of OCV (50-100V) depends on the type of base metal, composition of electrode coating, type of welding current and polarity, type of welding process etc. Base metal of low ionization potential (indicating ease of emitting free of electrons) needs lower OCV than that of high ionization potential metal. Presence of low ionization potential elements such as K, Na and Ca in electrode coating/flux in optimum amount reduces OCV setting required for welding. AC welding needs higher OCV compared with DC owing to problem of arc stability as in case of AC welding current continuously changes its direction and magnitude while in case DC it remains constant. In the same line, GTAW needs lower OCV than GMAW and other welding processes like SMAW and SAW because GTAW uses tungsten electrode which has good free electron emitting capability by thermal and field emission mechanism. Abundance of free electron in GTAW under welding conditions lowers the OCV needed for having stable welding arc.

Too high OCV may cause electric shock. OCV is generally found to be different from arc voltage. Arc voltage is potential difference between the electrode tip and work piece surface when there is flow of current. Any fluctuation in arc length affects the resistance to flow of current through plasma and hence arc voltage is also affected. Increase in arc length or electrode extension increases the arc voltage. Further, electrical Electrical resistance heating of electrode increases with electrode extension for given welding parameters.

9.2.2 Power factor (pf)

Power factor of a power source is defined as a ratio of actual power (KW) used to produce the rated load (which is registered on the power meter) and apparent power drawn from the supply line (KVA) during welding. It is always desired to have high power factor (pf). Low power factor indicates unnecessary wastage of power and less efficient utilization of power for welding. Welding transformers usually offer higher power factor than other power sources. However, sometimes low power factor is intentionally used with welding transformers to increase the stability of AC welding arc. The basic principle of using low power factor for better arc stability has been explained in section 6.2.2. Application of a welding power source with high power factor offers many advantages such as:

- Reduction of the reactive power in a system, which in turn reduces the power consumption and so drop in cost of power
- More economic operations at an electrical installation (higher effective power for the same apparent power)
- Improved voltage quality and fewer voltage drops
- Use of low cable cross-section
- Smaller transmission losses

9.2.3 Static Characteristic of power source

Static characteristic of a welding source exhibits the trend of variation in voltage with current when power source is connected to pure resistive load. This variation may be of three types, namely constant current (CC), constant voltage (CV), rising voltage (RV).

Constant current power source

The volt ampere output curves for constant current power source are called ‘drooper’ because of substantial downward or negative slope of the curves. With a change in arc voltage, the variation in welding current is small and, therefore, with a consumable electrode welding process, electrode melting rate remains fairly constant even with a minor change in arc length (Fig. 9.1). These power sources are required for processes that use relatively thicker consumable electrodes which may sometimes get stuck to workpiece or with non-consumable tungsten electrode where touching of electrode with base metal for starting of arc may lead to damage of electrode if current is unlimited. Under these conditions, the short circuiting current shall be limited which would provide safety to power source and the electrode.

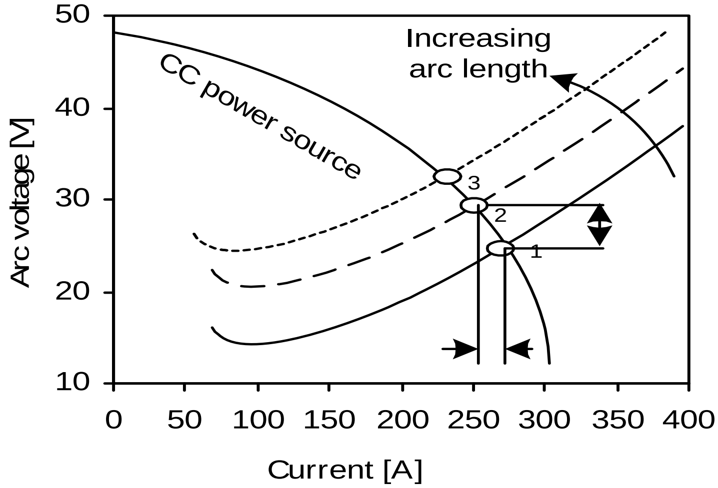

Fig. 9.1 Static characteristics of constant current welding power source

In constant current power source, variation in welding current with arc voltage (due to fluctuations in arc length) is very small therefore welding current remains more or less constant despite of fluctuations in arc voltage / length. Hence, this type of power source is also found suitable for all those welding processes where large fluctuation in arc length is likely to take place e.g., MMA and TIG welding.

Constant voltage power source

In CV power sources, a small variation in arc voltage (due to fluctuations in arc length) causes significant change in welding current. Since arc voltage remains almost constant during welding despite of fluctuations in arc length therefore this type of power source is called constant voltage type. Moreover, the constant voltage power sources do not offer true constant voltage output as current-voltage relationship curve shows slightly downward or negative slope. This negative slope is attributed to internal electrical resistance and inductance in the welding circuit that causes a minor droop in the output volt-ampere characteristics of the power source (Fig. 9.2). This type of power sources is found more suitable for all those welding processes where fluctuations in arc length during welding is limited like in semiautomatic welding process MIG, SAW and PAW. The power source shall supply necessary current to melt the electrode at the rate required to maintain the preset voltage or arc length. The speed of electrode drive is used to control feed rate of the electrode which in turns affects the arc gap/voltage. The variation arc voltage changes the average welding current. The use of such power source in conjunction with a constant speed electrode wire feed drive results in a self regulating or self adjusting arc system. Due to some internal or external fluctuation if the change in arc length occurs, then it regulates the electrode melting rate MR (by regulating current) to regain the desired arc length.

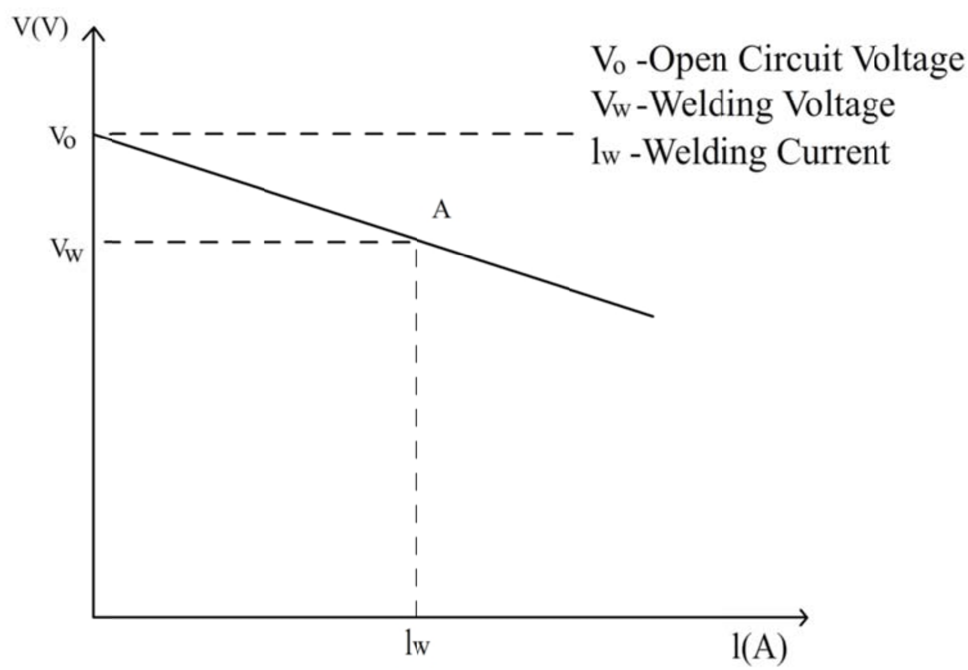

Fig. 9.2 Static characteristics of constant voltage welding power source

Self regulating arc

In semiautomatic welding processes where constant voltage power source is used in association with automatically fed (constant speed) small diameter consumable electrode, arc length is maintained by self-regulating arc. Self-regulating arc is one, which governs the melting/burn off rate of the electrode (by changing the current) so that feed rate becomes equal to melting rate for maintaining the arc length. For example, increase in arc length due to any reason shifts the operating point from 2 to 3 thus increases the arc voltage (Fig. 9.3). Operating point is the point of intersection of power source characteristics with arc characteristics. Rise in arc voltage decreases the welding current significantly. Decrease in welding current lowers the melting rate (see melting rate equation) of the electrode thus decreases the arc gap if electrode is fed at constant speed. Reverse phenomenon happens if arc length decreases (shifting the operating point from 2 to 1).

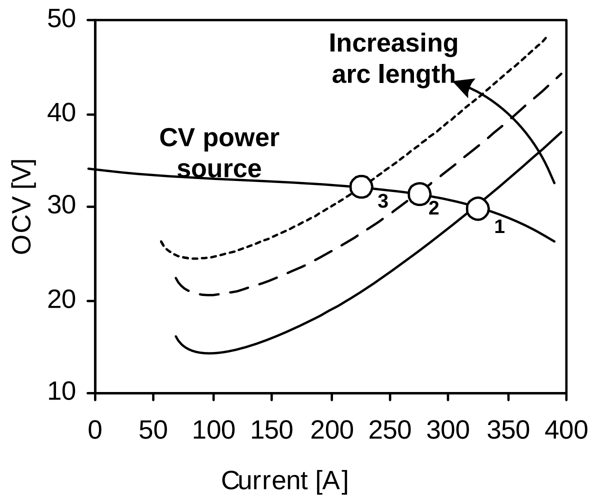

Fig. 9.3 Static characteristics of constant voltage welding power showing operating points with increasing arc length

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Lecture 10

Arc Welding Power Source II

This chapter presents the dynamic characteristics of welding power sources and classes of insulation used in windings and cables of power sources. The concept of duty cycle and its relationship with welding current has been elaborated. Further, need of high frequency unit in welding and different types of electrode wire feed drives have also been discussed.

Keywords: Dynamic characteristics, Duty cycle, class of insulation, HF unit, arc length, feed drives

10.1 Rising Characteristics

Power sources with rising characteristics show increase in arc voltage with increase of welding current (Fig.10.1). In automatic welding processes where strictly constant voltage is required, power sources with rising characteristics are used.

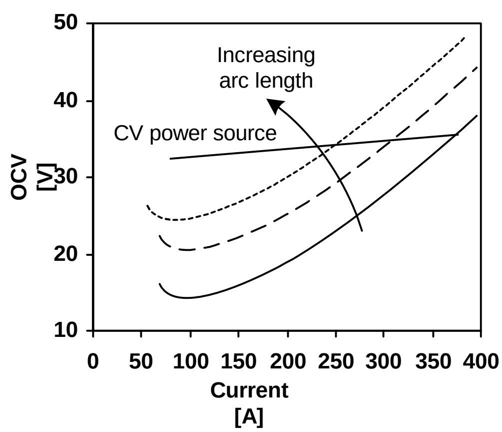
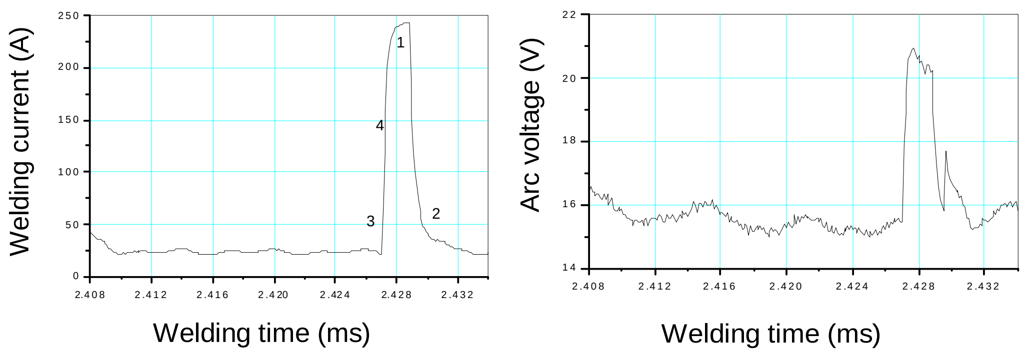


Fig. 10.1 Static characteristics of rising voltage welding power showing operating points with different arc length

10.2 Dynamic characteristic

Welding arc is subjected to severe and rapid fluctuations in arc voltage (due to continuous minor changes in arc length) and welding current (Fig. 10.2). Number from 1 to 4 in figure 5 indicates different stages of welding arc during welding, suggesting that welding arc is never in a steady state. It causes transients in starting, extinction and re-ignition after each half cycle in A.C. welding. To cope up with these conditions power source should have good dynamic characteristics to obtain stable and smooth arc. Dynamic characteristic of the power source describes the instantaneous variation in arc voltage with change in welding current over an extremely short period of welding. A power source with good dynamic characteristic results in an immediate change in arc voltage and welding current corresponding to the changing welding conditions so as to give smooth and stable arc.



a) b)

Fig. **10.3** Dynamic characteristics of a power source showing a) current vs time and b) voltage vs time relationship.

10.3 Duty Cycle

Duty cycle is defined as ratio of arcing time to the weld cycle time multiplied by 100. Welding cycle time is either 5 minutes as per European standards or 10 minutes as per American standard and accordingly power sources are designed. If arcing time is continuous for 5 minutes then as per European standard it is considered as 100% duty cycle and that will be 50% duty cycle as per American standard. At 100% duty cycle, minimum current is drawn from the welding power source. Welding power source operating at low duty cycle allows high welding current for welding purpose safely. The welding current which can be drawn at a duty cycle can be evaluated from the following equation;

$D_R \times I_R^2 = I^2_{100} \times D_{100}$……………………………………………..(equation 10.1)

Where I - Current at 100% duty cycle

D_{100} - 100% duty cycle

I_R - Current at required duty cycle

D_R - Required duty cycle

Example

Current rating for a welding power source is 400 A at 60% duty cycle. Determine the welding current for automatic continuous welding i.e. 100% duty cycle.

Solution:

Rated current: 400 A

Rated duty cycle: 60%

Desired duty cycle: 100%

Desired current ?

Desired duty cycle= $\frac{(\text{rated current})^2 \times \text{rated duty cycle}}{(\text{desired current})^2}$

$$100 = \frac{(400)^2 \times 60}{(\text{desired current})^2}$$

Answer: Desired current: 310A

10.3.1 Importance of duty cycle

During the welding, heavy current is drawn from the power source. Flow of heavy current through the transformer coil and connecting cables causes electrical heating. Continuous heating during welding for long time may damage coils and cables. Therefore, welding operation should be stopped for some time depending upon the level of welding current being drawn from the power source. The total weld cycle is taken as sum of actual welding time and rest time. Duty cycle refers to the percentage of welding time of total welding cycle i.e. welding time divided by welding time plus and rest time. Total welding cycle of 5 minutes is normally taken in India as in European standard. For example, welding for 3 minutes and followed by rest of 2 minutes in total welding cycle of 5 minutes corresponds to 60% duty cycle.Duty cycle and associated welding current are important as it ensures that power source is safe and its windings are not damaged due to increase in temperature due to electrical resistance heating beyond specified limit. Moreover, the maximum current which can be drawn from a power source at given a duty cycle depends upon size of winding wire, type of insulation and cooling system of the power source. In general, large diameter cable wire, high temperature resistant insulation and force cooling system allow high welding current drawn from the welding source at a given duty cycle.

10.4 Class of Insulation

The duty cycle of a power source for a given current setting is primarily governed by the maximum allowable temperature of various components (primary and secondary coils, cables, connectors etc.), which in turn depends on the quality and type of insulation and materials of coils used for manufacturing of power source. The insulation is classified as A, E, B, F& G in increase order of their maximum allowable temperature 60, 75, 80, 100 &125 ^{0}C respectively.

10.5 High Frequency Unit

Some power sources need high frequency unit to start the arc like in TIG and plasma arc welding. High frequency unit is introduced in the welding circuit. Filters are used between the control circuit and HF unit to avoid damage of control circuit. High frequency unit is a device which supplies pulses of high voltage (of the order of few kV) and low current at high frequency (of few kHz). The high voltage pulse supplied by HF unit ionizes the gaseous medium between electrode and workpiece/nozzle to produce starting pilot arc which ultimately leads to the ignitions of the main arc. Although high voltage can be fatal for operator but at high frequencies current passes through the skin and does not enter the body. This is called skin effect i.e. current passes through the skin without any damage to the operator.

10.6 Feed drives for constant arc length

Two types of feed systems are generally used for maintaining the arc length a) constant speed feed drive and b) variable speed feed drive. In constant speed feed drives, feed rollers rotating at fixed speed are used for pushing/pulling wire to feed into the weld so as to maintain the arc length during welding (Fig. 10.4 a). This type drive is normally used with constant voltage power sources in conjunction with small diameter electrodes where self regulating arc helps to attain the constancy in arc length. In case of variable speed feed drives, feed rollers used for feeding electrode wire (in consumable arc welding processes like SAW and GMAW) are rotated at varying speed as per need to maintain the arc length during welding. Fluctuation in arc length due to any reason is compensated by increasing or decreasing the electrode feed rate. The electrode feed rate is controlled by regulating the speed of feed rollers powered by electric motor (Fig. 10.4 b). Input power to the variable speed motor is regulated with help of sensor which takes inputs from fluctuations in the arc gap. For example, an increase in arc gap sensed by sensor increases the input power to the variable speed motor to increase the feed rate of electrode so as to maintain arc gap.

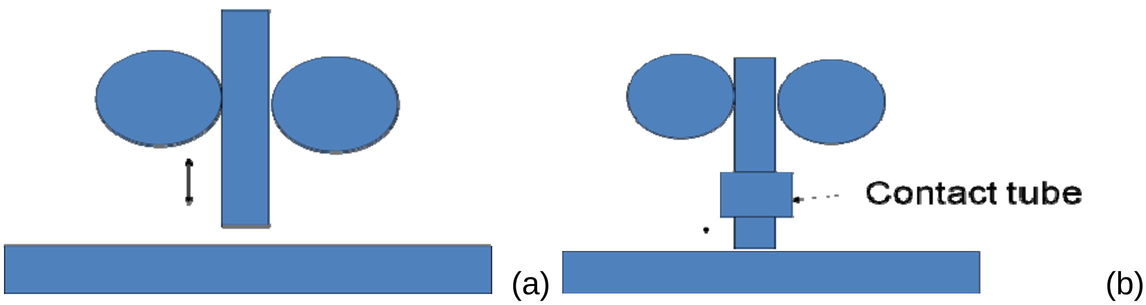


Fig. **10.4** Schematics diagrams show electrode feed drives for controlling arc length a) variable speed feed drive and b) constant speed feed drive

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Lecture 11

Arc welding processes (SMAW)

This chapter presents the basic principle of arc welding processes with focus on shielded metal arc welding. Further, the influence of welding parameters on performance of weld joint and the role of coating on electrode have been described.

Keywords: Arc welding, shielded metal arc welding, shielding in SMAW, electrode coating, welding current, electrode size

11.1 Arc Welding Process

All arc welding processes apply heat generated by an electric arc for melting the faying surfaces of the base metal to develop a weld joint (Fig. 11.1). Common arc welding processes are manual metal or shielded metal arc welding (MMA or SMA), metal inert gas arc (MIG), tungsten inert gas (TIG), submerged arc (SA), plasma arc (PA), carbon arc (CA) selding etc.

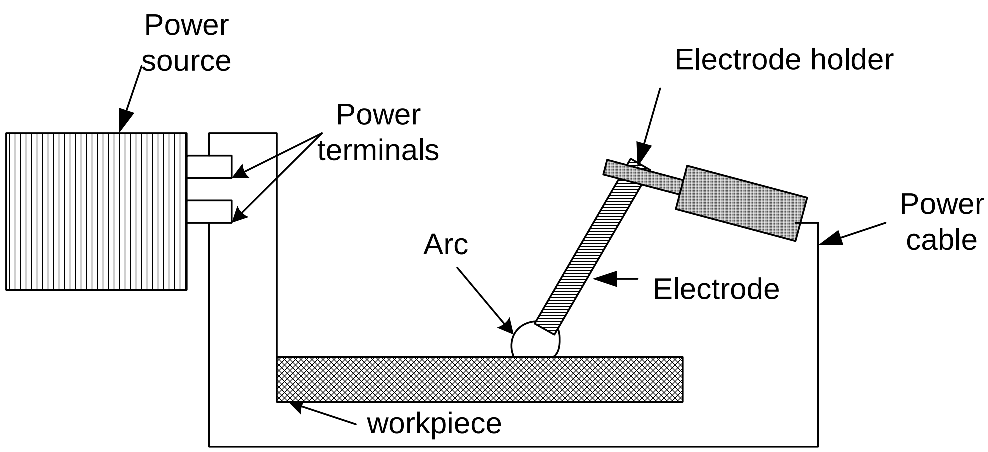

Fig. 11.1 Schematic diagram showing various elements of SMA welding system

11.2 Shielded Metal Arc Welding (SMAW)

In this process, the heat is generated by an electric arc between base metal and a consumable electrode. In this process electrode movement is manually controlled hence it is termed as manual metal arc welding. This process is extensively used for depositing weld metal because it is easy to deposit the molten weld metal at right place where it is required and it doesn’t need separate shielding. This process is commonly used for welding of the metals, which are comparatively less sensitive to the atmospheric gases.

This process can use both AC and DC. The constant current DC power source is invariably used with all types of electrode (basic, rutile and cellulosic) irrespective of base metal (ferrous and non-ferrous). However, AC can be unsuitable for certain types of electrodes and base materials. Therefore, AC should be used in light of manufacturer's recommendations for the electrode application. In case of DC welding, heat liberated at anode is generally greater than the arc column and cathode side. The amount of heat generated at the anode and cathode may differ appreciably depending upon the flux composition of coating, base metal, polarity and the nature of arc plasma. In case of DC welding, polarity determines the distribution of the heat generated at the cathode and anode and accordingly the melting rate of electrode and penetration into the base metal are affected.

Heat generated by a welding arc (J) = Arc voltage (V) X Arc current (A) X Welding time (s)--(equation 11.1)

If arc is moving at speed S (mm/min) then net heat input is calculated as:

H_{net}= VI (60)/(S X 1000) kJ/mm...................................(equation 11.2)

11.3 Shielding in SMA welding

To avoid contamination of the molten weld metal from atmospheric gases present in and around the welding arc, protective environment must be provided. In different arc welding processes, this protection is provided using different approaches (Table 1). In case of shielded metal arc welding, the protection to the weld pool is provided by covering of a) slag formed over the surface of weld pool/metal and b) inactive gases generated through thermal decomposition of flux/coating materials on the electrode (Fig. 11.2). However, relative effect of above two on the protection of the weld metal depends on type of flux coating. Few fluxes (like cellulosic coating) provide large amount of inactive gases for shielding of weld while other fluxes form slag in ample amount to cover the weld pool. Shielding of the weld pool by inactive gases in SMAW is not found very effective due to two reasons a) gases generated by thermal decomposition of coating materials don't necessarily form proper cover around the arc and welding pool and b) continuous movement of arc and varying arc gap during welding further decreases the effectiveness of shielding gas. Therefore, SMAW weld joints are often contaminated and are not very clean for their possible application to develop critical joints. Hence, it is not usually recommended for developing weld joints of reactive metals like Al, Mg, Ti, Cr and stainless steel. These reactive metal systems are therefore commonly welded using welding processes like GTAW, GMAW etc. that provide more effective shielding to the weld pool from atmospheric contamination.

11.4 Coating on electrode

The welding electrodes used in shielded metal arc welding process are called by different names like stick electrode, covered electrode and coated electrode. Coating or cover on the electrode core wire is provided with various hydrocarbons, compound and elements to perform specific roles. Coating on the core wire is made of hydrocarbons, low ionization potential element, binders etc. Na and K silicates are invariably used as binders in all kinds of electrode coatings. Coating on the electrode for SMAW is provided to perform some of the following objectives:

- To increase the arc stability with the help of low ionization potential elements like Na, K
- To provide protective shielding gas environment to the arc zone and weld pool with the help of inactive gases (like carbon dioxide) generated by thermal decomposition of constituents present in coatings such as hydrocarbon, cellulose, charcoal, cotton, starch, wood flour
- To remove impurities from the weld pool by forming slag as constituents present in coatings such as titania, fluorspar, china-clay react with impurities and oxides in present weld pool (slag being lighter than weld metal floats over the surface of weld pool which is removed after solidification of weld)
- Controlled alloying of the weld metal (to achieve specific properties) can be done by incorporating required alloying elements in electrode coatings and during welding these elements get transferred from coating to the weld pool. However, element transfer efficiency from coating to weld pool is influenced by the welding parameter and process itself especially in respect of shielding of molten weld pool.
- To deoxidize weld metal and clean the weld metal: Elements oxidized in the weld pool may act as inclusions and deteriorate the performance of the weld joint. Therefore, metal oxides and other impurities present in weld metal are removed by de-oxidation and slag formation. For this purpose, deoxidizers like Ferro-Mn, silicates of Mg and Al are frequently incorporated in the coating material.
- To increase viscosity of the molten metal and slag so as to reduce tendency of falling down of molten weld metal in horizontal, overhead and vertical welding. This is done by adding constituents like TiO_2 and CaF_2 in the coating material. These constituents increase the viscosity of the slag.

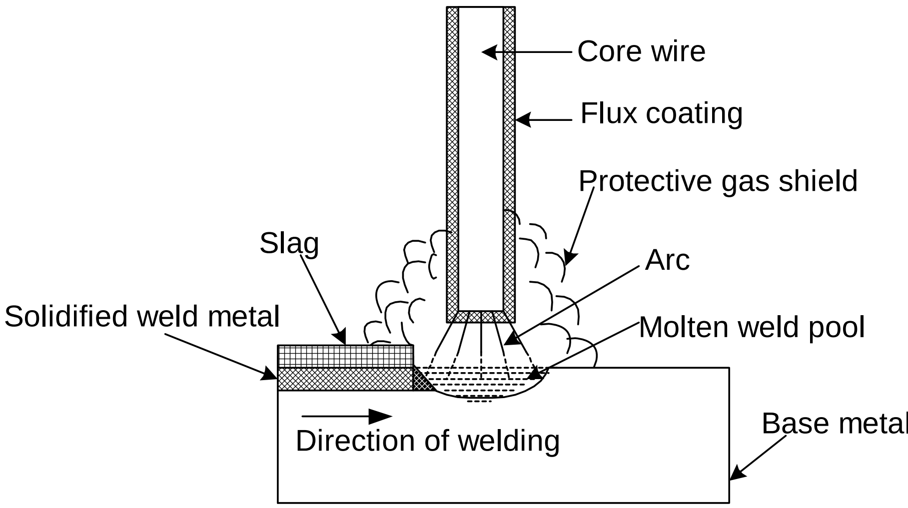

Fig. 11.2 Schematic diagram showing constituents of SMAW

Role of common constituents added in flux of SMAW electrode is given below. [Technical document, MMAW, Aachen, ISF, Germany, (2005)]

Constituent in flux	Role on welding arc features
Quartz (SiO_2)	Increases current-carrying capacity
Rutile (TiO_2)	Increases slag viscosity,good re-striking
Magnetite (Fe_3O_4)	Refines transfer of droplets through the arc
Calcareous spar ($CaCO_3$)	Reduces arc voltage, produces inactive shielding gas, slag formation
Fluorspar (CaF_2)	Increases slag viscosity of basic electrodes,decreases ionization
Calcareous- fluorspar (K_2O Al_2O_3 $6SiO_2$)	Improves arc stability by easy ionization
Ferro-manganese andferro-silicon	Acts as deoxidant
Cellulose	Produces inactive shielding gas
Potassium Sodium Silicate (K_2SiO_3 / Na_2SiO_3)	Acts as a bonding agent

11.5 Common types of SMAW electrodes

The steel electrode of a given composition is made available with different types of flux coating in order to make them suitable for different arc characteristics, welding position, welding speed, deposition rate, weld metal recovery, weld metal properties and variety of quality requirements. The selection of correct type of electrode coating results in weld metal with desired quality characteristics at low cost. In general, welding electrode is selected in such a way that characteristics of weld metal are similar to or better than the base material while keeping in mind the welding position and weld joints design as they significantly affect the properties of the weld.

11.5.1 Rutile electrode

These electrodes predominantly contain rutile (TiO_2) besides other constituents and are known to offer almost 100% weld metal recovery, easy arc striking and re-striking. These are found suitable for a) fillet welds, b) welding of sheet metal, c) good gap bridging capability, d) free from spatter losses and e) all position welding. These are recommended for welding low strength steel (<440 MPa). For welding of high strength steel (>440 MPa) generally weld metal should have low hydrogen level and therefore weld joints is developed using basic, rutile, basic-rutile and Zircon-based electrode.

11.5.2 Cellulosic electrodes

These electrodes are composed of large amount of hydrocarbon compounds and calcium carbonates besides other constituents and are found suitable for a) all welding positions especially for vertical and overhead welding position and b) realizing high mechanical properties in a weld metal of radiographic quality. These are preferred for vertical downward welding. However, these produce high hydrogen content in weld metal besides deep penetration.

11.5.3 Acidic electrode

Acidic electrodes offer a) easier arc striking than basic electrodes but poorer arc striking than rutile electrodes, b) moderate welding speed, c) smooth weld bead d) good slag detachability. However, acidic electrode has been replaced by rutile electrode and basic electrode for flat and positional welding respectively. The ductility and toughness weld metal developed by acidic electrode are better than those developed from rutile electrodes however yield and ultimate tensile strength are found inferior. This type of electrode results in minimal penetration which is good for very thin sheet but these are sensitive to moisture pick up.

11.5.4 Basic electrode

These electrodes have basic (alkali) coatings containing calcium carbonate / calcium fluoride.The basic electrodes are preferred over other electrode for developing weld joints of high strength steel (480-550 MPa) with weld metal having a) low hydrogen, b) good low temperature toughness, c) resistance to hot and cold cracking. However, these electrodes suffer from comparatively poor slag detachability. The welding speed and deposition rate offered by the basic electrodes especially in vertical welding position is much higher than the rutile and acidic electrode. Basic electrodes can sustain higher welding current even in vertical welding position.

11.5.5 Basic-rutile electrode

This type of electrode combines positives of both basic as well as rutile electrodes and therefore recommended for horizontal–vertical fillet welds of high strength steels.

11.6 Welding parameters for SMAW

SMA welding normally uses constant current type of power source with welding current 50-600A and voltage 20-80V at 60% duty cycle. Welding transformer (AC welding) and generator or rectifiers (DC welding) are commonly used as welding power sources. In case of AC welding, open circuit voltage (OCV) is usually kept 10-20% higher than that for DC welding to overcome the arc un-stability related problems due to fact that in case AC both current magnitude and direction changes in every half cycle while those remain constant in DC. OCV setting is primarily determined by factors like type of welding current and electrode composition which significantly affect the arc stability. Presence of low ionization potential elements (Ca, K) in coating and reduce the OCV required for stable arc.

Importance of welding current

Selection of welding current required for developing a sound weld joints is primarily determined by the thickness of base metal to be welded. In general, increase in thickness of plate to be welded increases the requirement of heat input to ensure proper melting, penetration and deposition rate. This increased requirement of heat input is fulfilled using higher welding current. Thus, need of high welding current dictates use of large diameter electrode. SMAW electrode are commercially available in different sizes and generally found in a range from 1-12.5 mm in steps like 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8 and 10 mm.

Upper and lower limits of welding current for SMAW are determined by possibility of thermal decomposition of electrode coating material and arc stability respectively. Welding current (A) is generally selected in range of 40-60 times of electrode diameter (mm). Too high current creates problem of damage to the electrode coating material due to thermal decomposition caused by electrical resistance heating of the core wire besides turbulence in the arc. Turbulence in the arc zone can lead to spatter and entrainment atmospheric gases. On other hand low current setting makes the arc unstable, poor penetration and low fluidity of molten weld metal. All these tend to develop discontinuities in weld joints.

In shielded metal arc welding process, lower limit of current is decided on the basis of requirement for stable arc, smooth metal transfer and penetration whereas higher limit of current is decided on the basis of extent of overheating of core wire that an electrode coating can bear without any thermal damage. High current coupled with long electrode extension causes overheating of core wire of electrode due to electrical resistive heating. Excessive heating may cause the combustion/decomposition of flux much earlier than when it is required to provide inactive shielding gases for protecting the weld pool and arc. Therefore, large diameter electrodes are selected for welding of thick sections as they can work with high welding current. Large diameter electrodes allow high current setting without any adverse effect on electrode coating materials because increased cross sectional area of electrode reduces resistance to the flow of current and so the electrical resistance heating of the core wired is reduced.

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Lecture 12

Shielded Metal Arc welding II

This chapter describes the factors to be considered for selection of suitable type of welding current and polarity. Further, the coating factor and its influences of quality of weld metal have also been elaborated. Mode of metal transfer in shielded metal arc welding and factor affecting the same have been presented.

Keywords: Selection of welding current, polarity, coating factor, weld bead, metal transfer in SMAW

12.1 Selection of type of welding current

It is important to consider various aspects while selecting suitable type of welding current for developing weld joints in a given situation. Some of the points need careful considerations for selection of welding current are given below.

1. Thickness of plate/sheet to be welded: DC for thin sheet to exploit better control over heat
2. Length of cable required: AC for situations where long cables are required during welding as they cause less voltage drop i.e. loading on power source
3. Ease of arc initiation and maintenance needed even with low current: DC preferred over AC
4. Arc blow: AC helps to overcome the arc blow as it is primarily observed with DC only.
5. Odd position welding: DC is preferred over AC for odd position welding (vertical and overhead) due to better control over heat input.
6. Polarity selection for controlling the melting rate, penetration and welding deposition rate: DC preferred over AC
7. AC gives the penetration and electrode melting rate somewhat in between that is offered by DCEN&DCEP.

DC offers the advantage of polarity selection (DCEN&DCEP) which helps in controlling the melting rate, penetration and required welding deposition rate (Fig. 12.1). DCEN results in more heat at work piece producing high welding speed but with shallow penetration. DCEN polarity is generally used for welding of all types of steel. DCEP is commonly used for welding of non-ferrous metal besides other metal systems. AC gives the penetration and electrode melting rate somewhat in between of that is offered by DCEN&DCEP.

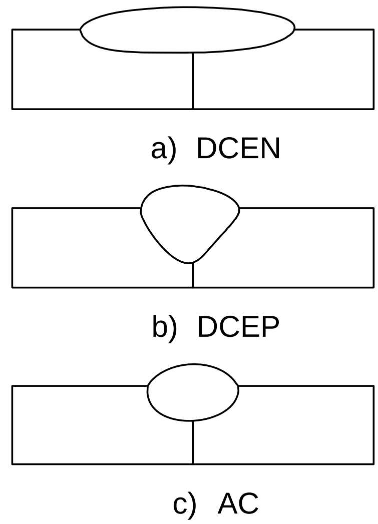


Fig. 12.1 Schematic diagram showing effect of welding current and polarity

12.1 Electrode size and coating factor

Diameter of the core wire of an electrode refers to electrode diameter (d). Diameter of electrode with coating (D) with respect to that of core wire (d) is used to characterize the coating thickness (Fig. 12.2). The ratio of electrode diameter with coating and core diameter (D/d) is called coating factor. Coating factor usually ranges from 1.2 to 2.2. According to the coating factor, coated electrodes can be grouped into three categories namely light coated (1.2-1.35), medium coated (1.4-1.7) and heavy coated (1.8-2.2). Stick electrodes are generally found of length varying from 250 to 400 mm. During the welding, length of the electrode is determined by welder’s convenience to strike the arc and current carrying capacity of electrode without causing excessive heating of coating materials due to electric resistive heating caused by flow of current through the core wire. Bare end of electrode is used to make electrical connection with power source with the help of suitable connectors.

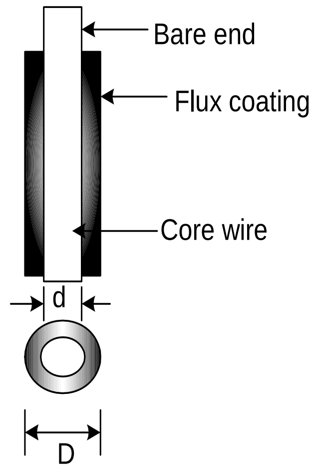
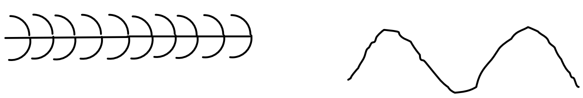


Fig. 12.2Schematic of electrode showing electrode size and its different components

12.3 Weld beads

Two types of beads are generally produced in welding namely stringer bead and weaver bead. Deposition of the weld metal in largely straight line is called stringer bead (Fig. 12.3 a). In case of weaver bead weld metal is deposited in different paths during the welding i.e. zigzag, irregular, curved (Fig. 12.3 b). Weaver bead helps to apply more heat input per unit length during welding than stringer bead. Therefore, weaver beads are commonly used to avoid problems related with welding of thin plates and that in odd position (vertical and overhead) welding in order to avoid melt through and weld metal falling tendency.



a) **b)**

Fig. 12.3 Schematic diagram showing weld bead a) stringer bead and b) weaver bead

12.4 Metal transfer in SMAW

Metal transfer refers to the transfer of molten metal droplets from the electrode tip to the weld pool in consumable arc welding processes. Metal transfer in SMA welding is primarily affected by surface tension of molten metal at the electrode tip. Presence of impurities and foreign elements in molten metal lowers the surface tension which in turn facilitates easy detachment of molten metal drop from the electrode tip. For details of different types of metal transfer modes see section 17.5. Therefore, type and amount of coating on electrode and effectiveness of shielding of arc zone from the atmospheric gases appreciably affect the mode of metal transfer. Acidic and oxide type electrodes produce molten metal with large amount of oxygen and hydrogen. Presence of these impurities in the molten weld metal lowers the surface tension and produces spray like metal transfer. Rutile electrodes are primarily composed of TiO_2 due to which molten metal drop hanging at tip of electrode is not much oxidized and therefore surface tension of the molten weld metal is not reduced appreciably. Hence, rutile electrodes produce more drop and less spray transfer. Basic electrode contains deoxidizers and at the same time moisture is completely driven off to render low hydrogen electrodes. Therefore, melt droplets at the tip of the electrode are of killed steel type having high surface tension. Since high surface tension of molten metal resists the detachment of drops from the electrode tip and hence the size of drop at tip of electrode increases to a great extent before it is detached under the effect of gravitational and electro-magnetic pinch forces. These conditions results in globular transfer with basic electrode.

In case of light coated electrodes incomplete de-oxidation (due to lack of enough flux), CO is formed which remains with single molten weld metal droplet until it grows to about half of electrode diameter. Eventually, drops with bubble of CO bursts which in turn results in metal transfer in form of fine drops and spatter. In case of basic electrode, metal transfer occurs by short circuiting mode if molten metal drop touches the weld pool and melt is transferred to weld pool by surface tension effect.

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Lecture 13

Submerged Arc Welding

This chapter presents the principle of submerged arc welding process besides methods of manufacturing and characteristics of different types of fluxes used in this process. Role of important welding parameters of SAW has also been discussed. Further, the advantages and limitations of this process have been described.

Keywords: Submerged arc welding, SAW flux, weld bead geometry, type of fluxes, limitation, advantages and application of SAW.

13.1 Introduction

Submerged arc welding (SAW) process uses heat generated by an electric arc established between a bare consumable electrode wire and the work piece. Since in this process, welding arc and the weld pool are completely submerged under cover of granular fusible and molten flux therefore it is called so. During welding, granular flux is melted using heat generated by arc and forms cover of molten flux layer which in turn avoids spatter tendency and prevents accessibility of atmospheric gases to the arc zone and the weld pool. The molten flux reacts with the impurities in the molten weld metal to form slag which floats over the surface of the weld metal. Layer of slag over the molten weld metal results:

- Increased protection of weld metal from atmospheric gas contamination and so improved properties of weld joint
- Reduced cooling rate of weld metal and HAZ owing to shielding of the weld pool by molten flux and solidified slag in turn leads to a) smoother weld bead and b) reduced the cracking tendency of hardenable steel

13.2 Components of SAW System

SAW is known to be a high current (sometimes even greater 1000A) welding process that is mostly used for joining of heavy sections and thick plates as it offers deep penetration with high deposition rate and so high welding speed. High welding current can be applied in this process owing to three reason a) absence of spatter, b) reduced possibility of air entrainment in arc zone as molten flux and slag form shield the weld metal a.d c) large diameter electrode. Continuous feeding of granular flux around the weld arc from flux hopper provides shielding to the weld pool from atmospheric gases and control of weld metal composition through presence of alloying element in flux. Complete cover of the molten flux around electrode tip and the welding pool during the actual welding operation produces weld joint without spatter and smoke. In following sections, important components of SAW system and their role have been presented (Fig. 13.1).

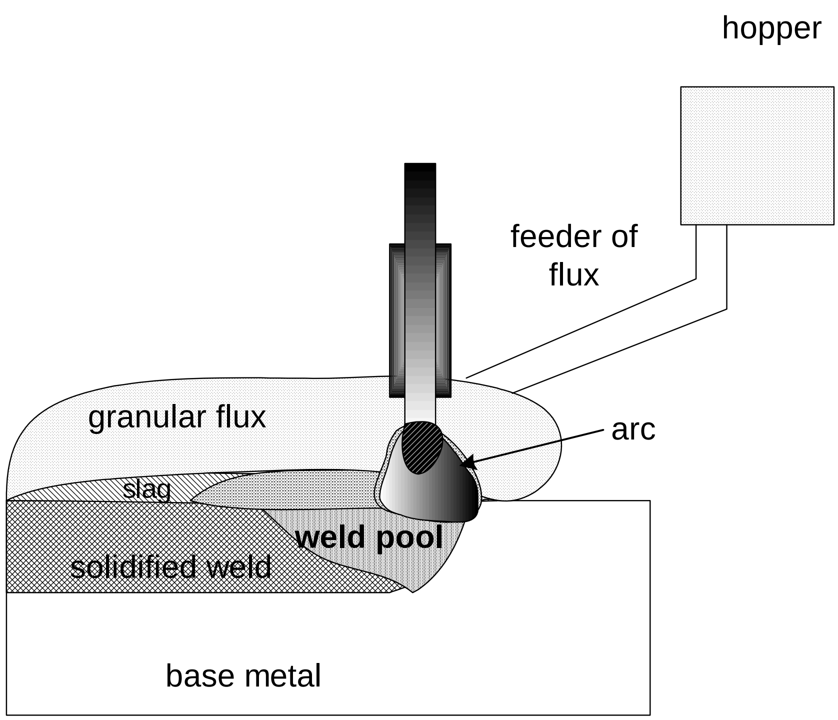

Fig. 13.1 Schematic of submerged arc welding system

13.2.1 Power source

Generally, submerged arc welding process uses power source at 100 % duty cycle; which means that the welding is done continuously for minimum 5 min without a break or more. Depending upon the electrode diameter, type of flux and electrical resistivity submerged arc welding can work with both AC and DC. Alternating current and DCEN polarity are generally used with large diameter electrode (>4mm). DC with constant voltage power source provides good control over bead shape, penetration, and welding speed. However, DC can cause arc blow under some welding conditions. Polarity affects weld bead geometry, penetration and deposition rate. DCEP offers advantage of self regulating arc in case of small diameter electrodes (< 2.4mm) and high deposition rate while DCEN produces shallow penetration.

13.2.2 Welding Electrode

The diameter of electrodes used in submerged arc welding generally ranges from 1–5 mm. The electrode wire is fed from the spool through a contact tube connected to the power source. Electrode wire of steel is generally copper coated for two reasons a) to protect it from atmospheric corrosion and b) to increase their current carrying capacity. However, stainless steel wires are not coated with copper.

13.2.3 SAW Flux

Role of fluxes in SAW is largely similar that of coating in stick electrodes of SMAW i.e. protection of weld pool from inactive shielding gases generated by thermal decomposition of coating material. SAW fluxes can influence the weld metal composition appreciably in the form of addition or loss of alloying elements through gas metal and slag metal reactions. Few hygroscopic fluxes are baked (at 250–300° C for 1-2 hours) to remove the moisture. There are four types of common SAW fluxes namely fused flux, agglomerated flux, bonded flux and mechanical fluxes. Manufacturing steps of these fluxes are given below.

- Fused fluxes: raw constituents-mixed-melted-quenched-crushed-screened-graded
- Bonded fluxes: raw constituents-powdered-dry mixed-bonded using K/Na silicates-wet mixed-pelletized-crushed-screened
- Agglomerated fluxes: made in similar way to bonded fluxes but ceramic binder replaces silicate binder
- Mechanically mixed fluxes: mix any two or three type of above fluxes in desired ratios

Specific characteristics of each type of flux

Fused fluxes

- Positives
  - Uniformity of chemical composition
  - No effect of removal of fine particles on flux composition
  - Non-hygroscopic: easy handling and storage
  - Easy recycling without much change in particle size and composition
- Limitation is related with difficulty in
  - incorporating deoxidizers and ferro alloys
  - melting due to need of high temperature

Bonded fluxes

- Positives
  - Easy to add deoxidizers and alloying elements
  - Allows thicker layer of flux during welding
- Limitation
  - Hygroscopic
  - Gas evolution tendency
  - Possibility of change in flux composition due to removal of fine particles

Agglomerated fluxes

These are similar to that of bonded fluxes except that these use ceramic binders

Mechanical fluxes

- Positives
  - Several commercial fluxes can be easily mixed & made to suit critical application to get desired results
- Limitations
  - Segregation of various fluxes
    - during storage / handling
    - in feeder and recovery system
    - inconsistency in flux from mix to mix

13.3 Composition of the SAW fluxes

The fused and agglomerated types of fluxes usually consist of different types of halides and oxides such as MnO, SiO_2, CaO, MgO, Al_2O_3, TiO_2, FeO, and CaF_2 and sodium/potassium silicate. Halide fluxes are used for high quality weld joints of high strength steel to be used for critical applications while oxide fluxes are used for developing weld joints of non-critical applications. Some of oxides such as CaO, MgO, BaO, CaF_2, Na_2O, K_2O, MnO etc. are basic in nature (donors of oxygen) and few others such as SiO2, TiO_2, Al_2O_3 are acidic (acceptors of oxygen). Depending upon relative amount of these acidic and basic fluxes, the basicity index of flux is decided. The basicity index of flux is ratio of sum of (wt. %) all basic oxides to all non-basic oxides. Basicity of flux affects the slag detachability, bead geometry, mechanical properties and current carrying capacity as welding with low basicity fluxes results in high current carrying capacity, good slag detachability, good bead appearance and poor mechanical properties and poor crack resistance of the weld metal while high basicity fluxes produce opposite effects on above characteristics of the weld.

13.4 Fluxes for SAW and Recycling of slag

The protection to the weld pool in submerged arc welding process is provided by molten layer of flux covering to the weld pool. Neutral fluxes are found mostly free from de-oxidizers (like Si, Mn) therefore loss of alloying elements from weld metal becomes negligible and hence chemical composition of the weld metal is not appreciably affected by the application of neutral fluxes. However, base metal having affinity with oxygen exhibits tendency of porosity and cracking along the weld centerline. Active fluxes contain small amount of de-oxidizer such as manganese, silicon singly or in combination. The deoxidizers enhance resistance to porosity and weld cracking tendency.

The submerged arc welding fluxes produce a lot of slag which is generally disposed off away as a waste. The disposal of slag however imposes many issues related with storage, and environmental pollution. The recycling of the used flux can reduce production cost appreciably without any compromise on the quality of the weld. However, recycling needs extensive experimentation to optimize the composition of recycled flux so as to achieve the desired operational characteristics and the performance of the weld joints. The recycling of flux basically involves the use of slag with fresh flux. The slag developed from SAW process is crushed and mixed with new flux. This process is different from recycling of un-fused flux which is collected from the clean surface and reused without crushing. Slag produced during submerged arc welding while using a specific kind/brand of the flux is crushed and then used as flux or used after mixing with original unused flux to ensure better control over the weld properties. Building of slag with unused flux modifies the characteristics of original unused flux therefore the blending ratio must be optimized for achieving the quality weld joints.

13.5 Welding parameters

Welding parameters namely electrode wire size, welding voltage, welding current and welding speed are four most important parameters (apart from flux) that play a major role on soundness and performance of the weld therefore these must be selected carefully before welding.

13.5.1 Welding Current

Welding current is the most influential process parameter for SAW because it determines the melting rate of electrode, penetration depth and weld bead geometry. However, too high current may lead to burn through owing to deep penetration, excessive reinforcement, increased residual stresses and high heat input related problems like weld distortion. On the other hand, selection of very low current is known to cause lack of penetration & lack of fusion and unstable arc. Selection of welding current is primarily determined by thickness of plates to be welded and accordingly electrode of proper diameter is selected so that it can withstand under the current setting required for developing sound weld with requisite deposition rate and penetration (Fig. 2).

Diameter (mm)	Welding Current (A)
1.6	150-300

2.0	200-400
2.5	250-600
3.15	300-700
4.0	400-800
6.0	700-1200

13.5.2 Welding Voltage

Welding voltage has marginal affect on the melting rate of the electrode. Welding voltage commonly used in SAW ranges from 20-35 V. Selection of too high welding voltage (more arc length) leads to flatter and wider weld bead, higher flux consumption, and increased gap bridging capability under poor fit-up conditions while low welding voltage produces narrow & peaked bead and poor slag detachability (Fig. 2).

13.5.3 Welding speed

Required bead geometry and penetration in a weld joint are obtained only with an optimum speed of welding arc during SAW. Selection of a speed higher than optimum one reduces heat input per unit length which in turn results in low deposition rate of weld metal, decreased weld reinforcement and shallow penetration (Fig. 13.2). Further, too high welding speed increases tendency for a) undercut in weld owing to reduced heat input, b) arc blow due to higher relative movement of arc with respect to ambient gases and c) porosity as air pocket are entrapped due to rapid solidification of the weld metal. On other hand low welding speed increases heat input per unit length which in turn may lead to increased tendency of melt through and reduction in tendency for development of porosity and slag inclusion.

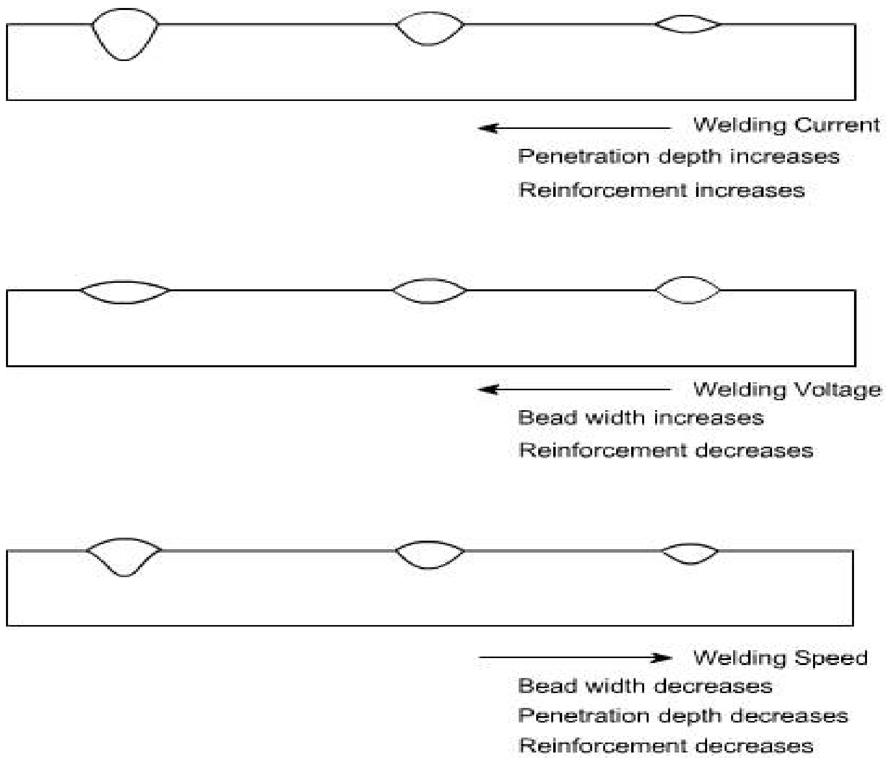

Fig. 13.2 Influence of welding parameters on weld bead geometry

13.6 Bead geometry and effect of welding parameters

Bead geometry and depth of penetration are two important characteristics of the weld bead that are influenced by size of the electrode for a given welding current setting. In general, an increase in size of the electrode decreases the depth of penetration and increases width of weld bead for a given welding current (Fig. 13.3). Large diameter electrodes are primarily selected to take two advantages a) higher deposition rate owing to their higher current carrying capacity and b) good gap bridging capability under poor fit-up conditions of the plates to be welded due to wider weld bead.

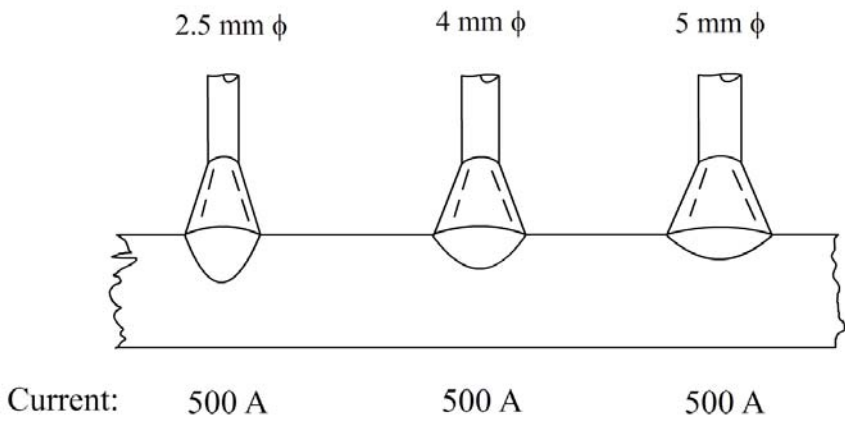

Fig. 13.3 Influence of electrode diameter on weld bead geometry

13.7 Advantage

Due to unique features like welding arc submerged under flux and use of high welding current associated with submerged arc welding processes compared with other welding process, it offers following important advantages:

- High productivity due to high deposition rate of the welding metal and capability weld continuously without interruptions as electrode is fed from spool, and the process works under 100% duty cycle.
- High depth of penetration allows welding of thick sections
- Smooth weld bead is produced without stresses raisers as SAW is carried out without sparks, smoke and spatter

13.8 Limitations

There are three main limitations of SAW a) invisibility of welding arc during welding, b) difficulty in maintaining mound of the flux cover around the arc in odd positions of welding and cylindrical components of small diameter and c) increased tendency of melt through when welding thin sheet. Invisibility of welding arc submerged under un-melted and melted flux cover in SAW makes it difficult to ensure the location where weld metal is being deposited during welding. Therefore, it becomes mandatory to use an automatic device (like welding tractors) for accurate and guided movement of the welding arc in line with weld groove so that weld metal is deposited correctly along weld line only.

Applications of SAW process are mainly limited to flat position only as developing a mound of flux in odd position to cover the welding arc becomes difficult which is a requisite for SAW. Similarly, circumferential welds are difficult to develop on small diameter components due to flux falling tendency away from weld zone. Plates of thickness less than 5 mm are generally not welded due to risk of burn through.

Further, SAW process is known as high heat input process. High heat input however is not considered good for welding of many steels as it leads to significant grain growth in weld and HAZ owing to low cooling rate experienced by them during welding. Low cooling rate increases the effective transformation temperature which in turn lowers nucleation rate and increases the growth rate during solid state transformation. A combination of low nucleation rate and high the growth rate results in coarse grain structure. Coarse grain structure in deteriorate the mechanical properties of the weld joint specifically toughness. Therefore, SAW weld joints are sometime normalized to refine the grain structure and enhanced the mechanical properties so as to reduce the adverse effect of high input of SAW process on mechanical properties of the weld joints.

13.9 Applications

Submerged arc welding is used for welding of different grades of steels in many sectors such as shipbuilding, offshore, structural and pressure vessel industries fabrication of pipes, penstocks, LPG cylinders, and bridge girders. Apart from the welding, SAW is also used for surfacing of worn out parts of large surface area for different purposes such as reclamation, hard facing and cladding. The typical application of submerged arc welding for weld surfacing includes surfacing of roller barrels and wear plates. Submerged arc welding is widely used for cladding carbon and alloy steels with stainless steel and nickel alloy deposits

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Lecture 14

Gas Tungsten Arc welding I

This chapter presents the principle of tungsten inert gas (TIG) welding process besides important components of TIG welding system and their role. This process is also known as gas tungsten arc welding (GTAW) process. Further, fundamentals of heat generation, arc stability and arc efficiency have also been described. Additionally, comparison of argon and helium as shielded gases has been discussed.

Keywords: Tungsten inert gas welding, shielding gas, welding torch, arc stability, Arvs. He

14.1 Introduction

Tungsten inert gas welding process also called as gas tungsten arc welding is named so because it uses a) electrode primarily made of tungsten and b) inert gas for shielding the weld pool to prevent its contamination from atmospheric gases especially when joining high strength reactive metals and alloys such as stainless steel, aluminium and magnesium alloys, wherever high quality weld joints need to be developed for critical applications like nuclear reactors, aircraft etc. Invention of this process in middle of twentieth century gave a big boost to fabricators of these reactive metals as none of the processes (SMAW and Gas welding) available at that time were able to weld them successfully primarily due to two limitations a) contamination of weld from atmospheric gases and b) poor control over the heat input required for melting (Fig. 14.1). Moreover, welding of aluminium and its alloys with shielded metal arc welding process can be realized using halide flux coated electrodes by overcoming the problems associated with Al_2O_3, however, halides are very corrosive and therefore welding of aluminium is preferable carried out using inert shielding environment with the lerp of processes like GTAW and GMAW. Despite of so many developments in the field of welding, TIG process is invariably recommended for joining of thin aluminium sheets of thickness less than 1mm.

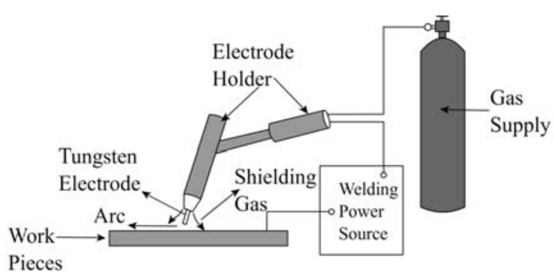


Fig. 14.1 Schematic of tungsten inert gas welding process

14.2 TIG welding system

There are four basic components (Fig. 14.2) of TIG welding system namely a) DC/AC power source to deliver the welding current as per needs, b) welding torch (air/water cooled) with tungsten electrode and gas nozzle, c) inert shielding gas (He, Ar or their mixture) for protecting the molten weld pool contamination from atmospheric gases and d) controls for moving the welding torch as per mode of operation (manual, semi-automatic and automatic). This process uses the heat generated by an electric arc between the non-consumable tungsten electrode and work piece (mostly reactive metals like stainless steel, Al, Mg etc.) for melting of faying surfaces and inert gas is used for shielding the arc zone and weld pool from the atmospheric gases.

14.2.1 Power source

TIG welding normally uses constant current type of power source with welding current ranging from 3-200A or 5-300A or higher and welding voltage ranging from 10-35V at 60% duty cycle. Pure tungsten electrode of ball tip shape with DCEN provides good arc stability. Moreover, thorium, zirconium and lanthanum modified tungsten electrodes can be used with AC and DCEP as coating of these elements on pure tungsten electrodes improves the electron emission capability which in turn enhances the arc stability. TIG welding with DCEP is preferred for welding of reactive metals like aluminium to take advantage of cleaning action due to development of mobile cathode spots in work piece side during welding which loosens the tenacious alumina oxide layer. This helps to clean the weld pool.DCEN polarity is used for welding of metal such as carbon steel that don’t require much cleaning.

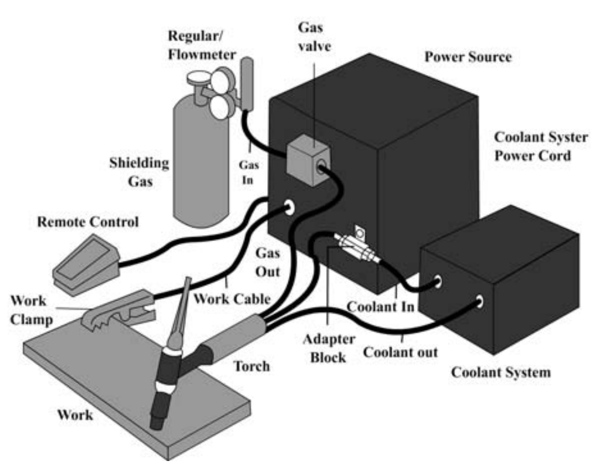


Fig. 14.2 Details of components of GTAW system [Millerweld.com]

14.2.2 Welding Torch

TIG welding torch includes three main parts namely non-consumable tungsten electrode, collets and nozzle. A collet is primarily used to hold the tungsten electrodes of varying diameters in position. Nozzle helps to form a firm jet of inert gas around the arc, weld pool and the tungsten electrode. The diameter of the gas nozzle must be selected in light of expected size of weld pool so that proper shielding of the weld pool can be obtained by forming cover of inert gas. The gas nozzle needs to be replaced at regular interval as it is damaged by wear and tear under the influence of intense heat of the welding arc. Damaged nozzle does not form uniform jet of inert gas around the weld pool for protection from the atmospheric gases. Typical flow rate of shielding inert gas may vary from 5-50 liters/min.

TIG welding torch is generally rated on the basis of their current carrying capacity as it directly affects the welding speed and so the production rate. Depending upon the current carrying capacity, the welding torch can be either water or air cooled. Air cooled welding torch is generally used for lower range of welding current than water cooled torches.

14.2.3 Filler wire

Filler metal is generally not used for welding thin sheet by TIGW. Welding of thick steel plates by TIG welding to produce high quality welds for critical applications such as joining of nuclear and aero-space components, requires addition of filler metal to fill the groove. The filler wire can be fed manually or using some wire feed mechanism. For feeding small diameter filler wires (0.8-2.4mm) usually push type wire feed mechanism with speed control device is used. Selection of filler metal is very critical for successful welding because in some cases even use of filler metal similar to that base metal causes cracking of weld metal especially when their solidification temperature range is every wide (>50^{o}C). Therefore, selection of filler wire should be done after giving full consideration to the following aspects such as mechanical property requirement, metallurgical compatibility, cracking tendency of base metal under welding conditions, fabrication conditions etc.

For welding of aluminium alloys, Al-(5-12wt.%) Si filler is used as general purpose filler metal. Al-5%Mg filler is also used for welding of some aluminium alloys.

Welding of dissimilar steels namely stainless steel with carbon or alloy steels for high temperature applications needs development of buttering layer before welding for reducing carbon migration and residual stress development related problems.

14.2.4 Shielding gas

Helium, Argon and their mixtures are commonly used as inert shielding gas for protecting the weld pool depending upon the metal to be welded, criticality of application and economics. Helium or hydrogen is sometimes added (1-2%) in argon for specific purposes such as increasing the arc voltage and arc stability which in turn helps to increase the heat of arc. The selection of inert gases to be used as shielding gas in GTAW and GMAW process depends upon the type of metal to be welded and criticality of their applications. Carbon dioxide is not used with GTAW process, at high temperature in arc environment, the thermal decomposition of the carbon dioxide produces CO and O_2. Generation of these gases adversely affect the quality and soundness of the weld joint and reduces the life of tungsten electrode.

Inert Gases

Argon and helium are the mostly commonly used shielding gases for developing high quality weld joints of reactive and ferrous metals. Small amount of hydrogen or helium is often added in argon to increase the penetration capability and welding speed. These two inert gases as shielding gas are different in many ways. Some of these features are described in following section.

A. Heat of welding arc

The ionization potential of He (25eV) is higher than Ar (16eV). Therefore, application of He as shielding gas results in higher arc voltage and hence different VI arc characteristics of arc than when argon is used as shielding gas. In general, arc voltage generated by helium for a given arc length during welding is found higher than argon. This results in hotter helium arc than argon arc. Hence, helium is preferred for the welding of thick plates at high speed especially metal systems having high thermal conductivity and high melting point.

B. Arc efficiency

Helium offers higher thermal conductivity than argon. Hence, He effectively transfers the heat from arc to the base metal which in turn helps in increasing the welding speed and arc efficiency.

C. Arc stability

He is found to offer more problems related with arc stability and arc initiation than Ar as a shielding gas. This behaviour is primarily due to higher ionization potential of Hethan Ar. High ionization potential of helium means it will result in presence of fewer charged particles between electrode and work piece required for initiation and maintenance of welding arc. Therefore, arc characteristics are found to be different for Ar and He. A minima arc voltage is found in VI characteristics curve of an arc when both the gases are used as shielding gas but at different level of welding currents. With argon as shielding gas the welding current corresponding to the lowest arc voltage is found around 50A while that for helium occurs at around 150A (Fig. 14.3). Reduction in welding current below this critical level (up to certain range) increases the arc voltage; which permits some flexibility in arc length to control the welding operation.

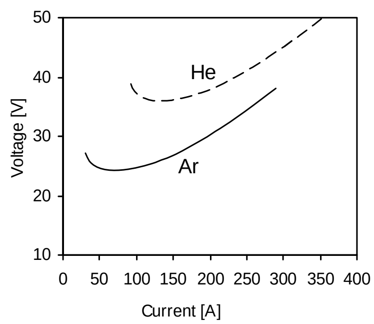


Fig. 14.3 Influence of shielding gas on VI characteristics of GTAW process

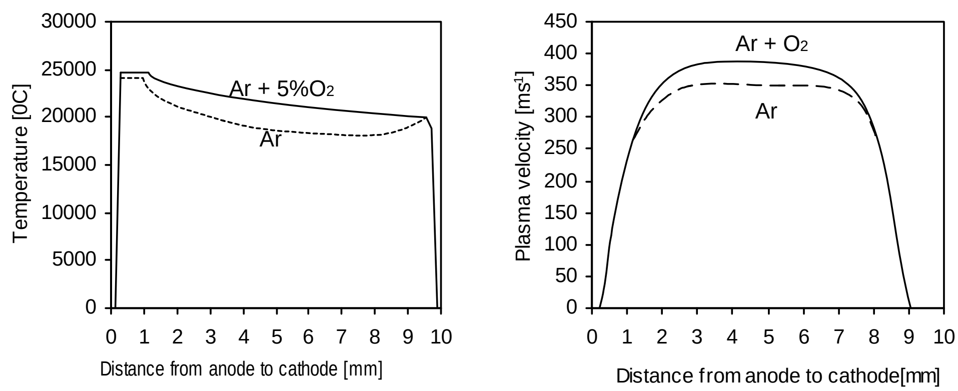
D. Flow rate of shielding gas

Argon (density 1.783g/l) is about 1.33 and 10 times heavier than the air and the helium respectively. This difference in density of air with shielding gases determines the flow rate of particular shielding gas required to form a blanket over the weld pool and arc zone to provide protection against the environmental attack. Helium being lighter than air tends to rise up immediately in turbulent manner away from the weld pool after coming out of the nozzle. Therefore, for effective shielding of the arc zone, flow rate of helium (12-22 l/min) must be 2-3 times higher than the argon (5-12 l/min).

Flow rate of shielding gas to be supplied for effective protection of weld pool is determined by the size of molten weld pool, sizes of electrode and nozzle, distance between the electrode and work piece, extent of turbulence being created ambient air movement (above 8-10km/hr). For given welding conditions and welding torch, flow rate of the shielding gas should be such that it produces a jet of shielding gas so as to overcome the ambient air turbulence and provides perfect cover around the weld pool. Unnecessarily high flow rate of the shielding gas leads to poor arc stability and weld pool contamination from atmospheric gases due to suction effect.

E. Mixture of shielding gases

Small addition of hydrogen in argon increases arc voltage which burns the arc hotter and this in turn increases the weld penetration and welding speed like He. To take the advantage of good characteristics of He (thermal conductivity, high temperature arc) and Ar (good arc initiation and stability) a mixture of these two gases Ar-(25-75%)He is also used. Increasing proportion of He in mixture increases the welding speed and depth of penetration of weld. Addition of oxygen in argon also helps to increase the penetration capability of GTAW process owing to increase in arc temperature and plasma velocity (Fig. 14.4)



a) b)

Fig. 14.4 Influence of oxygen addition in Ar on a) arc temperature and b) plasma velocity of GTAW process

F. Advantages of Ar over He as Shielding Gas

For general, purpose quality weld, argon offers many advantages over helium a) easy arc initiation, b) cost effective and good availability c) good cleaning action with (AC/DCEP in aluminium and magnesium welding) and d) shallow penetration required for thin sheet welding of aluminium and magnesium alloys.

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Lecture 15

Gas Tungsten Arc welding II

This chapter describes different types of tungsten electrodes used in TIG welding process besides selection of polarity and methods of initiating welding arc for TIGW process. Further, the basic principle of pulse gas tungsten arc welding process has also been presented.

Keywords: Tungsten electrode, coated W electrode, DCEN, DCEP, TIG arc initiation, carbon block, pilot arc method, pulse TIG welding

15.1 Electrode for TIG torch

The electrode for tungsten inert gas welding process can be pure (uncoated) or coated with Zr, La or Th. However, pure tungsten electrode offers shorter life than coated electrodes because of rapid wear and tear of the pure tungsten electrode owing to thermal damage caused by their low current carrying capacity. The damage to electrode primarily occurs due to the fact that tungsten carbide (formed during steel welding of reaction between W and C) has lower melting point than tungsten. Particles generated from pure tungsten electrode due to thermal damage cause contamination of the weldment as tungsten particles inclusions therefore; pure tungsten electrodes are not used for critical welding applications.

Pure tungsten electrodes are frequently coated oxides of Th, Zr, La, and Ce. These oxides are expected to perform two important functions a) increasing arc stability and b) increasing the current carrying capacity of the electrodes.

Increase in arc stability of tungsten electrode in presence of the oxides of thorium, cerium, zirconium and lanthanum is primarily attributed to lower work function of these oxides than pure tungsten. Work function of pure tungsten electrode is 4.4eV while that of Zr, Th, La and Ce is 4.2, 3.4, 3.3 and 2.6 eV respectively. Lower the work function of the electrode material easier will be emission of electrons in the gap between electrode and work piece which in turn will improve the arc stability even at low arc voltage, and welding current.

Addition of the oxides of thorium, cerium, zirconium and lanthanum helps to increase the current carrying capacity of pure tungsten electrode up to 10 folds. Size of tungsten electrode is generally specified on the basis of its diameter as it largely determines the current carrying capacity of a given electrode material. The current carrying capacity of an electrode is also influenced by cooling arrangement in a welding torch (air/water cooled), type of power source (DCEP/DCEN, AC), electrode extension beyond collets, nozzle diameter and shielding gas. Typical electrodes for TIG welding and suitable type of current are given below.

- 2% Cerium coated electrodes: Good for both AC and DC welding
- 1.5−2% Lanthanum coated electrode: Gives excellent low current starts for AC and DC welding
- 2% Thorium coated electrode: Commonly used for DC welding and is not preferred for AC.

15.2 Type of welding torch

Air cooled welding torch offers lower current carrying capacity than water cooled due to the fact that water cooling reduces overheating of the electrode during welding by extracting the heat effectively from the electrode.

15.2.1 Type of welding current and polarity

Current carrying capacity of an electrode with DCEN polarity is found to be higher than DCEP and AC because DCEN generates lesser (30% of arc power) heat in tungsten electrode side compared to the DCEP and AC. Therefore, electrodes with DCEN polarity offer longer life with same level of welding current conversely higher current capacity for the same life. Size of welding electrode for DCEP (for the same current and life) should be larger than that for DCEN owing to higher heat generation at anode than cathode for the same welding current. Current carrying capacity of electrode for AC welding is generally found between that in case of DCEP and DCEN as continuous change in polarity during the AC welding allows the somewhat cooling of electrode when electrode is negative for one half of the cycle.

The selection of polarity for GTAW is primarily determined by the type of metal to be welded. The DCEN polarity is preferred for welding of steel, and nickel alloys and other metals where cleaning action is not very crucial for developing successful weld joints. The application of DCEP polarity is not common and is preferred for shallow penetration welding application like thin sheet welding. AC is commonly used for welding of aluminum and magnesium to get advantage of cleaning action and avoiding overheating of tungsten electrode.

15.2.2 Electrode diameter and welding current

The diameter of tungsten electrode is usually found in a range of 0.3-8 mm and length varies from 75 to 610 mm. The selection of electrode material and diameter is governed by the section thickness of the material to be welded. Thick plates demand greater heat input so high welding current which in turn dictates the selection of large diameter electrodes. Excessive welding current causes erosion of electrodes and tungsten inclusion due to thermal damage. Erosion of electrode reduces the electrode life. Low welding current results in erratic wandering of welding arc over the tip of electrode, which reduces the arc stability. However, wandering of the arc at low current can be corrected by tapering the electrode tip (included angle 30-120^0). Taper angle affects the penetration and weld bead width. Low taper angle results in deeper the penetration and narrower the bead than high angle taper.

15.3 TIG Arc Initiation

Direct work piece touch start method of initiating TIGW arc is not considered as a good approach because it generally leads to many undesirable effects a) contamination of tungsten electrode, b) partial melting of electrode tip (due to short circuiting) so reduction in life of the electrode and c) formation of tungsten inclusions which deteriorate the mechanical performance of weld joint. Therefore, alternative methods of TIG arc initiation have been developed over the years so as to avoid undesirable effects of touch start method. Three methods are commonly used for initiating TIG welding arc a) use of carbon block as scrap material, b) use of high frequency high voltage unit and c) use of low current pilot arc.

15.3.1 Carbon block method

This method is based on the principle similar to that of touch start method where tungsten electrode is brought in contact of a scrap material or carbon block placed in area which is close to the region where arc is to be applied during welding. However, this method doesn’t necessarily prevent electrode contamination but reduces tendency for the same.

15.3.1 High frequency unit

This method is based on field emission principle by applying high frequency (100-2000 KHz) and high voltage (3000-5000V) pulse to initiate the welding arc. The high voltage pulse ensures the availability of electrons in arc gap by field emission and ionization of gases between the electrode and work piece required to initiate the arc. This method is mainly used in automatic TIG welding process. Absence of contact between electrode and work piece reduces the electrode contamination hence increases life of the electrode.

15.3.1 Pilot arc method

Pilot arc method is based on the principle of using low current for initiating the arc 50 to reduce adverse effects of high heat generation in form of electrode contamination and electrode melting during the arc initiation (Fig. 15.1). For this purpose, an additional power source can be used to strike the arc between the tungsten electrode and auxiliary anode (fitted in nozzle) using low current called pilot arc. This pilot arc is then brought close to base metal to be welded so as to ignite the main arc between electrode and work piece. Once the main arc is established auxiliary power source is taken off.

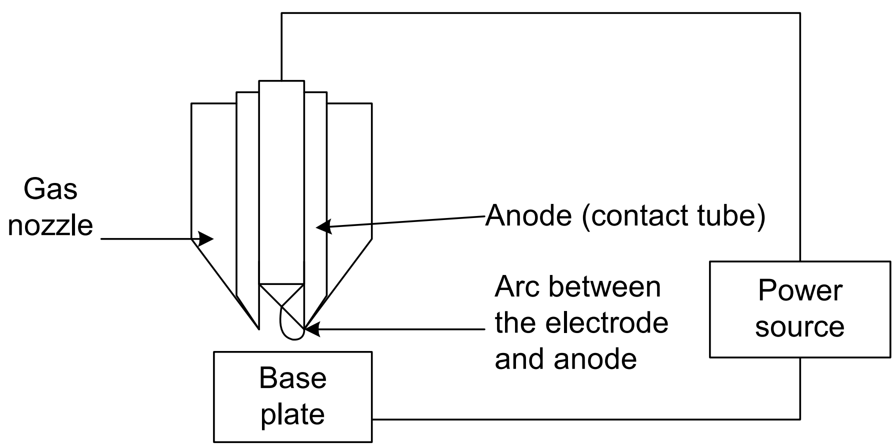

Fig. 15.1 Schematic showing the mechanism of pilot arc imitation method

15.4 Maintenance of TIG welding arc

Arc maintenance in TIG welding with DC power supply does not create any problem. However, in case of AC TIG welding, to have smooth and stable welding arc, methods like use of high OCV, imposing the high frequency and high voltage pulse at the moment when current is zero can be used so that arc is not extinguished.

15.5 Pulse TIG Welding

Pulse TIG is a variant of tungsten inert gas welding. In this process, welding current is varied between a high and a low level at regular time intervals. This variation in welding current between high and low level is called pulsation of welding current (Fig. 15.2). High level current is termed as peak current and is primarily used for melting of faying surfaces of the base metal while low current is generally called background current and it performs two functions 1) maintenance of the welding arc while generating very low heat and 2) allows time for solidification of the weld pool by dissipating the heat to base metal. This feature of current pulsation associated with this process effectively reduces net heat input to the base metal during welding which in turn facilitates a) easy welding especially of thin sheets and b) refinement of grain structure of the weld. Reduction in net heat input using arc pulsation decreases undesirable effects of comparatively high heat input of conventional TIG welding such as melt through, wrapping/buckling and fit-up.

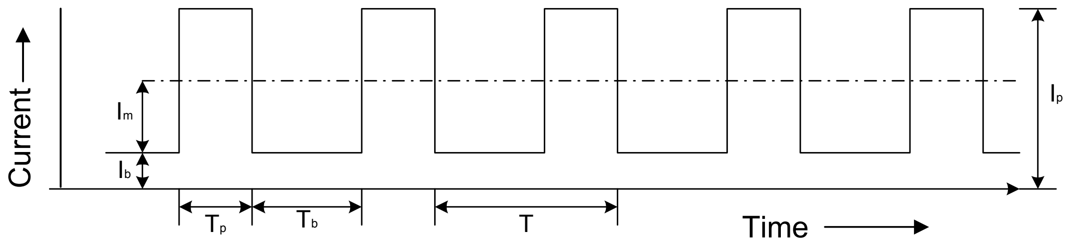

Fig. 15.2 Schematic showing parameters related with the pulse current and time. Where I_p, I_b & I_m are peak current, base current and mean current respectively while T_p, T_b & T show pulse current duration, base current duration and total cycle time for one pulse i.e. sum of pulse and base current period (in ms).

15.5.1 **Process Parameters of Pulse TIG welding**

Important variables in this variant of TIG welding are peak current, background current, peak current duration (pulse duration) and duration of background current. Peak and background current can be controlled independently depending upon the characteristics of the base metal to be welded such as thickness, materials etc.

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Lecture 16

Gas Tungsten Arc welding III & Plasma Arc Welding

This chapter presents the influence of process parameters of pulse TIG welding process on the development of sound weld joint. Further, the concept of hot wire TIG welding process has also been elaborated. Additionally, basic principle of plasma arc welding has been described with help of suitable schematic diagrams.

Keyword: Peak current, background current, pulse frequency, hot wire GTAW, plasma arc welding, transferred and non-transferred arc welding,

16.1 Selection of pulse parameters

High peak current setting is required for welding of thick section of metal with high thermal conductivity. Background current or low level of current must be high enough to maintain the stable arc with lowest possible heat input so that solidification of the molten weld can take place without any heat buildup. Duration of the pulse and background currents determines the pulse frequency. The frequency of the pulses and so their durations are selected as per heat input and degree of control over the weld pool required. In Pulsed TIG welding , the weld bead is composed of a series of overlapping weld spots, especially when welding is done at low frequency (Fig. 16.1).

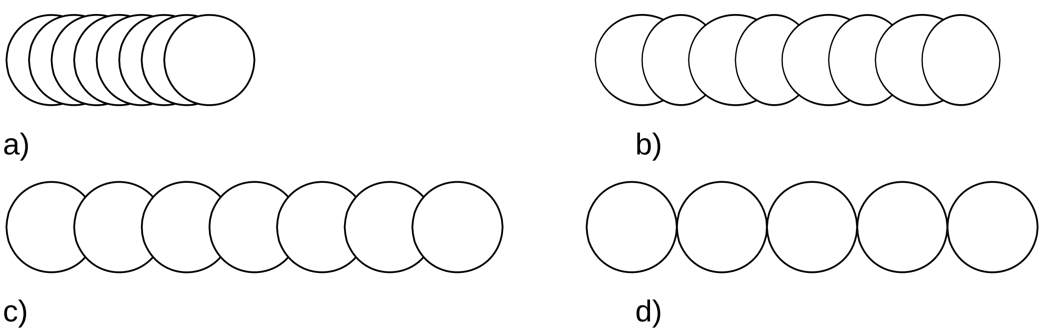


Fig. 16.1 The relationship between the overlapping of weld spot and pulse frequency in reducing order (for a given welding speed)

Average welding current during pulse welding for calculation of heat input can be obtained by using following equation:

I_p= peak current (A).

T_p= peak pulse current duration (ms).

I_b= background current (A).

T_b= background current duration (ms).

I_m= Average current (A), defined as:

I_m= [(I_p X t_p) + (I_b X t_b)] / (t_p + t_b)……………….Equation 16.1

16.1.1 Pulse current

Generally, background current varies from 10 to 25% of peak current depending upon the thickness base metal whereas peak current is generally set at 150 to 200% of steady current corresponding to the conventional TIG welding for the same base metal. Selection of the pulse peak current duration depends on the weld pool size and penetration required for welding of the work piece of a particular thickness while background current duration is determined on the basis of cooling rate required in weld to achieve better control over the weld pool and the microstructure of weld metal so that desired mechanical performance of the weld joints can be obtained.

16.1.2 Pulse Frequency

Very low pulse frequency (conversely longer background current duration and short peak current period) during Pulse TIG welding, reduces heat available for welding input which in turn increases the solidification rate. Too high solidification rate increases porosity formation in weld primarily due to inadequate opportunities for escaping of gases from the weld pool. A fine grained structure can be achieved using both low and high pulse frequencies. Fine microstructure is known to improve the mechanical properties of the weld joint in general except creep resistance. Low pulse frequency (up to 20 Hz) has more effect on the microstructure and mechanical properties. Pulse TIG welding is commonly used for root pass welding of tubes and pipe welding to take the advantage of low heat input.

16.2 Hot wire Tungsten Arc Welding

This process is based on the principle of using preheated filler in TIG welding and is primarily designed to reduce heat input to the base metal while realizing higher increase the deposition rate (Fig. 16.2). Preheating of the filler increases welding speed and so productivity. Preheating of the filler can be done using an external source of heat. AC current is commonly used to preheat the filler wire by electrical resistance heating (Fig. 16.3). This process can be effectively used for welding of ferrous metals and Ni alloys. Welding of aluminium and copper by this process is somewhat limited mainly due to difficulties associated with preheating of Al and Cu fillers as they need heavy current for electrical resistive heating of filler wire.

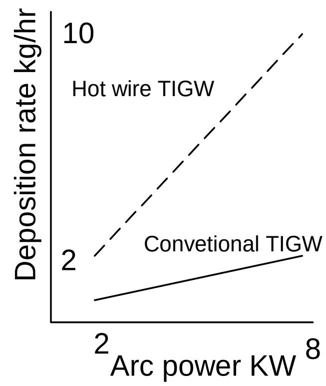


Fig. 16.2 Comparative deposition rates of conventional and hot wire GYAW process

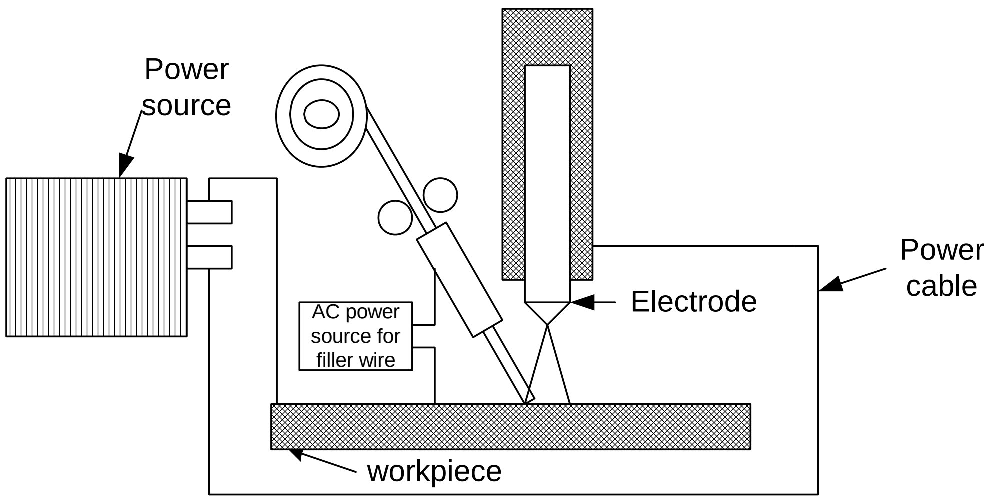
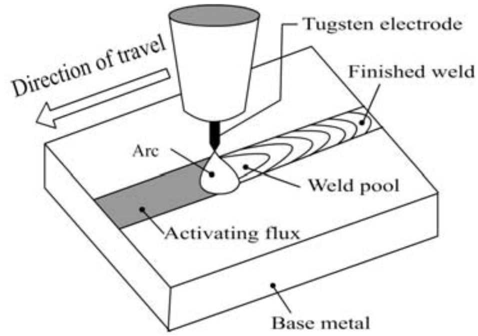


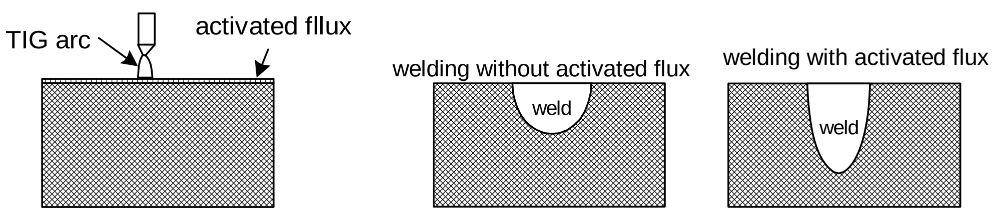
Fig. 16.3 Schematic showing the principle of hot wire GTAW process

16.3 Activated flux assisted welding processes

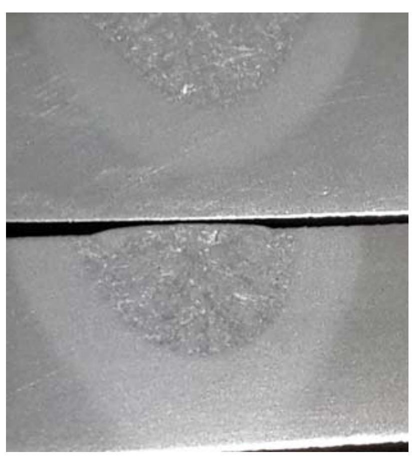
Activated flux assisted GTA and GMA welding processes are also being explored to take advantage of high penetration which is typically achieved by these processes. The flux assisted processes use common fluxes like TiO_2, SiO_2, Cr_2O_3, ZrO_2 halide fluxes. The flux is usually applied in the form of paste on to the faying surfaces of base metal followed by application of welding arc for melting the base metal. Application of these fluxes results in many desirable effects on the welding a) increasing the arc voltage compared with conventional GTAW or GMAW process under identical conditions of arc length, welding current which in turn burns the arc hotter and increases the depth of penetration and b) increasing the constriction of the arc which in turn facilitates the development of weld of high depth to width ratio. Increase in depth of the penetration in turn increases the rate of lateral heat flow from the weld pool to the base metal. Increased rate of heat flow from the weld pool causes grain refinement owing to the high cooling rate and low solidification time. High depth to width ratio, effect imparted to the weld pool by activated fluxes is found similar to the high energy density process. Activated flux assisted GTA and GMA welding processes have been developed for joining of titanium and steel for nuclear and aerospace applications.



a)



b) c) d)



e)

Fig. 16.4 Schematic of activated flux TIG welding: a) method of applying flux, b) application of flux and arc, c) weld bead geometry without activated flux and d) weld bead geometry without activated flux [H Huang, MTA, 41A, 2010, 2829] and e) photograph of weld bead geometry with activated flux and without GTAW

Plasma Arc Welding

16.4 Introduction

The plasma arc welding (PAW) can be considered as an advanced version of TIG welding. Like TIGW, PAW also uses the tungsten electrode and inert gases for shielding of the molten metal. Low velocity plasma and diffused arc is generated in the TIG welding while in case of PAW very high velocity and coherent plasma is generated. Large surface area of the arc exposed to ambient air and base metal in case of TIG welding causes greater heat losses than PAW and lowers the energy density. Therefore, TIG arc burns at temperature lower than plasma arc.

16.5 Principle of PAW

In plasma arc welding, arc is forced to pass through nozzle (water cooled copper) which causes the constriction of the arc (Fig. 16.5). Constriction of arc results in (a) reduction in cross-sectional area of arc, (b) increases (d) increases energy density and (c) increases to velocity of plasma approaching to the sound velocity and temperature to about 25000 ^{0}C. these factors together make PAW, a high energy density and low heat input welding process therefore; it poses fewer which in turn reduces problems associated with weld thermal cycle.

Constriction of arc increases the penetration and reduces the width of weld bead. Energy associated with plasma depends on plasma current, size of nozzle, plasma gas (Fig. 16.6). A coherent, calumniated and stiff plasma is formed due to constriction therefore it doesn’t get deflected and diffused. Hence, heat is transferred to the base metal over a very small area which in turns results in high energy density and deep of penetration and small width of the weld pool / key hole / cut. Further, stiff and coherent plasma makes it possible to work having stable arc with very low current levels (<15 A) which in turn has led to development micro-plasma system.

Energy density and penetration capability of plasma jet is determined by the various process parameters namely plasma current, nozzle orifice diameter and shape, plasma forming gas (Air, He, Ar) and flow rate of plasma carrying. Increasing plasma current, flow rate, thermal conductivity of plasma forming gas and reducing nozzle orifice diameter increases together result in the energy density and penetration capability of plasma jet. In general, the plasma cutting uses high energy density in combination with high plasma velocity and high flow rate of high thermal conductivity plasma forming gas. A combination of such characteristics for plasma cutting is achieved by controlling above process parameters. Further, thermal conductivity of plasma forming gas must be high enough for cutting operation so that heat can be effectively transferred rapidly to the base metal. Plasma welding needs comparatively low energy density and low velocity plasma to avoid melt through or blowing away tendency of molten metal.

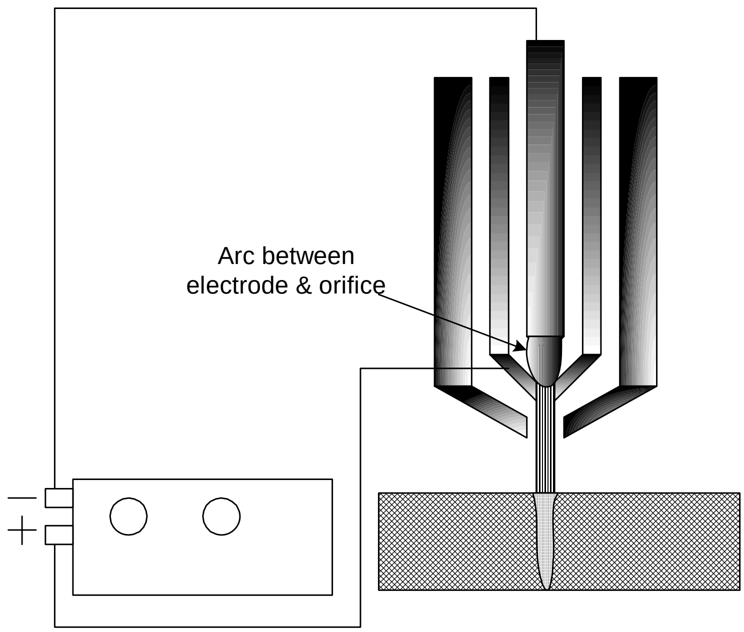


Fig. 16.5 Schematic of plasma arc welding system showing important components

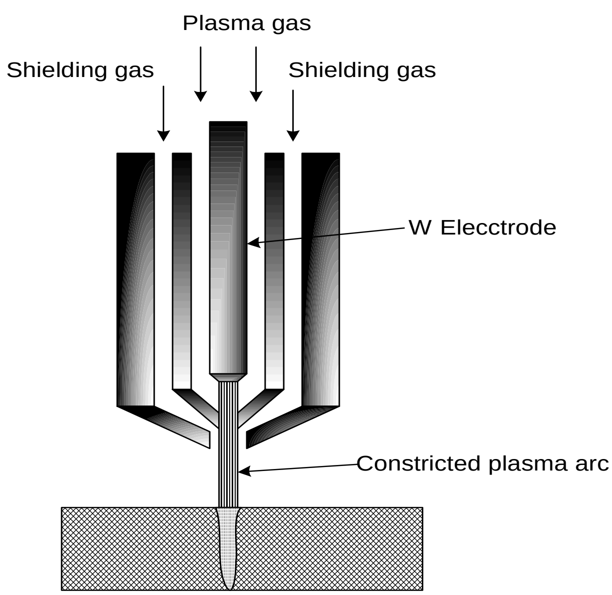


Fig. 16.6 Schematic of constriction of arc in PAW

High energy density associated with plasma arc produces a temperature of order of 25,000 ^{0}C. This process uses the heat transferred by plasma (high temperature charged gas column) produced by a gas (Ar, Ar-H_2 mixture) passing through an electric arc, for melting of faying surfaces. Inert gas (Ar, He) is used to protect the molten weld pool from the atmospheric gases. Charged particles (electrons and ions) formed as a result of ionization of plasma gas tends to reunite when they strike to the surface of work piece. Recombination of charged particles liberates heat which is also used in melting of base metal. Electric arc can be produced between non-consumable electrode and work-piece or non-consumable electrode and nozzle. As discussed above, plasma arc welding uses two types of gases one is called plasma gas and other is inert gas primarily for shielding the weld pool from the contamination by atmospheric gases. Plasma gas is primarily used to develop plasma by passing through arc zone and transfer the heat to the weld pool.

PAW uses the constant current type power source with DCEN polarity. The DCEN polarity is invariable used in PAW because tungsten electrode is used for developing the arc through which plasma forming gas is passed. Tungsten electrode has good electron emitting capability therefore it is made cathode. Further, DCEN polarity causes less thermal damage to the electrode during welding as about one third of total heat is generated at the cathode and balance two-third of arc heat is generated at the anode side i.e. work-piece. DCEP polarity does not help the process in either way. Current can vary from 2-200 A.

The plasma arc in PAW is not initiated by the conventional touch start method but it heavily depend on use of high frequency unit. Plasma is generated using two cycles approach a) producing very small high-intensity spark (pilot arc) within the torch body by imposing pulses of high voltage, high frequency and low current about 50A (from HF unit) between the electrode and nozzle which in turn generates a small pocket of plasma gas and then as soon as torch approaches the work-piece main current starts flowing between electrode and job leading to the ignition of the transferred arc. At this stage pilot is extinguished and taken off the circuit.

16.6 Types of PAW

Plasma generated due to the arc between the non-consumable electrode and work-piece is called transferred plasma whereas that due to arc between non-consumable electrode and nozzle is called non-transferred plasma. Non-transferred plasma system to a large extent becomes independent of nozzle to work piece distance.

Transferred plasma offers higher energy density than non-transferred plasma and therefore it is preferred for welding and cutting of high speed steel, ceramic, aluminium etc. Non-transferred plasma is usually applied for welding and thermal spray application of steel and other common metals. Depending upon the current, plasma gas flow rate, and the orifice diameter following variants of PAW has been developed such as:

- Micro-plasma (< 15 Amperes)
- Melt-in mode (15–400 Amperes) plasma arc
- Keyhole mode (>400 Amperes) plasma arc

Micro-plasma welding systems work with very low plasma forming current (generally lower than 15 A) which in turn results in comparatively low energy density and low plasma velocity. These conditions become good enough to melt thin sheet for plasma welding.

Plasma for melt-in mode uses somewhat higher current and greater plasma velocity than micro-plasma system for welding applications. This is generally used up to 2.4 mm thickness sheet. For thickness of sheet greater than 2.5 mm normally welding is performed using key-hole technique. The key hole technique uses high current and high pressure plasma gas to ensure key-hole formation. High energy density of plasma melts the faying surfaces of base metal and high pressure plasma jet pushes the molten metal against vertical wall created by melting of base metal and developing key-hole. Plasma velocity should be such that it doesn’t push molten metal out of the hole. The key is formed under certain combination of plasma current, orifice gas flow rate and velocity of plasma welding torch and any disturbance to above parameters will cause loss of key-hole. For key-holing, flow rate is very crucial and therefore is controlled accurately ± 0.14 liter/min. Nozzles are specified with current and flow rate.

16.7 Advantage of PAW

With regard to energy density, PAW stands between GTAW/GMAW and EBW/LBW accordingly it can be used using melt-in mode and key-hole mode. Melt-in mode results in greater heat input and higher width to depth of weld ratio than key-hole mode. Higher energy density associated with PAW than GTAW produces narrow heat affected zone and lowers residual stress and distortion related problems. High depth to width ratio of weld produced by PAW reduces the angular distortion. It generally uses about one tenth of welding current as compared to GTAW for same thickness therefore it can be effectively applied for joining of the thin sheets. Further, non-transferred plasma offers flexibility of variation in stand off distance between nozzle and work-piece without extinction of the arc.

16.8 Limitation of PAW

Infrared and ultra-violet rays generated during the PA welding are found harmful to human being. High noise (100dB) associated with PAW is another undesirable factor. PAW is a more complex, costlier, difficult to operate than GTAW besides generating high noise level during welding. Narrow width of the PAW weld can be problematic from alignment and fit-up point of view. Productivity of the PAW in respect of welding speed is found lower than LBW.

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Lecture 17

Metal Inert Gas Welding

This chapter presents the basic components and principle of metal inert gas welding (MIG) and pulse-MIG welding process with help of suitable schematic diagrams besides the influence of welding parameters in melting rate, and metal transfer. This process is also termed as gas metal arc welding (GMAW). Further, the factors affecting the metal transfer in MIG welding process have been elaborated.

Keywords: Metal inert gas welding, burn-off rate, electrode extension, metal deposition rate, metal transfer in GMAW, transition current, pulse GMAW

17.1 Fundamentals of MIG welding

This process is based on the principle of developing weld by melting faying surfaces of the base metal using heat produced by a welding arc established between base metal and a consumable electrode. Welding arc and weld pool are well protected by a jet of shielding inactive gas coming out of the nozzle and forming a shroud around the arc and weld. MIG weld is not considered as clean as TIG weld. Difference in cleanliness of the weld produced by MIG and TIG welding is primarily attributed to the variation in effectiveness of shielding gas to protect the weld pool in case of above two processes. Effectiveness of shielding in two processes is mainly determined by two characteristics of the welding arc namely stability of the welding arc and length of arc besides other welding related parameters such as type of shielding gas, flow rate of shielding gas, distance between nozzle and work-price. The MIG arc is relatively longer and less stable than TIG arc. Difference in stability of two welding arcs is primarily due to the fact that in MIG arc is established between base metal and consumable electrode (which is consumed continuously during welding) while TIG welding arc is established between base metal and non-consumable tungsten electrode. Consumption of the electrode during welding slightly decreases the stability of the arc. Therefore, shielding of the weld pool in MIGW is not as effective as in TIGW.

Metal inert gas process is similar to TIG welding except that it uses the automatically fed consumable electrode therefore it offers high deposition rate and so it suits for good quality weld joints required for industrial fabrication (Fig. 17.1). Consumable electrode is fed automatically while torch is controlled either manual or automatically. Therefore, this process is found more suitable for welding of comparatively thicker plates of reactive metals (Al, Mg, Stainless steel). The quality of weld joints of these metals otherwise is adversely affected by atmospheric gases at high temperature.

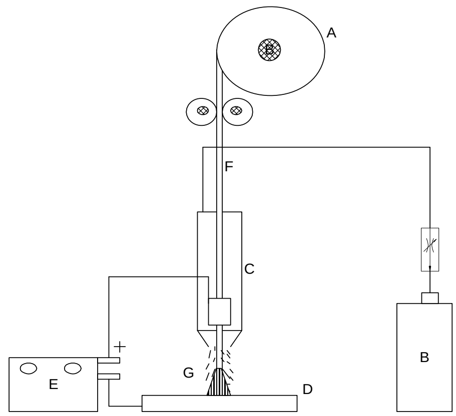

Fig. 17.1 Schematic of GMAW process showing important elements A) Welding spool, B) Shielding gas cylinder, C) welding torch, D) base plate, E) welding power source, and F) consumable electrode.

17.2 Power source for MIG welding

Depending upon the electrode diameter, material and electrode extension required, MIG welding may use either constant voltage or constant current type of the welding power source. For small diameter electrodes (< 2.4 mm) when electrical resistive heating controls the melting rate predominantly, constant voltage power source (DCEP) is used to take advantage of the self regulating arc whereas in case of large diameter electrode constant current power source is used with variable speed electrode feed drive system to maintain the arc length (Fig. 17.2).

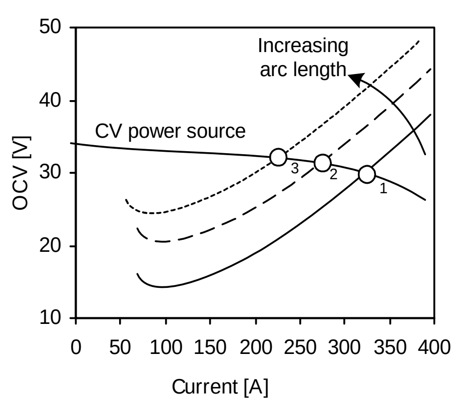

Fig. 17.2 Static characteristics of constant voltage power source showing effect of arc length on operating point

17.3 Shielding gases for MIG welding

Like TIG welding, shielding gases such as Ar, He, CO_2 and their mixtures are used for protecting the welding pool from the atmospheric gases. Effect of the shielding gases on MIG weld joints is similar to that of TIG welding. Inert gases are normally used with reactive metal like Al, Mg and while carbon dioxide can be used for welding of steel for reasonably good quality of weld joints. Application of CO_2 in welding of reactive none-ferrous metal is not preferred as decomposition of CO_2 in arc environment produces oxygen. Interaction of oxygen with reactive metals like Al and Mg (which show greater affinity to the oxygen) form refractory oxides having higher melting point than the substrate which interferes with melting as well as increases the inclusion formation tendency in the weld metal. Moreover, shielding gases in MIGW also affect the mode of metal transfer from the consumable electrode to the weld pool during welding (Fig. 17.3). MIG welding with Ar as shielding gas results in significant change in the mode of metal transfer from globular to spray and rotary transfer with maximum spatter while He mainly produces globular mode of metal transfer. MIG welding with CO_2 results in welding with a lot of spattering. Shielding gas also affects width of weld bead and depth of penetration owing to difference in heat generation during welding.

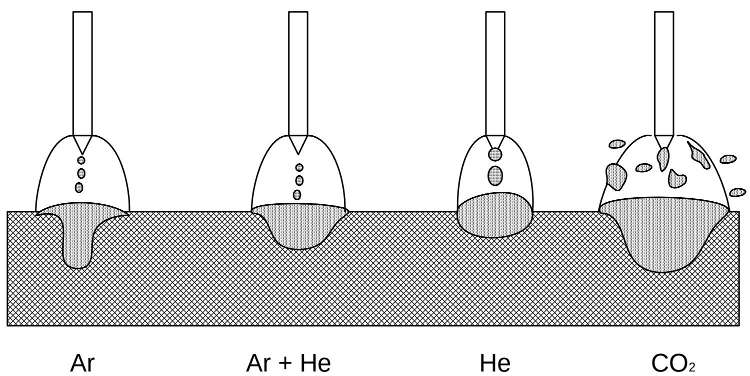

Fig. 17.3 Schematic showing influence of shielding gas on mode of metal transfer

17.4 Effect of MIG welding process parameters

Among various welding parameters such as welding current, voltage and speed probably welding current is most influential parameters affecting weld penetration, deposition rate, weld bead geometry and quality of weld metal (Fig. 17.4). However, arc voltage directly affects the width of weld bead. An increase in arc voltage in general increases the width of the weld. Welding current is primarily used to regulate the overall size of weld bead and penetration. Too low welding current results pilling of weld metal on the faying surface in the form of bead instead of penetrating into the work piece. These conditions increase the reinforcement of weld bead without enough penetration. Excessive heating of the work piece due to too high welding current causes weld sag. Optimum current gives optimum penetration and weld bead width.

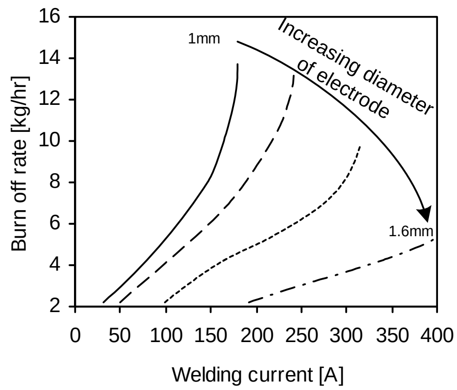

Fig. 17.4 Effect of welding current on melting of electrode of different diameters

Stick out of the electrodes (electrode extension) affects the weld bead penetration and metal deposition rate because it changes the electrode heating due to electric resistance. Increase in stick out increases the melting rate and reduces the penetration due to increased electrical resistive heating of the electrode itself. Selection of welding current is influenced by electrode stick out and electrode diameter. In general, high welding current is preferred for large diameter electrodes with small electrode extension in order to obtain optimal weld bead geometry (Fig.17.5). Increase in welding speed reduces the penetration.

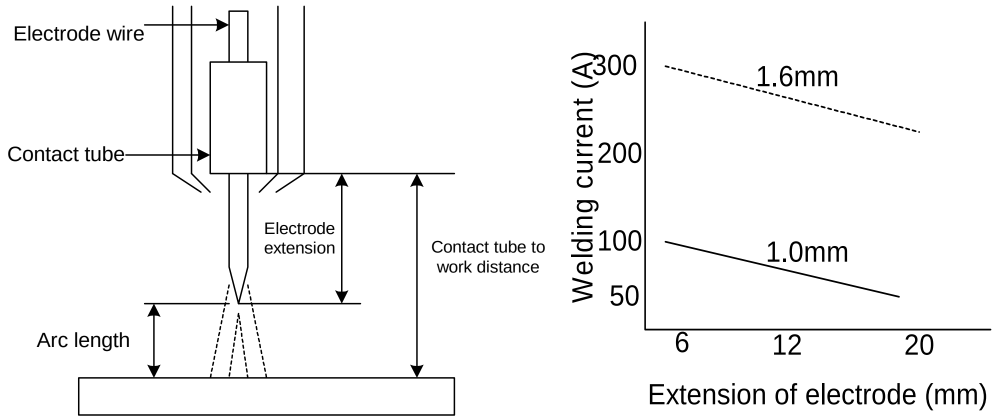

Fig.17.5 Schematic diagram showing a) electrode extension and b) effect of electrode extension on welding current for different electrode diameters

17.5 Metal transfer in MIG welding

Metal transfer during MIG welding depending up on the welding current, electrode diameter and shielding gas can take place through different modes such as short circuit, globular, spray (Fig. 17.6). Mechanisms for these metal transfer modes have already been describe and rotational transfer in section8.2.

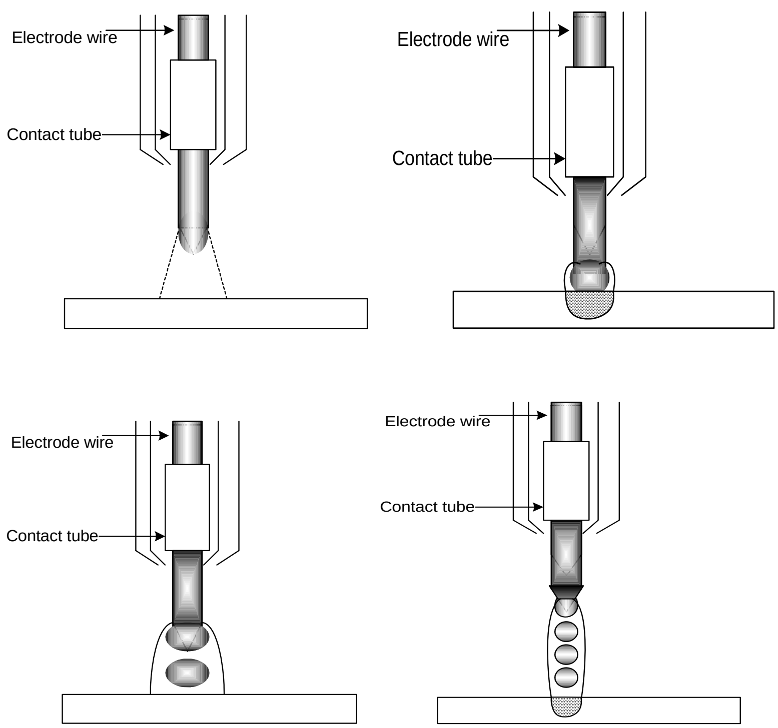

Fig. 17.6 Schematic of modes of metal transfer in MIG welding a) typical set, b) short circuiting transfer, c) globular transfer, and c) spray transfer

Increase in welding current changes mode of metal transfer from short circuiting to globular to spray transfer specially when Ar is used as a shielding gas(Fig. 17.7). Increase in welding current (over a narrow range) leads to significant increase in drop transfer rate per unit time coupled with reduction volume of drops being transferred due to two reasons a) increase in melting rate of the electrode and b) increase in pinch force. This current is called transition current at which major change in mode of metal transfer from globular to spray takes place.

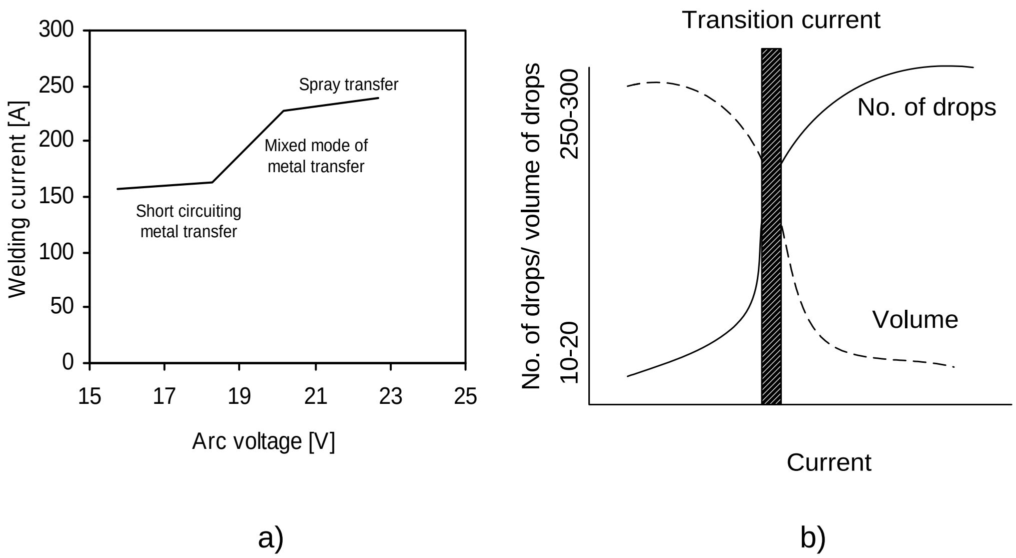

Fig. 17.7 Effect of a) welding parameters on modes of metal transfer and b) on number/volume of drops vs. welding current during metal transfer

17.6 Pulse MIG Welding

Pulse MIG welding is a variant of metal inert gas welding. Pulse MIG welding is also based on the principle of pulsation of welding current between a high and a low level at regular time intervals like Pulse TIG welding (Fig. 17.8). However, back ground and peak current perform slightly different roles. The low level current also called background current is mainly expected just to maintain welding arc while high level welding current called peak current is primarily used for a) melting of faying surfaces with desired penetration of the base metal and b) high melting rate of electrode and c) detachment of molten droplets hanging to the tip of the electrode by pinch force to facilitate spray transfer. An optimum combination of pulse parameters results in transfer of one molten metal drop per peak pulse. This feature of current pulsation in pulse MIG welding reduces net heat input to the base metal during welding which in turn facilitates welding of especially thin sheets and odd position welding.

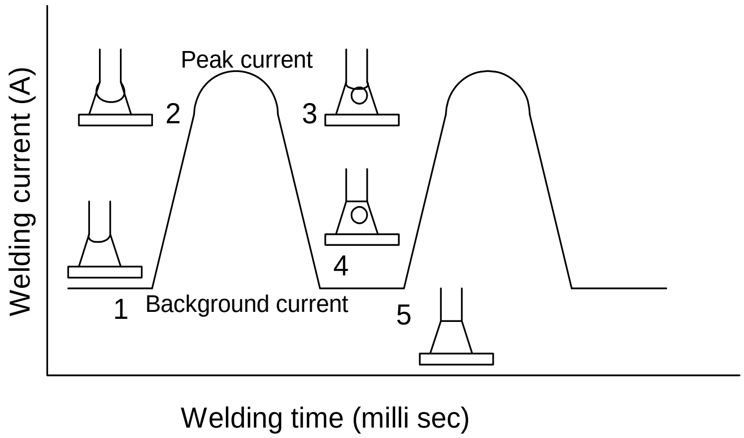

Fig. 17.8 The relationship between the welding current and time with metal drop formation tendency

17.7 Flux cored arc welding process

The flux cored arc welding (FCAW) is another variant of gas metal arc welding process. Like GMAW, this process mainly uses constant voltage power supply. The FCAW uses a tubular electrode filled with flux and other constituents that decompose at high temperature in arc environment to produce inactive gases to protect the weld pool and arc zone from contamination by atmospheric gases (Fig. 17.9). The role of flux in FCAW process is also similar to shielded metal arc welding, however unique feature of filling of flux in continuously fed tubular electrode associated with this process for welding gives freedom from regular stoppage of welding for replacement of electrode. This in turn results in high welding speed and productivity. Since protective gases are generated in the arc environment itself therefore ambient air flow/turbulence doesn't affect the protection of the weld pool appreciably.

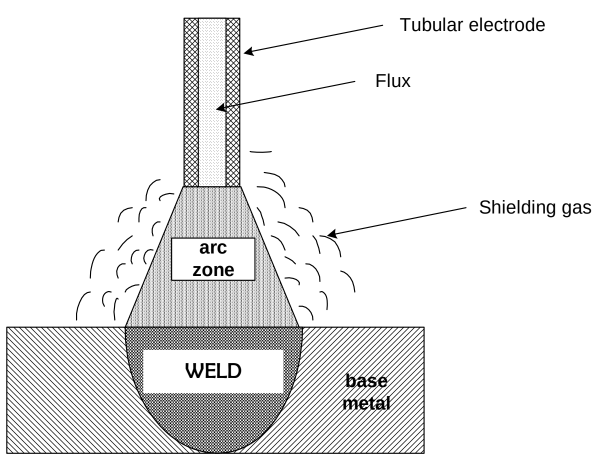

Fig. 17.9 Schematic of FCAW process without shielding gas

This process also used in two ways a) FCAW without shielding gas and b) FCAW with external shielding gas arrange like GMAW. The FCAW process with shielding gas results in somewhat more sound weld with better mechanical properties than FCAW without shielding gas owing to the possibility of formation of few weld discontinuities in weld metal like porosity, slag inclusion etc. in later case. FCAW without shielding gas suffers from a) poor slag detachability, b) porosity formation tendency, c) greater operator-skill requirement and d) emission of harmful noxious gases and smokes imposes need of effective ventilation. Further, excessive smoke generation in case of FCAW without shielding gas can reduce visibility of weld pool during welding which can make the process control difficult. FCAW with external shielding gas provide much better protection to the welding pool and arc zone. FCAW is commonly used for welding of mild steel, structural steel, stainless steel and nickel alloys.

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Lecture 18

Brazing, soldering and Friction Stir Welding

This chapter presents the basic concept of brazing and soldering processes and fabrications conditions where these joining processes are found suitable. Further, brazing filler, flux and temperature have also been described. A solid state a newly developed friction stir welding process has also be presented briefly.

Keywords: Brazing, soldering, joint design, clearance, brazing flux, brazing filler, brazing temperature, friction stir welding and processing

18.1 Basics of Brazing and Soldering

Brazing and soldering both are solid liquid processes primarily involve three steps a) heating of plates to be joined using suitable heat source, b) placing and melting of solder or brazing materials followed by heating to the molten state and c) filling of molten filler metal between the faying surfaces of the components to be joined by capillary action and then solidification results in a joint. These three steps are schematically shown in Fig. 18.1 (a-c). An attractive feature of these processes is that a permanent joint produced without melting of parent work pieces. Owing to this typical feature of developing a joint, brazing and soldering are preferred under following situations.

1. Metallurgical incompatibility: Joining of metals having entirely different physical, chemical and mechanical characteristics
2. Poor Weldability: Joining of metals of poor weldability in fusion welding due to cracking tendency, chemical reactivity to ambient gases etc.
3. Unfavorable HAZ: Heat affected zone formed in metal being welded by fusion welding process due to weld thermal cycle causes excessive hardening or softening thus making it not acceptable
4. Odd position welding: Locations of joint which do not allow application of conventional fusion welding technique due to working difficulties like melting of faying surfaces, placing molten metal in places where it is required.
5. Light service conditions: Joint is not expected to take high load & temperature, other adverse atmospheric conditions.

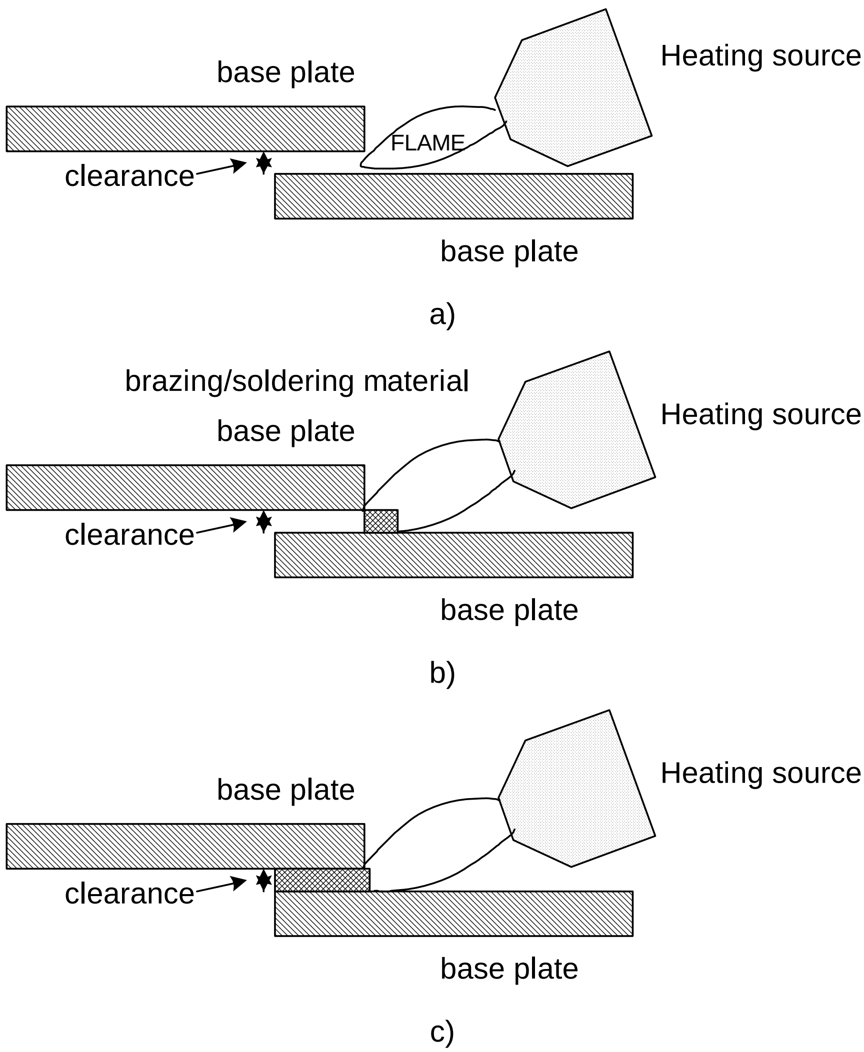

Fig. 18.1 Schematic of Step used for brazing and soldering process a) heating of plates, b) placing brazing/soldering metal and heating and c) filling of molten metal by capillary action followed by solidification

18.2 Joints for Brazing and Soldering

Lap joint is commonly developed using both the techniques. Clearance (0.075-0.125mm) between the plates to be joined is of great importance as it affects the capillary action and so distribution of joining metal between the faying which in turn affects the strength of joint (Fig. 18.2a). Both too narrow clearance and too wide clearance reduce sucking tendency of liquid joining metal by capillary action. To ensure good and sound joint between the sheets, surfaces to be joined must be free from impurities to ensure proper capillary action. Butt joint can also be developed between the components with some edge preparation primarily to increase the contact area between the plates to be joined (Fig. 18.2b).

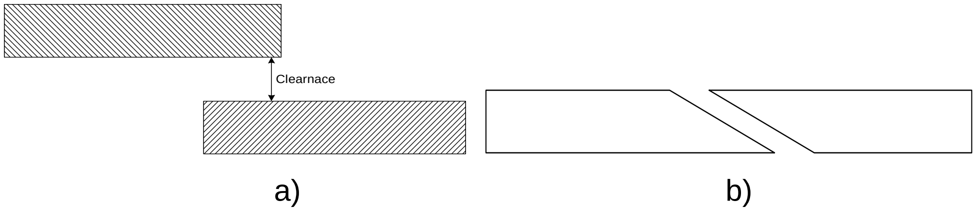

Fig. 18.2 Schematic of lap joint for brazing and soldering

18.3 Comparison of brazing and soldering

Both these solid/liquid joining processes can be compared in respect of various factors such as melting point of filler and strength of joint, ability to withstand at high temperature, heating source for developing joint and their applications.

18.3.1 Melting point of filler

Soldering uses the filler metal system having low melting point (183-275^0 C generally than 450^{0}C) called solder (alloy of lead and tin) while brazing uses comparatively higher melting point (450-1200^{0}C) filler metals (alloys of Al, Cu and Ni).

18.3.2 Strength of Joint

Strength of solder joint is limited by the strength of filler metal. In general, brazed joints offer greater strength than solder joints. Accordingly, brazed joints are used for somewhat higher loading conditions than solder joint.

18.3.3 Ability to withstand under high temperature conditions

In general, braze joints offer higher resistance to thermal load than soldered joint primarily due to difference in melting temperature of solder and braze metal. Therefore, solder joints are preferred mainly for low temperature applications.

18.4 Application

Soldering is mostly used for joining electronic components where they are normally not exposed to severe temperature and loading conditions during service. Brazing is commonly used for joining of tubes, pipes, wires cable, and tipped tool.

Common filler metals with brazing temperatures and applications

Filler metal	Al-Si	Cu	Cu-P	Cu-Zn	Au-Ag	Ni-Cu
Brazing temperature (^oC)	600	1120	850	925	950	1120
Parent metal	Al	Ni & Cu	Cu	Steel, cast iron, Ni	Stainless steel, Ni	Stainless steel, NI

Common soldering fillers and their applications

Solders	Applications
Tin-Lead (Sn-Pb)	General Purpose
Tin-Zinc (Sn-Zn)	Aluminum
Tin-Silver (Sn-Ag)	Electronics
Tin-Bismuth (Sn-Sb)	Electronics
Lead-Silver (Pb-Ag)	Strength at Higher Temperatures
Cadmium-Silver (Cd-Ag)	Strength at Higher Temperatures
Zinc-Aluminum (Zn-Al)	Aluminum; Corrosion resistance

18.5. Source of Heat for Joining

Soldering can be carried out using heat from soldering iron (20-150W), dip soldering and wave soldering. Brazing can performed using gas flame torch, furnace heating, induction heating, and infrared heating methods.

18.6 Limitation of Brazing and Soldering

These processes have major limitation of poor strength and inability to withstand at higher temperature with some possibility of colour mismatch with parent metals.

18.7 Role of flux in brazing

Fluxes react with impurities present on the surface of base metal or those formed during joining to form slag apart from reducing contamination of the joints from atmospheric gases (formation of oxides and nitrides due to atmospheric gases). For performing above role effectively fluxes should have low melting point and molten filler should have low viscosity. Fluxes applied over the surface of work piece for developing joint must be cleaned from the work surface after brazing/soldering as these are corrosive in nature.

18.7 Friction stir welding and processing

The friction stir welding is a comparatively new solid state joining process developed by the Welding Institute U.K. in 1991. This process is based on the simple principle of thermal softening of metal followed by sever plastic deformation to develop a weld joint. The thermal softening is facilitated by heat generation from two sources a) friction between tool and base metal and b) plastic deformation. The development of weld joints is facilitated by transport of metal from one side to another followed by consolidation by forging action (Fig. 18.3). To ensure proper performance of tool, its material must be strong and heat and wear resistant. The typical solid state joining feature of this process lowers undesirable effects of common fusion weld thermal cycle. This process is common applied for developing butt joints. The friction stir-welding has been applied in many ways for producing other weld configuration like T joints and Lap joints. Friction stir spot welding is one of the typical variant of friction stir welding used for producing lap joints. The strength of friction stir spot weld joints is found comparable or even better than spot weld joints in lap weld configuration.

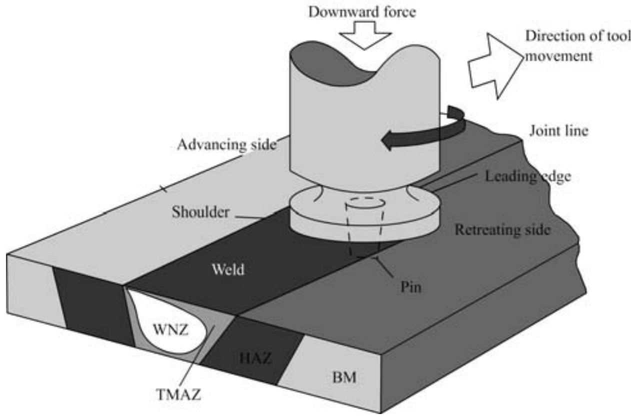

Fig. 18.3 Schematic of friction stir welding showing different parts of tool and zones of weld joints (Steve Hensley, Modern Machine Shop, 2008)

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Lecture 19

Heat Flow in Welding I

This chapter describes the need of studying the heat flow in welding and concept of weld thermal cycle. Different factors related with welding affecting the weld thermal cycle have been elaborated. Further, the need of evaluating the cooling rate during welding of hardenable steels has also been presented.

Keywords: Weld thermal cycle, cooling rate, continuous cooling transformation, critical cooling rate

19.1 Importance

Arc welding processes involve the melting of the faying surfaces and the filler metal, if any, followed by solidification of the molten weld metal. Melting and solidification steps of welding are associated with the flow of heat and are affected by rate of heat transfer in and around the weld metal. Metallurgical structure of metal in weld and region close to the weld metal is mainly determined by the extent of rise in temperature and then cooling rate experienced by the metal at particular location of HAZ and weld. Further, differential heating and cooling experienced of different zones of weld joint cause not only metallurgical heterogeneity but also non-uniform volumetric change which in turn produces the residual stresses. These residual stresses adversely affect the mechanical performance of the weld joint besides distortion in the welded components if proper care is not taken. Since heating, soaking and cooling cycle affect the metallurgical & mechanical properties, development of residual stresses and distortion of the weld joints therefore it is pertinent to study various aspects related with heat flow in welding such as weld thermal cycle, cooling rate and solidification time, peak temperature, width of heat affected zone. Further, mechanisms of development of residual stresses and common methods relieving residual stresses apart from the distortion and their remedy will be discussed in this chapter on heat flow in welding.

19.2 Weld Thermal Cycle

Weld thermal cycle shows variation in temperature of a particular location (in and around the weld) during the welding as a function of welding time. As the heat source (welding arc or flame) approaches close to the location of interest first temperature increases heating regime followed by gradual decrease in temperature cooling regime. A typical weld thermal cycle shows (Fig. 19.1) the rate of heating (slope of a b), peak temperature, and time required for attaining the peak temperature, cooling rate (slope of b c). Since distance of the point of interest away from the weld centerline directly affects all the above parameters heating and cooling rate, peak temperature of weld thermal cycle therefore each location/point offers different and unique weld thermal cycle (Fig. 19.2). In general, an increase in distance of point of interest away from the weld centre-line:

– decreases the peak temperature
– decreases the rate of heating and cooling
– increases time to attain peak temperature
– decreases rate of cooling with increase in time

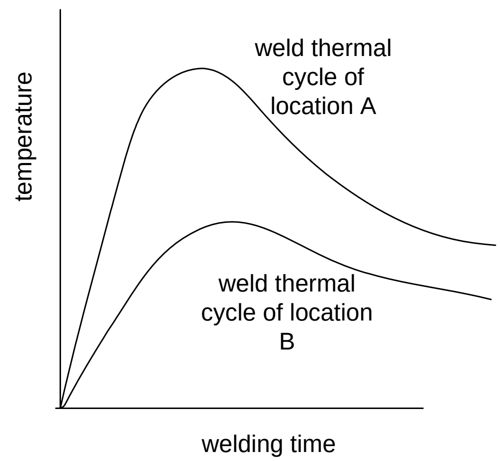

Fig. 19.1 Schematic of weld thermal cycle of two different locations away from the weld centerline

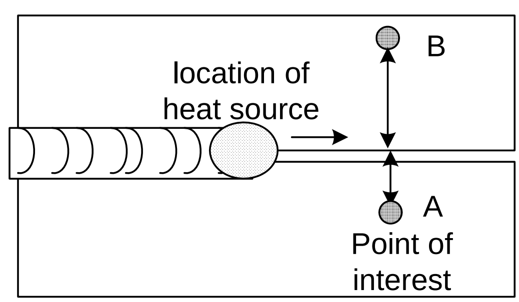

Fig. 19.2 Schematic of welding showing location of two points A & B

19.2.1 Factors affecting welding thermal cycle

However, weld thermal cycle varies with distance form the weld centre line but it is also influenced by heat input rate, amount of heat supplied for welding, weldment geometry, thermal properties of base metal and initial plate temperature. Rate of heat input is primarily governed by the energy density of heat input source which to a great extent depends upon the welding process being used for development of weld joints besides the welding parameters. High energy density processes like plasma arc welding and laser beam welding offer higher rate of heating, peak temperature and cooling rates than low energy density processes such as gas welding, shielded metal arc welding as shown in Fig. 19.3. Higher is the energy density of welding process, lower will be the heat input. Weld geometry parameters such as thickness of plates being welded also affect the heating rate, soaking time and cooling rate for a given rate of heat input (welding parameters) owing to changes in heat transfer conditions. In general, an increase in thickness of plate increases the rate of heat transfer from the weld pool/heat affected zone to the base metal which in turn a) decreases the high temperature retention time of HAZ, b) decreases the solidification time and c) increases the cooling rate experienced by the HAZ and weld metal.

Thermal properties of metal like thermal conductivity and specific heat also have affect on weld thermal cycle similar to that of thickness of plates as they increase the rate of heat transfer from the weld metal and HAZ. Preheating of the plates reduces the rate of heating and cooling and increases the peak temperature and soaking period above certain temperature because preheating reduces the rate of heat transfer away from the weld zone.

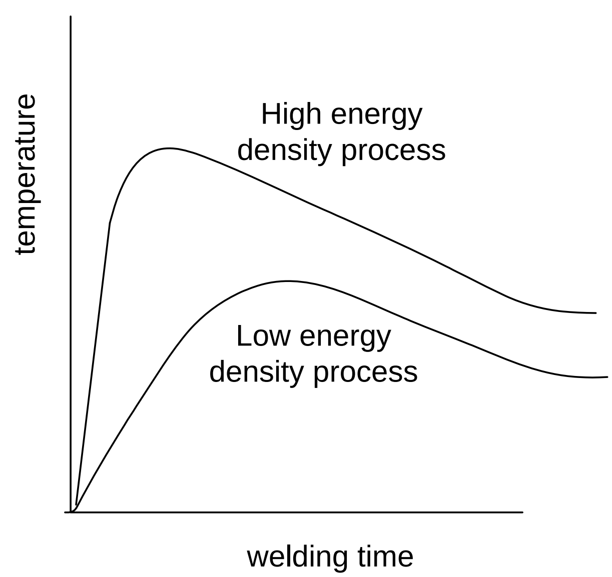

Fig. 19.3 Influence of energy density of heat source related with welding process on weld thermal cycle of HAZ.

Peak temperature near the weld fusion boundary decides the width of heat affected zone (HAZ). Heating and cooling rate affect the microstructure of weld metal and HAZ therefore weld thermal cycle of each point becomes of great interest especially in structure sensitive metals like high carbon steels.

19.3 Cooling Rate

The final microstructure of weld zone and HAZ is primarily determined by the cooling rate (CR) from the peak temperature attained due to weld thermal cycle during welding. Cooling rate above a particular temperature say 550^{o}C for plain carbon eutectoid steel is of great importance in case of hardenable steel where a cooling rate (CR) determines the final microstructure and mechanical properties of weldment and HAZ. Since microstructure of hardenable steel has direct correlation with mechanical properties therefore, structure sensitive mechanical properties are affected by the cooling rate experienced by the weld metal and heat affected zone. This is evident from the continuous cooling diagram of hypo-eutectoid steel as shown in Fig. 19.4. In the diagram, letter A, F, P, B, M indicates regions of austenite, ferrite, pearlite, bainite and martensite respectively.

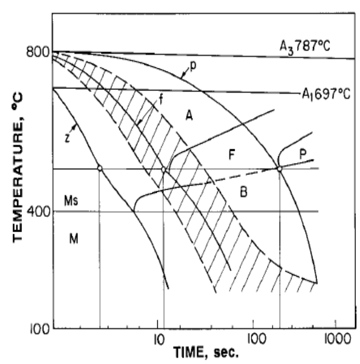

Fig. 19.4 Effect of cooling on structure of weld joints shown in form of CCT diagram (S Kou, 2003)

Weld thermal cycle indicates both heating and cooling rate. Cooling rate varies as a function of time, location of point of interest and temperature (at any moment on commencement of the cooling) during cooling regime of weld thermal cycle. The cooling rate calculation for HAZ of hardenable steel weld joint is mostly made at 550 ^{0}C (corresponding to nose temperature of CCT) as cooling rate at this temperature predominantly decides the end microstructure and mechanical properties of the HAZ and weld joint. During welding, two welding parameters dictate the cooling rate a) net heat input during the welding and b) initial plate temperature besides the thermal and dimensional properties of material being welded. In general, increases in heat input decreases the cooling rate while reverse happens with increase of initial plate temperature during welding of a given metal having specific thickness and thermal properties. An increase in both heat input and initial plate temperature raises temperature of base metal around the weld which in turn decreases the rate of transfer away from the weld zone primarily due to reduction in temperature difference between the weld zone and surrounding base metal. Reduction in heat transfer rate from the weld metal to the base metal with increase in heat input and initial plate temperature means decrease in cooling rate. In view of above, major practical application of cooling rate equation is to determine the preheat requirement for plate to be welded so as to avoid critical cooling rate in weld and HAZ.

Net heat input (H_{net}) during welding is obtained using following relationship:

$$H_{net} = f\ .VI/S$$

where V is arc voltage (V), I welding current (A) and S welding speed mm/sec and f is the fraction of heat generated and transferred to the plate.

Example

Calculate the net heat input used during welding of plates if welding of steel plate is given below:

- Welding current: 150 A
- Arc voltage: 30 V
- Welding speed: 0.5 mm/sec
- 80 % of heat generated by the arc is used for welding.

Solution

Net heat input : Hnet = f .VI/S

= 0.8 X 30 X150/0.5

= 600 J/mm

= 0.6 kJ/mm

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Lecture 20

Heat flow in welding II

This chapter describes method of calculating the cooling rate in HAZ during welding of thick and thin plates besides that of critical cooling rate for steel under welding conditions. Further, significance of peak temperature in heat affected zone and solidification time of weld metal for development of sound weld joint has also been presented.

Keywords: Peak temperature, solidification time, width of HAZ, weld structure

20.1 Calculations of cooling rate

Thickness of the plate to be welded directly affects the cross sectional area available for the heat flow from the weld which in turn governs cooling rate of a specific location. Accordingly, two different empirical equations are used for calculating the cooling rate in HAZ for a) thin plates and b) thick plates, depending upon the thickness of plate and welding conditions. There is no clear demarcating thickness limit to define a plate thick or thin. However, two methods have been proposed to take decision whether to use thick or thin plate equation for calculating the cooling rates and these are based on

1) number of passes required for completing the weld
2) relative plate thickness

According to first method, if number of passes required for welding of two plates is less than 6 then it is considered as thin plate else thick plate for selection of suitable equation to calculate cooling rate. Since this method is not very clear as number of passes required for completing the weld can vary with diameter of electrode and groove geometry being used for welding, therefore a more logical second method based on relative plate thickness criterion is commonly used. The relative plate thickness criteria is more logical as it considers all the relevant factors which can affect the cooling rate such as thickness of the plate (h), heat input (Hnet), initial plate temperature (To), temperature of interest at which cooling rate is desired (Ti) and physical properties of plate like (specific heat C, density ρ). Relative plate thickness (τ) can be calculated using following equation: $h\{\rho C(T_i - T_o)/H_{net}\}^{1/2}$

Thin plate cooling rate equation is used when relative plate thickness $\tau < 0.6$ and thick plate cooling rate equation is used when $\tau > 0.9$. If value of τ is in range of 0.6 to 0.9 then 0.75 is used as a limit value to decide the cooling rate equation to be used.

Cooling rate (R) equation for thin plates: $\{2\pi k\rho C\ (h/\ H_{net})(T_i - T_o)^3\}\ ^0C/sec$…..(1)

Cooling rate (R) equation for thick plates: $\{2\pi k(T_i - T_0)^2\}/H_{net}\ ^0C/sec$ ………………(2)

Where h is the plate thickness (mm), k is thermal conductivity, ρ is the density (g/cm^3), C is specific heat ($kCal/^0C.g$), T_i is the temperature of interest (^0C), and T_o is the initial plate temperature (^0C).

Cooling rate equations can be used to a) calculate the critical cooling rate (CCR) under a given set of welding conditions and b) determine the preheat temperature requirement for the plate in order to avoid the CCR.

20.2 Critical cooling rate (CCR) under welding conditions

To determine the critical cooling rate for a steel plate under welding conditions, bead on plate welds are made with varying heat input. On the basis of thickness of the plate (5 mm) to be welded suitable electrode diameter is chosen first and then accordingly welding current and arc voltage are selected (20V, 200A, $T_o=30^0C$) for bead-on-plate (BOP) welding. Number of BOP welds is deposited using increasing welding speed (8, 9, 10, 11, 12……mm/sec). Once the BOP weld is completed at different welding speed, transverse section of weld is cut to measure the hardness. Thereafter, hardness vs. welding speed plot is made to identify the welding speed above which abrupt increase in hardness of the weld and HAZ takes place. This welding speed is identified as critical welding speed (say 10mm/min in this case) above which cooling rate of the weld & HAZ becomes greater than critical cooling rate. This abrupt increase in hardness of the weld and HAZ is attributed to martensitic transformation during welding as cooling rate becomes greater than critical cooling rate owing to the reduction in heat input (H_{net}) with increase of welding speed. Using welding conditions corresponding to this critical welding speed for a given steel plate, critical cooling rate can be calculate using appropriate cooling rate equation.

Corresponding H_{net} = f X VI/S = 0.9 X 20 X 200 /10 = 360 J/mm or 0.36 kJ/mm.

Calculate relative plate thickness (RPT) parameter for these conditions: $h\ [(Ti-T0)C/Hnet]^{1/2}$: 0.31

RPT suggests use of thin plate equation for calculating the cooling rate: $2\pi k\rho c(h/Q)(tc-to)^3$

Cooling Rate (R): 5.8 $^0C/s$ and it will be safer to consider CCR: 6 $^0C/s$

Similarly these equations can also be used for calculating the cooling rate or identifying the preheat temperature to avoid CCR for a particular location under -a- given set of welding conditions.

20.3 Peak temperature and Heat Affected Zone

The weld thermal cycle of a particular location exhibits peak temperature and cooling rate as function of time apart from other factors.

Peak temperature distribution around the weld-centre line determines a) shape of the weld pool, b) size of heat affected zone and c) type of metallurgical transformation and so mechanical properties of weld and HAZ.

Variation in heat input and initial plate temperature affects the peak temperature distribution on the plates along the weld line during welding. An increase in heat input by increasing the welding current (for a given welding speed) in general increases the peak temperature of a particular location and makes the temperature distribution equal around the welding arc (almost circular or oval shape weld pool). Increase in welding speed however makes the weld pool (peak temperature distribution) of tear drop shape (Fig. 20.1).

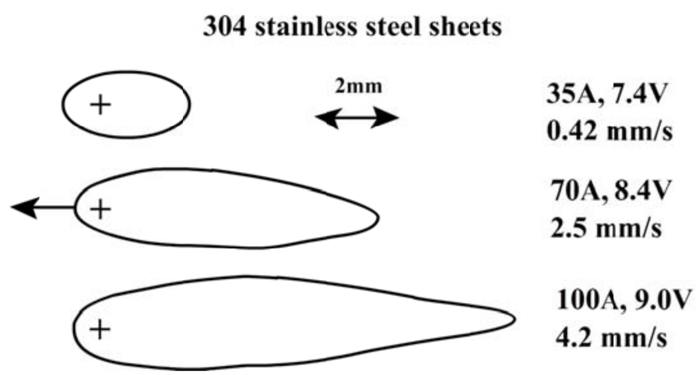

Fig. 20.1 Effect of welding parameters on weld pool profile as dictated by peak temperature

Cooling from the peak temperature determines final microstructure of the weld and heat affected zone. Therefore, peak temperature in the region close to the fusion boundary becomes of great engineering importance as metallurgical transformations (hence mechanical properties) at a point near fusion boundary are influenced by peak temperature (Fig. 20.2). Peak temperature at any point near the fusion boundary for single pass full penetration weld can be calculated using following equation.

$$1/(t_p - t_o) = (4.13 \rho c h Y / H_{net}) + (1/(t_m - t_o)) \quad (3)$$

Where t_p is peak temperature in ºC, t_o is initial temperature in ºC, t_m is melting temperature in ºC, H_{net} is net heat input, J/mm, h is plate thickness in mm, Y is width of HAZ in mm and ρc is volumetric specific heat (J/mm^3 ºC).

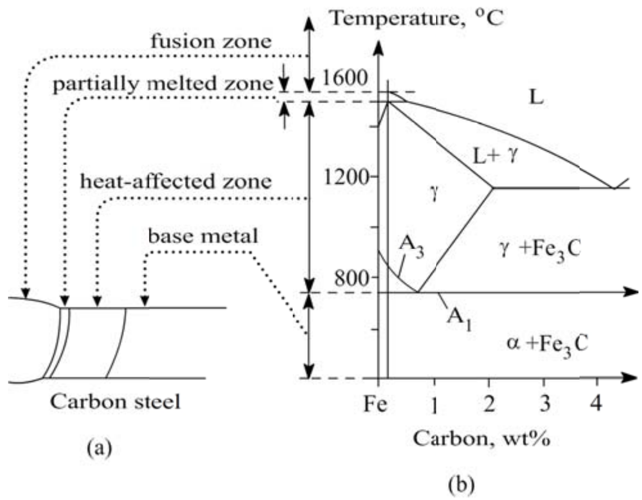

Fig. 20.2 Schematic showing relationship between Fe-C diagram and different zones of weld joints (S Kou, Welding metallurgy, 2003)

This equation can be used for a) calculating peak temperature at a point away from the fusion boundary, b) estimating width of heat-affected zone and c) studying the effect on initial plate temperature/preheating and heat input on width of HAZ. Careful observation of equation reveals that an increase in initial plate temperature and net heat input will increase the peak temperature at y distance from the fusion boundary and so width of heat affected zone.

To calculate the width of HAZ, it is necessary to mention the temperature of interest/ critical temperature above which microstructure and mechanical properties of a metal will be affected by application of welding heat. For example, the plain carbon steels are subjected to metallurgical transformation above 727 ^{0}C i.e. lower critical temperature, hence temperature of interest/ critical temperature for calculating of HAZ width becomes 727 ^{0}C. Similarly, a steel tempered at 300^{0}C after quenching treatment whenever heated to a temperature above 300 ^{0}C, it is over-tempered so the structure and properties are affected hence for quenched and tempered steel, tempering temperature (300^{0}C) becomes the critical temperature.

A single pass full penetration weld pass is made on steel plates having ρc=.0044 J/mm^3 ºC, t=5 mm, t_p=25ºC, t_m=1510ºC, Q=720J/mm. Calculate the peak temperatures at 3.0 mm and 1.5 mm and 0 mm distance from the fusion boundary.

On replacing of values of different factors, in $1/(t_p-t_o) = (4.13\rho chY / H_{net}) + (1/(t_m-t_o))$ the peak temperature at distance 3 mm, 1.5 mm and 0 mm is obtained as 1184 ºC, 976ºC and 1510 ºC respectively.

20.4 Solidification Rate

The solidification of weld metal takes place in three stages a) reduction in temperature of liquid metal, b) liquid to solid state transformation and c) finally reduction in temperature of solid metal up to room temperature. The time required for solidification of weld metal depends up on the cooling rate. Solidification time is the time interval between start to end of solidification. Solidification time is also of great importance as it affects the structure, properties and response to the heat treatment of weld metal. It can be calculated using following equation:

Solidification time of weld $(S_t) = LQ/2\pi k\rho c(t_m-t_o)^2$ in sec……………………(5)

Where L is heat of fusion (for steel 2 J/mm^3)

Above equation indicates that solidification time is the function of net heat input, initial plate temperature and material properties such as latent heat of fusion (L), thermal conductivity (k), volumetric specific heat (ρC) and melting point (t_m). Long solidification time allows each phase to grow to a large extent which in turn results in coarse-grained structure of weld metal. An increase in net heat input (with increase in welding current / arc voltage or reduction in welding speed) increases the solidification time. An increase in solidification time coarsens the grain structure which in turn adversely affects the mechanical properties. Non-uniformity in solidification rates in different regions of molten weld pool also brings variation in grain structure and so mechanical properties. Generally, centerline of the weld joint shows finer grain structure (Fig. 20.3) and better mechanical properties than those at fusion boundary primarily because of difference in solidification times. Micrographs indicate the coarser structure near the fusion boundary than the weld center.

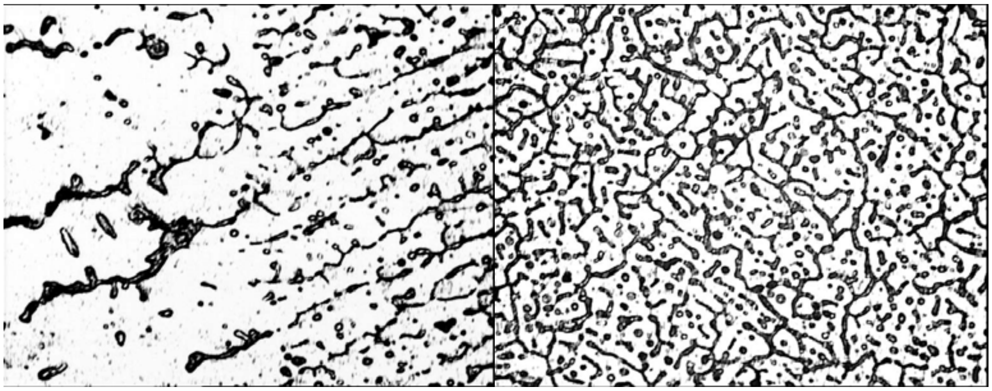

Fig. 20.3 Variation in microstructure of weld of Al-Si alloys of a) fusion boundary and b) weld centre owing to difference in cooling rate (200X)

Example

A single pass full penetration weld pass is made using net heat input at the rate of 500 J /mm on steel having ρc=.0044 J/mm^3 ºC, t=5mm, to=25ºC, tm=1540ºC, and thermal conductivity k= 0.025 J/mm.s. ºC and latent heat of fusion 2.4 J/mm^3. Determine the solidification time.

Solution

Solidification time: LQ/2πkρc(tm-to)^2 in sec

Solidification time: 2.4 X 500/(2π X 0.025 X 0.0044 (1540-25)2 in sec

Solidification time : 1200/1585.54

Solidification time : 0.75 sec

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Lecture 21

Residual stresses in weld joints

This chapter defines residual stresses, and describes the mechanisms of development residual stress in weld joints. Further, the influence of residual stress on performance of weld joints has also been elaborated. Methods of controlling the residual stresses have also been presented.

Keywords: Residual stresses, transformation stress, thermal stress, quench stress, distortion, SCC, control of residual stress

21.1 Residual stresses

Residual stresses are locked-in stresses present in the engineering components even when there is no external load and these develop primarily due to non-uniform volumetric change in metallic component irrespective of manufacturing processes such as heat treatment, machining, mechanical deformation, casting, welding, coating etc. However, maximum value of residual stresses doesn't exceed the elastic limit of the metal because stresses higher than elastic limit leads to plastic deformation and thus residual stresses greater than elastic limit are accommodated in the form of distortion of components. Residual stresses can be tensile or compressive depending up on the location and type of non-uniform volumetric change taking place due to differential heating and cooling like in welding and heat treatment or localized stresses like in contour rolling, machining and shot peening etc.

21.2 Residual stresses in welding

Residual stresses in welded joints primarily develop due to differential weld thermal cycle (heating, peak temperature and cooling at the any moment during welding) experienced by the weld metal and region closed to fusion boundary i.e. heat affected zone (Fig. 21.1). Type and magnitude of the residual stresses vary continuously during different stages of welding i.e. heating and cooling. During heating primarily compressive residual stress is developed in the region of base metal which is being heated for melting due to thermal expansion and the same (thermal expansion) is restricted by the low temperature surrounding base metal. After attaining a peak value compressive residual stress gradually decreases owing to softening of metal being heated. Compressive residual stress near the faying surfaces eventually reduces to zero as soon as melting starts and a reverse trend is observed during cooling stage of the welding. During cooling as metal starts to shrink, tensile residual stresses develop (only if shrinkage is not allowed either due to metallic continuity or constraint from job clamping) and their magnitude keeps on increasing until room temperature is attained. In general, greater is degree of constraint and elastic lami of melt higher will be the value of residual stresses.

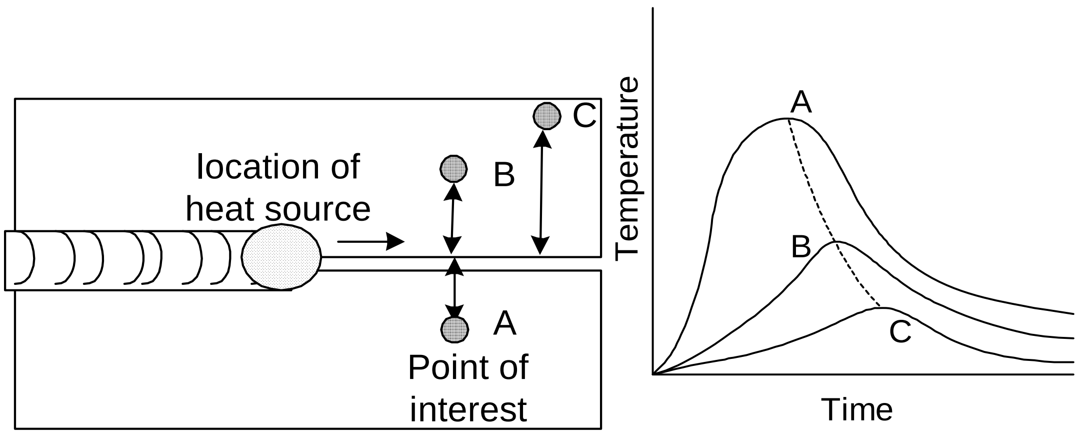


Fig. 21.1 weld thermal cycle of a) locations A, B, C and b) temperature vs time relation of A, B and C

21.3 Mechanisms of residual stress development

The residual stresses in the weld joints develop mainly due to typical nature of welding process i.e. localized heating and cooling leading to differential volumetric expansion and contraction of metal around the weld zone. The differential volumetric change occurs both at macroscopic and microscopic level. Macroscopic volumetric changes occurring during welding contribute to major part of residual stress development and are caused by a) varying expansion and contraction and b) different cooling rate experienced by top and bottom surfaces of weld & HAZ. Microscopic volumetric changes mainly occur due to metallurgical transformation (austenite to martensitic transformation) during cooling. Further, it is important to note that whenever residual stresses develop beyond the yield point limit, the plastic deformation sets in the component. If the residual stress magnitude is below the elastic limit then a stress system having both tensile and compressive stresses for equilibrium is developed.

21.3.1 Differential heating and cooling

Residual stresses develop due to varying heating and cooling rate in different zones near the weld as function of time are called thermal stresses. Different temperature conditions lead to varying strength and volumetric changes in base metal during welding. The variation in temperature and residual stresses owing to movement of heat source along the centerline of weldment is shown schematically in Fig. 21.2. As heat source comes close to the point of interest, its temperature increases. Increase in temperature decreases the yield strength of material and simultaneously tends to cause thermal expansion of the metal being heated. However, surrounding low temperature base metal restricts any thermal expansion which in turn develops compressive strain in the metal during heating. Compressive strain initially increases non-linearly with increase in temperature due to variation in yield strength and expansion coefficient of metal with temperature rise. Further, increase in temperature softens the metal, therefore, compressive strain reduces gradually and eventually it is vanished. As the heat source crosses the point of interest and starts moving away from the point of interest, temperature begins to decrease gradually. Reduction in temperature causes the shrinkage of hot metal in base metal and HAZ. Initially at high temperature contraction occurs without much resistance due to low yield strength of metal but subsequently shrinkage of metal is resisted as metal gains strength owing to reduction in temperature during cooling regime of weld thermal cycle (Fig. 21.3). Therefore, further contraction in shrinking base and weld metal is not allowed with reduction in temperature. This behavior of contraction leaves the metal in strained condition which means that metal which should have contracted, is not allowed to do so and this leads to development of the tensile residual stresses (if the contraction is prevented). The magnitude of residual stresses can be calculated from the product of locked-in strain and modulus of elasticity of metal being welded. The residual stress along the weld is generally tensile in nature while balancing compressive residual stress is developed adjacent to the weld in heat affected zone on cooling to the room temperature as evident from the Fig. 21.2 (b).

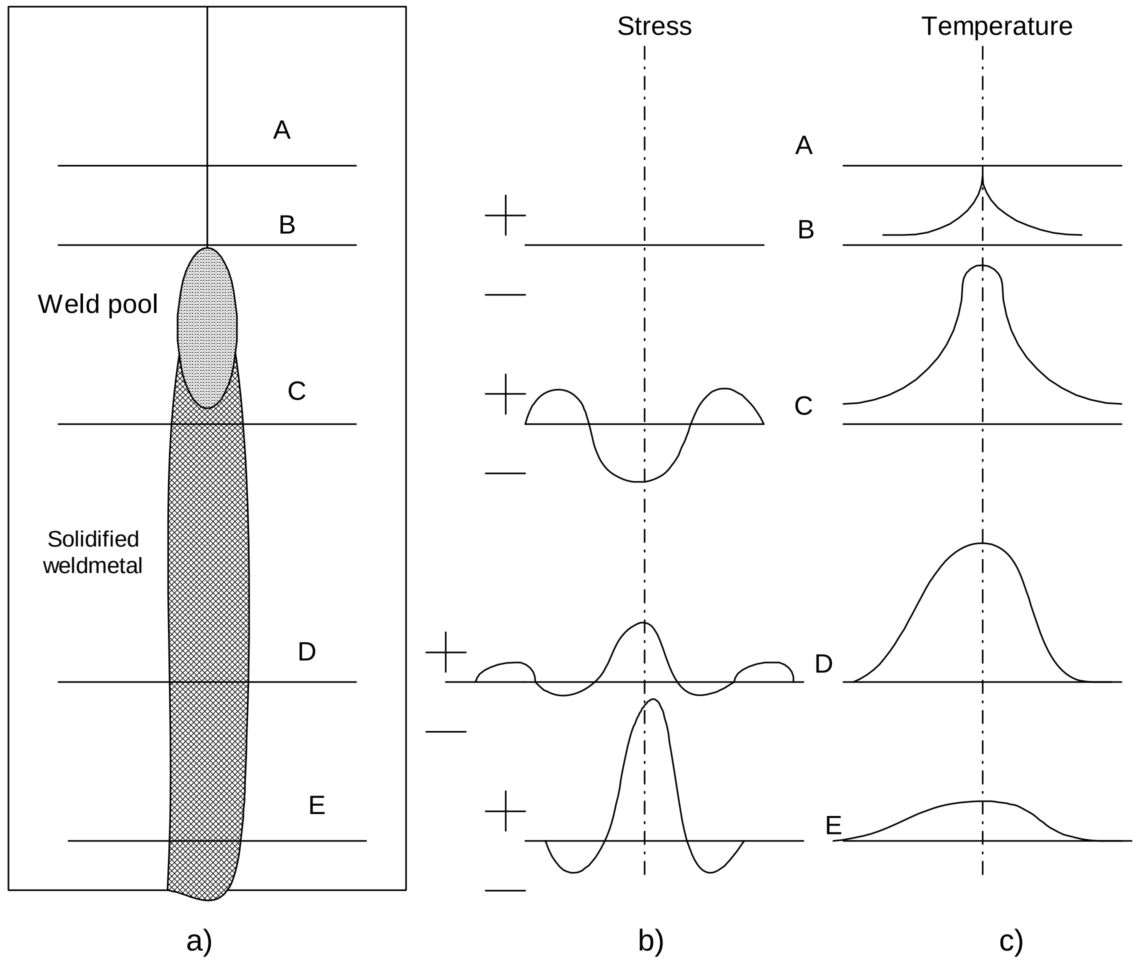


Fig. 21.2 Schematic diagram showing a) plate being welded, b) stress variation across the weld centerline at different locations and c) temperature of different locations

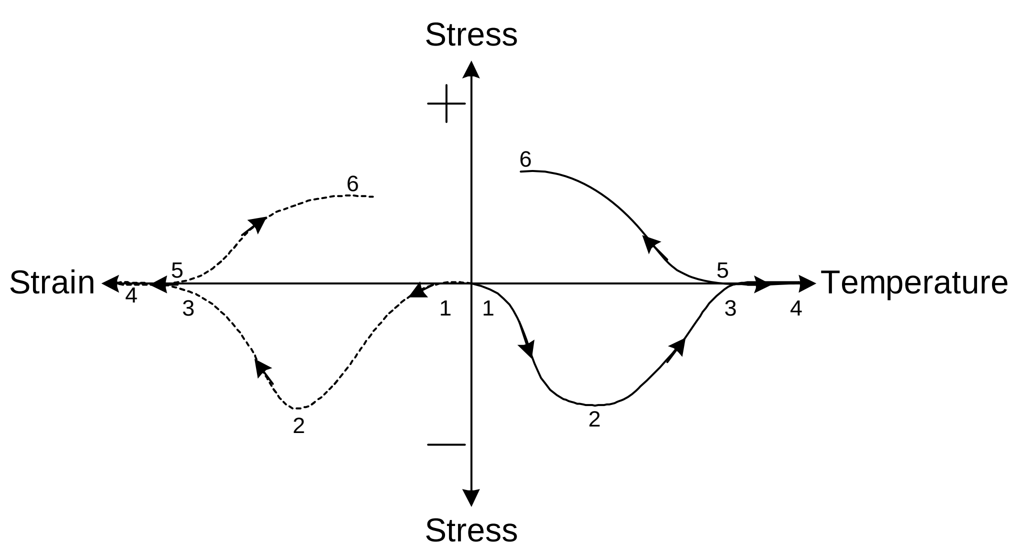


Fig. 21.3 Effect of temperature on variation in stress and strain during welding

21.3.2 Differential cooling rate in different zone

During welding, higher cooling rate is experienced by the top and bottom surfaces of weld joint than the core/middle portion of weld and HAZ (Fig. 21.4). This causes differential expansion and contraction through the thickness (direction) of the plate being welded. Contraction of metal near the surface starts even when material in core portion is still hot. This leads to the development of compressive residual stresses at the surface and tensile residual stress in the core.

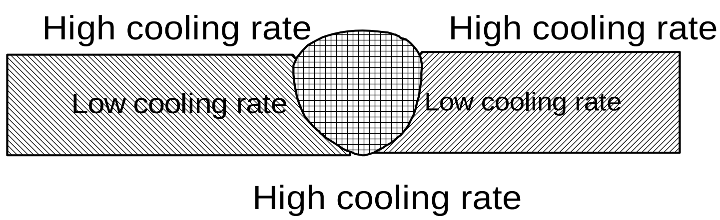


Fig. 21.4 Schematic showing different cooling rates at surface and core regions of the weld

21.3.3 Metallurgical Transformation

During welding, heat affected zone of steel and weld zone invariably experience transformation of austenite into other phases phase mixture like pearlite, bainite or martensite. All these transformations occur with increase in specific volume at microscopic level. The transformations (from austenite to pearlite and bainite) occurring at high temperature are easily accommodated with this increase in specific volume owing to low yield strength and high ductility of these phases and phase mixtures at high temperature (above 550 ^{0}C) therefore such metallurgical transformations don't contribute much towards the development of residual stresses. Transformation of austenite into martensite takes place at very low temperature with significant increase in specific volume. Hence, this transformation contributes significantly towards development of residual stresses. Depending upon the location of the austenite to martensitic transformation, residual stresses may be tensile or compressive. For example, shallow hardening causes such transformation from austenite to martensite near the surface layers only and develops compressive residual stresses at the surface and balancing tensile stress in core while through section hardening develops reverse trend of residual stresses i.e. tensile residual stresses at the surface and compressive stress in the core.

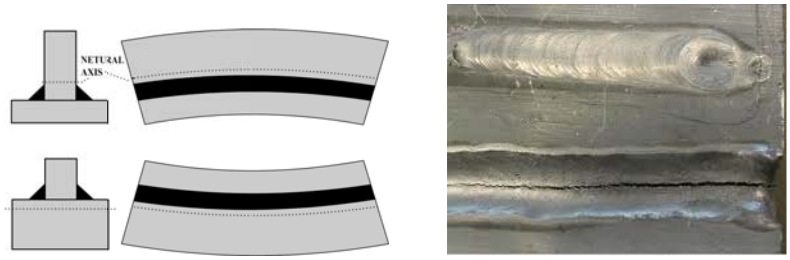
21.4 Effect of residual stresses

The residual stresses whether they are tensile or compressive type predominantly affect the soundness, dimensional stability and mechanical performance of the weld joints. Since magnitude of residual stresses increases gradually to peak value until weld joint is cooled down to the room temperature therefore mostly the effects of residual stresses are observed either near the last stage of welding or after some time of welding in the form of cracks (hot cracking, lamellar tearing, cold cracking), distortion and reduction in mechanical performance of the weld joint (Fig. 21.5).

Presence of residual stresses in the weld joints can encourage or discourage failures due to external loading as their effect is additive in nature. Conversely, compressive residual stresses decrease failure tendency under external tensile stresses primarily due to reduction in net tensile stresses acting on the component (net stress on the component: external stresses $\pm$ residual stresses). Residual stress of the same type as that of external one increases the failure tendency while opposite type of stresses (residual stress and externally applied stress) decrease the same. Since more than 90% failure of mechanical component occurs under tensile stresses by crack nucleation and their propagation under tensile loading conditions therefore presence of tensile residual stresses in combination with external tensile loading adversely affect the performance in respect of tensile load carrying capacity while compressive residual stresses under similar loading conditions reduce the net stresses and so discourage the failure tendency. Hence, compressive residual stresses are intentionally induced to enhance tensile and fatigue performance of mechanical components whereas efforts are made to reduce tensile residual stresses using various approaches such as post weld heat treatment, shot peeking , spot heating etc.

In addition to the cracking of the weld joint under normal ambient conditions, failure of weld joints exposed in corrosion environment is also accelerated in presence of tensile residual stresses by a phenomenon called stress corrosion cracking.

Presence of tensile residual stresses in weld joints causes cracking problems which in turn adversely affect their load carrying capacity. The system residual stress is usually destabilized during machining and may lead to distortion of the weld joints. Therefore, residual stresses must be relieved from the weld joint before undertaking any machining operation.



a) b)

Fig. 21.5 Typical problems associated with residual stress a) distortion and b) solidification cracking

21.5 Controlling the residual stresses

The critical applications frequently demands relieving residual stresses of weld joints by thermal or mechanical methods. Relieving of residual stresses is primarily based on releasing the locked-in strain by developing conditions to facilitate plastic flow so as to relieve stresses.

(a) *Thermal method* is based on the fact that the yield strength and hardness of the metals decrease with increase of temperature which in turn facilitates the release of locked in strain thus relieves residual stresses. Reduction in residual stresses depends on “how far reduction in yield strength and hardness take place with increase of temperature”. Greater is the softening more will be the relieving of residual stresses. Therefore, in general, higher is the temperature of thermal treatment of the weld joint greater will be reduction in residual stresses.

(b) *Mechanical method* is based on the principle of relieving residual stresses by applying external load beyond yield strength level to cause plastic deformation so as to release locked-in strain. External load is applied in an area which is expected to have peak residual stresses.

(c) *Mechanical Vibration : The vibrations of a frequency close to natural frequency of* welded joint is applied on the component to be stress relieved. The vibratory stress can be applied in whole of the components or in localized manner using pulsators. The development of resonance state of mechanical vibrations on the welded joints helps to release the locked in strains so to reduce residual stresses.

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Lecture 22

DESIGN OF WELDED JOINTS I

The performance of weld joints is determined by not only the load resisting cross sectional area of joint but also properties of region close to the weld metal i.e. heat affected zone (HAZ). The design engineer must keep in mind that HAZ can be significantly wider or stronger than weld and so accordingly various parameters of weld joint design should be established. This module based on design of weld joints has been covered in next nine lectures (Lecture 22 to 30). This chapter describes the fundamentals of weld joint design including the parameters that are obtained after designing a weld joint.

Keywords: Modes of failure, rigidity and stiffness, loading condition, welding symbol, type of weld and weld joint,

22.1 Introduction

Weld joints may be subjected to variety of loads ranging from a simple tensile load to the complex combination of torsion, bending and shearing loads depending upon the service conditions. The capability of weld joints to take up a given load comes from metallic continuity across the members being joined. Mechanical properties of the weld metal and load resisting cross section area of the weld (besides heat affected zone characteristics) are two most important parameters which need to be established for designing a weld joint.

22.2 Modes of failure of the weld joints

A poorly designed weld joint can lead to the failure of an engineering component in three ways namely a) elastic deformation (like bending or torsion of shaft and other sophisticated engineering systems like precision measuring instruments and machine tools) of weld joint beyond acceptable limits, b) plastic deformation (change in dimensions beyond acceptable limits as-decided by application) of engineering component across the weld joint and c) fracture of weld joint into two or more pieces under external tensile, shear, compression, impact creep and fatigue loads.

Therefore, depending upon the application, failure of weld joints may occur in different ways and hence a different approaches are needed for designing the weld joints as per application and service requirements.

22.3 Design of weld joints and mechanical properties

Stiffness and rigidity are important parameters for designing weld joints where elastic deformation is to be controlled. Under such conditions, weld metal of high modulus of elasticity (E) and rigidity (G) is deposited for producing weld joints besides selecting suitable load resisting cross sectional area. When the failure criterion for a weld joint is the plastic deformation, then weld joints are designed on the basis of yield strength of the weld metal. When the failure criterion for weld joint is to avoid fracture under static loading, then ultimate strength of the weld metal is used as a basis for design. While under fatigue and creep conditions design of weld joints is based on specialized approaches which will be discussed in later stages of this chapter. Under simplified conditions, design for fatigue loads is based on endurance limit. Weld joints invariably possess different types of weld discontinuities of varying sizes which can be very crucial in case of critical applications e.g. weld joints used in nuclear reactors, aerospace and space craft components. Therefore, weld joints for critical applications are designed using fracture mechanics approach which takes into account the size of discontinuity (in form of crack, porosity or inclusions), applied stresses and weld material properties (yield strength and fracture toughness) in design of weld joints.

22.4 Factors affecting the performance of the weld joints

It is important to note that the mechanical performance of the weld joints is governed by not only mechanical properties of the weld metal and its load resisting cross sectional area (as mentioned above) but also on the welding procedure used for developing a weld joint which includes the edge preparation, weld joint design, and type of weld, number of passes, preheat and post weld heat treatment, if any, welding process and welding parameters (welding current, arc length, welding speed) and method used for protecting the weld contamination from atmospheric gases. As most of the above mentioned steps of welding procedure influence metallurgical properties and residual stresses in weld joint which in turn affect the mechanical (tensile and fatigue) performance of the weld joint.

22.5 Design of weld joints and loading conditions

Design of weld joints for static and dynamic loads needs different approaches because in case of static loads the direction and magnitude become either constant or changes very slowly while in case of dynamic loads such as impact and fatigue conditions, the rate of loading is usually high. In case of fatigue loading both magnitude and direction of load may fluctuate. Under the static load condition, low rate of loading increases the time available for localized yielding to occur in area of high stress concentration which in turn causes stress relaxation by redistribution of stresses through-out the cross section while under dynamic loading conditions, due to lack of availability of time, yielding across the section of weld doesn't take place and only localized excessive deformation occurs near the site of a high concentration stress which eventually provide an easy site for nucleation and growth of cracks as in case of fatigue loading.

22.6 Need of welding symbols

It is important to communicate information about welding procedure without any ambiguity to all those who are involved in various steps of fabrication of successful weld joints ranging from edge preparation to final inspection and testing of welds. To assist in this regard, standard symbols and methodology for representing the welding procedure and other conditions have been developed. Symbols used for showing the type of weld to be made are called weld symbols. Some common weld symbols are shown below in Fig. 22.1.

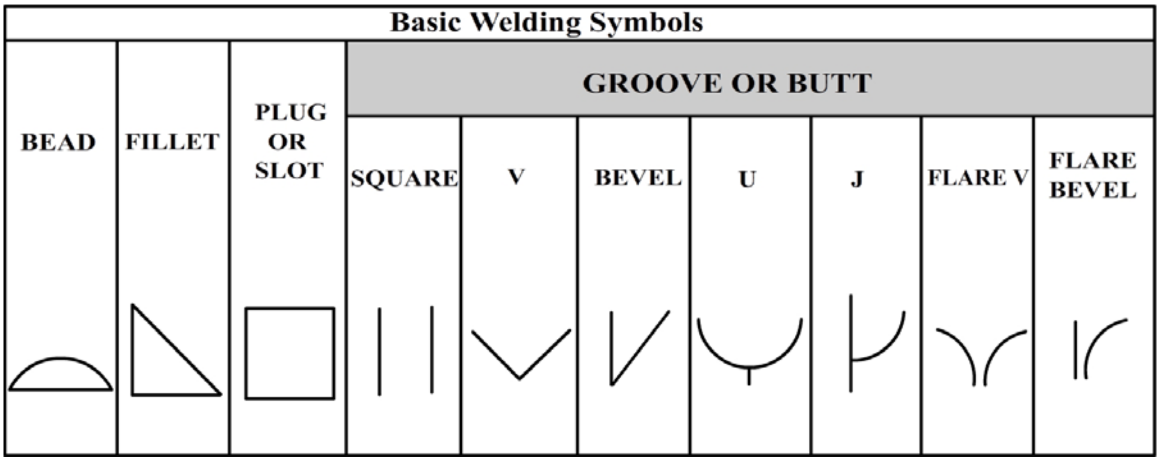


Fig. 22.1 Basic weld symbols

Symbols which are used to show not only the type of weld but all relevant aspects related with welding like size & location of weld, welding process, edge preparation, bead geometry and weld inspection process and location of the weld to be fabricated and method of weld testing etc. are called welding symbols. Following sections present standard terminologies and joints used in field of welding engineering.

22.7 Types of weld Joints

The classification of weld joints is based on the orientation of plates/members to be welded. Common types of weld joints and their schematics are shown in Fig. 22.2 (a-e).

- ☑ Butt joint: plates are in same horizontal plane and aligned with maximum-deviation of 5^0.
- ☑ Lap joint: plates overlapping each other and the overlap can just one side or both the sides of plates being welded
- ☑ Corner joint: joint is made by melting corners of two plates being welded and therefore plates are approximately perpendicular (75^0 - 90^0) to each other at one side of the plates being welded
- ☑ Edge joint: joint is made by melting the edges of two plates to be welded and therefore the plates are almost parallel (0^0 - 5^0)
- ☑ T joint: one plate is approximately perpendicular to another plate (85^0 - 90^0)

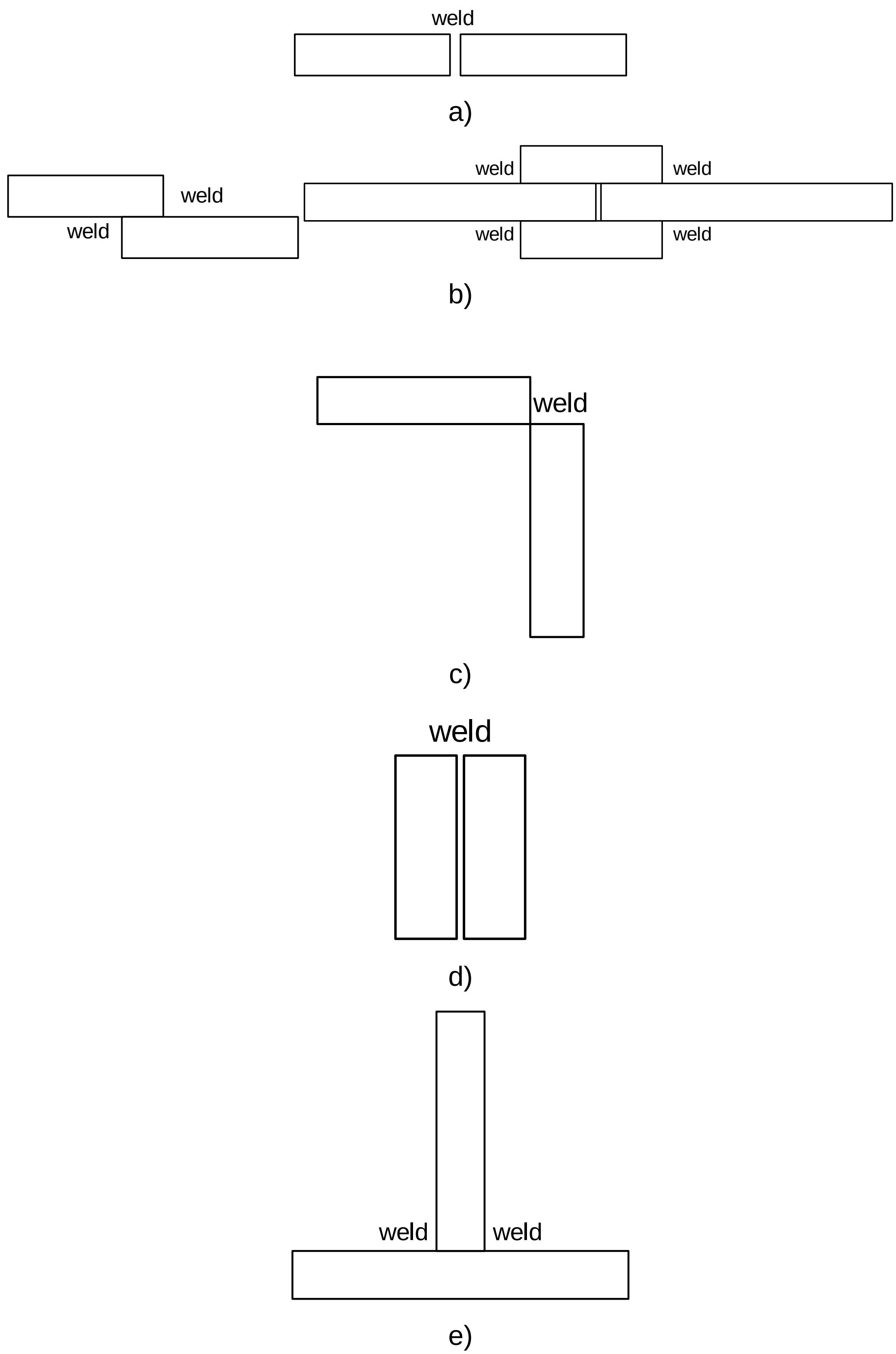
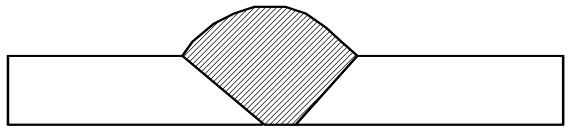


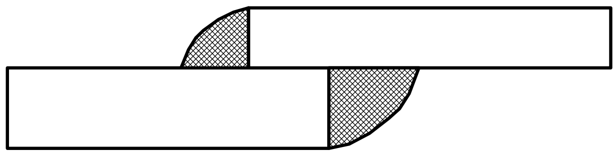
Fig. 22.2 Schematic of different types of weld joints a) butt, b) lap, c) corner, d) edge and e) T joint

3.0 Types of weld

This classification in based on the combined factors like “how weld is made” and “orientation of plates” to be welded. Common types of weld joints and their schematics are shown in Fig. 22.3 (a-e).



a)



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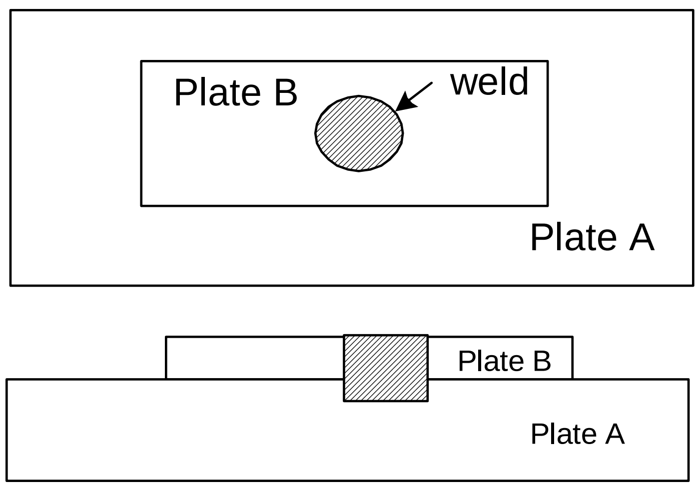
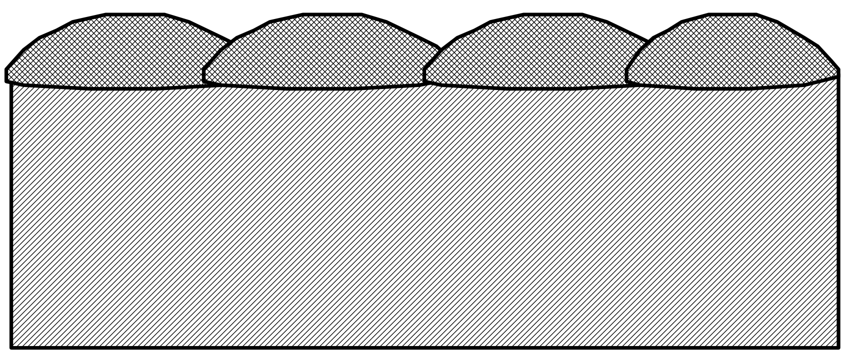


c)



d)

Fig. 22.3 Schematic of different types of weld a) groove, b) fillet, c) plug and d) bead on plate

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Lecture 23

DESIGN OF WELDED JOINTS II

This chapter presents common types of welding position and various difficulties associated with them. Further, need for edge preparation and the rationale for selection of suitable groove design have also been presented.

Keywords: Flat welding, horizontal welding, vertical and overhead welding, groove weld, edge preparation

23.1 Welding position

The welding positions are classified on the basis of the plane on which weld metal is deposited.

- ✓ Flat welding

  In flat welding, plates to be welded are placed on the horizontal plane and weld bead is also deposited horizontally (Fig. 23.1). This is one of most commonly used and convenient welding position. Selection of welding parameters for flat welding is not very crucial for placing the weld metal at desired location in flat welding.

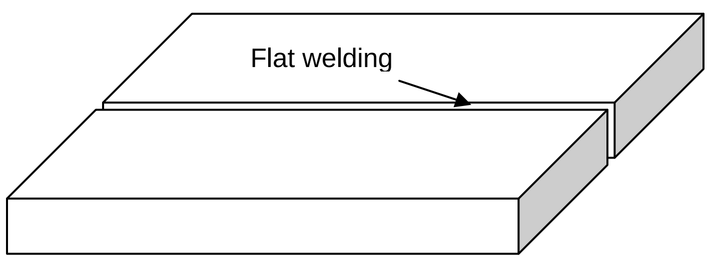

Fig. 23.1 Scheme of placement of components to be welded for flat welding

- ✓ Horizontal welding

  In horizontal welding, plates to be welded are placed in vertical plane while weld bead is deposited horizontally (Fig. 23.2). This technique is comparatively more difficult than flat welding. Welding parameters for horizontal welding should be selected carefully for easy manipulation/placement of weld metal at the desired location.

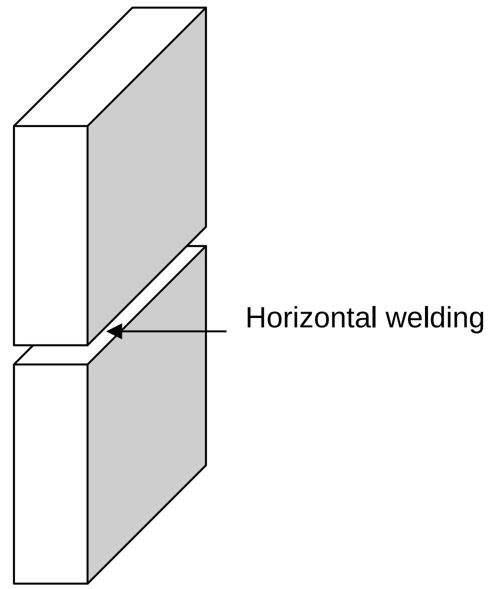

Fig. 23.2 Scheme of placement of components to be welded for horizontal welding

✓ Vertical welding

In vertical welding, plates to be welded are placed on the vertical plane and weld bead is also deposited vertically (Fig. 23.3). It imposes difficulty in placing the molten weld metal from electrode in proper place along the weld line due to tendency of the melt to fall down under the influence of gravitational force. Viscosity and surface tension of the molten weld metal which are determined by the composition of weld metal and its temperature predominantly control the tendency of molten weld metal to fall down due to gravity. Increase in alloying elements/impurities and temperature of melt in general decrease the viscosity and surface tension of the weld metal and thus making the liquid weld metal more thin and of higher fluidity which in turn increases tendency of weld metal to fall down conversely these factors increase difficulty in placing weld metal at desired location.

Therefore, selection of welding parameters (welding current, arc manipulation during welding and welding speed all are influencing the heat generation) and electrode coating (affecting composition of weld metal) dilution becomes very crucial for placing the weld metal at desired location in vertical welding.

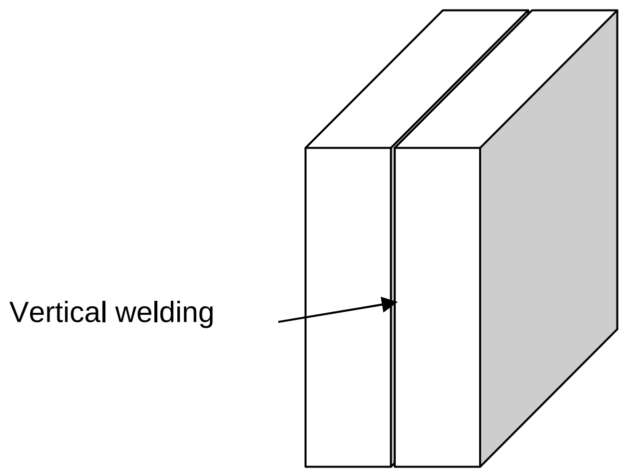

Fig. 23.3 Scheme of placement of components to be welded for vertical welding

✓ Overhead welding

In overhead welding, weld metal is deposited in such a way that face of the weld is largely downward and there is high tendency of falling down of weld metal during welding (Fig. 23.4). Molten weld metal is moved from the electrode (lower side) to base metal (upper side) with great care and difficulty hence, it imposes problems similar to that of vertical welding but with greater intensity. Accordingly, the selection of welding parameters, arc manipulation and welding consumable should be done after considering all factors which can decrease the fluidity of molten weld metal so as to reduce the weld metal falling tendency. This is most difficult welding position and therefore it needs great skill to place the weld metal at desired location with close control.

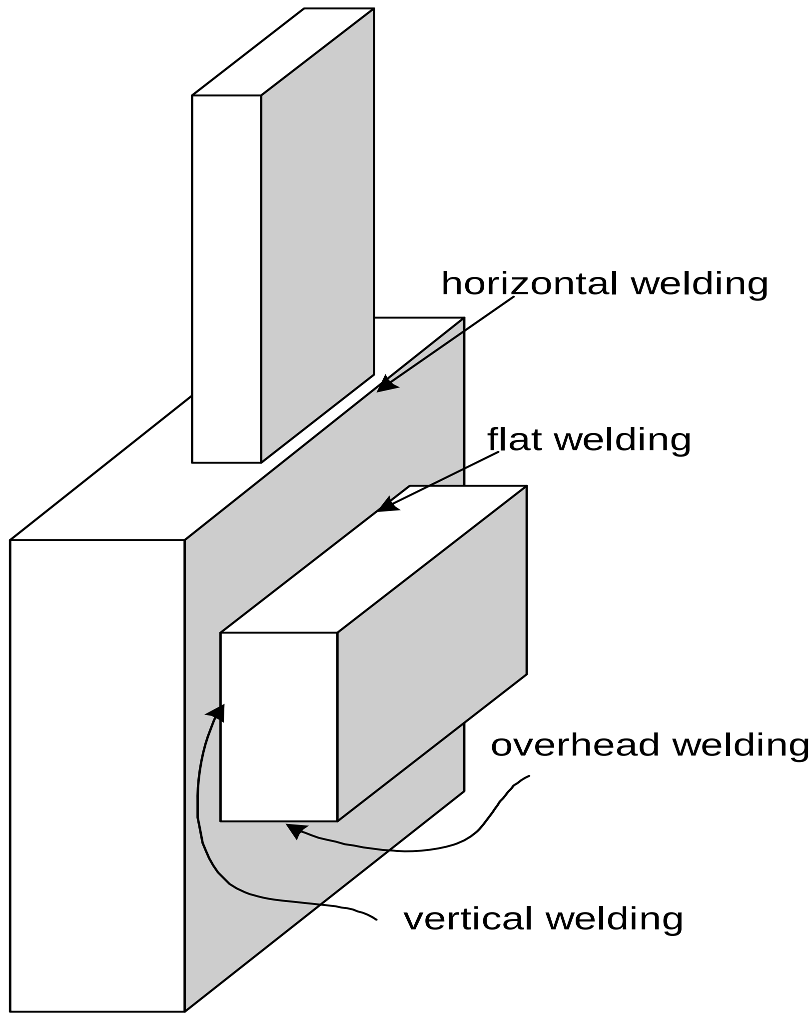

Fig. 23.4 Scheme of placement of components to be welded for different types of welding positions including overhead welding

23.2 Rationale behind selection of weld and edge preparation

23.2.1 Groove weld

Groove weld is called so because a groove is made first between plates to be welded. This type of weld is used for developing butt joint, edge and corner joint. The groove preparation especially in case of thick plates ensures proper melting of the faying surfaces by providing proper access of heat source up to the root of the plates and so as to help in developing sound weld joint. It is common to develop grooves of different geometries for producing butt, corner and edge joint such as square, U (single and double), V (single and double), J (single and double) and bevel (single and double). Following sections describe various technical aspects of different types of groove welds.

Single groove weld

Single groove means edge preparation of the plates to produce desired groove from one side only resulting in just one face and one root of the weld. While in case of double groove, edge preparation is needed from both sides of the plates which in turn results in two faces of the weld and welding is needed from both sides of the plates to be welded. Single groove weld is mainly used in case of plates of thickness more than 5 mm and less than 15 mm. Moreover, this range is not very hard and fast as it depends on penetration capability of welding process used for welding besides weld parameters, as welding parameters affect the depth up to which melting of plates can be achieved from the top.

Double groove weld

Double groove edge preparation is used especially under two conditions a) when thickness of the plate to be welded is more than 25 mm, so the desired penetration up to root from one side is not achievable and b) distortion of the weld joints is to be controlled. Further, double groove edge preparation lowers the volume of weld metal to be deposited by more than 50% as compared to that for the single groove weld especially in case of thick plates. Therefore, selection of double groove welds helps to develop weld joints more economically, at much faster welding speed than the single groove weld for thick plates.

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Lecture 24

DESIGN OF WELDED JOINTS III

This chapter describes the factors affecting the selection of suitable groove geometry for edge preparation and influence of welding parameters on weld bead geometry. Additional design aspects of the weld joints have also been presented.

Keywords: Selecting groove geometry, fillet weld, bead weld, dilution, stress concentration, plug weld, weld bead geometry

24.1 Factors affecting selection of suitable groove geometry

Selection of a particular type of groove geometry is influenced by the compromise of two main factors a) machining cost to obtain desired groove geometry and b) cost of weld metal (on the basis of volume) need to be deposited, besides other factors such as welding speed, accessibility of groove for depositing the weld metal, residual stress and distortion control requirement.

U and J groove geometries are more economical (than V and bevel grooves) in terms of volume of weld metal to be deposited, and offer less distortion and residual stress related problems besides higher welding speed but these groove geometries suffer from difficulty in machining and poor accessibility of heat sources to the root of groove for achieving desired penetration and fusion of the faying surfaces. On contrary V and bevel groove geometries can be easily and economically produced by machining or flame cutting besides providing good accessibility for applying heat up to root of groove. However, these groove geometries need comparatively more volume of weld metal and so these cause more residual stress and distortion related problems than U and J groove geometries.

Square groove geometry does not need edge preparation except making edges clear and square, but this geometry can be used only up to 10 mm plate thickness. However, this limit can vary significantly depending upon the penetration capability of welding process and welding parameters. Square groove is usually not used for higher thicknesses (above 10 mm) mainly due to difficulties associated with poor penetration, poor accessibility of root and lack of fusion tendency at the root side of the weld. Therefore, it is primarily used for welding of thin sheets by TIG/MIG welding or thin plates by SAW.

Groove butt welds are mainly used for general purpose and critical applications where tensile and fatigue loading is expected during the service. Since butt groove geometry does not cause any stress localization (except those which are caused by poor weld geometry and weld defects) therefore stresses developing in weld joints due to external loading largely become uniform across the section of the weld hence fatigue crack nucleation and subsequent propagation tendency are significantly lowered in butt groove weld as compared with fillet and other type of welds.

24.2 Fillet weld

Fillet welds are used for producing lap joint, edge joint, and T joint more commonly for non-critical applications. Generally, these do not require any edge preparation, hence these are more economical to produce especially in case of comparatively thin plates as compared to groove weld. However, to have better penetration sometimes groove plus fillet weld combination is also used. An increase in size of weld (throat thickness and leg length of the weld) when welding thick plates increases the volume of weld metal in case of fillet welds significantly; hence fillet welds become uneconomical for large size weld compared to groove weld. Due to inherent nature of fillet weld geometry, stresses are localized and concentrated near the toe of the weld which frequently becomes an easy site for nucleation and growth of tensile/fatigue cracks. The stress concentration in fillet weld near the toe of the weld occurs mainly due to abrupt change in load resisting cross sectional area from the base metal to weld zone. To reduce the adverse effect of stress localization, efforts are made to have as gradual transition/change as possible in load resisting cross sectional area from the base metal to weld either by controlled deposition of the weld metal using suitable weld parameters (so as to have as low weld bead angle as possible), and manipulation of molten weld metal while depositing the same or controlled removal of the weld metal by machining / grinding.

24.3 Bead weld

The bead weld is mainly used to put a layer of a good quality metal over the comparatively poor quality base metal so as to have functional surfaces of better characteristics such as improved hardness, wear and corrosion resistance. To reduce degradation in characteristics of weld bead of good quality materials during welding, it is important that inter-mixing of molten weld bead metal with fused base metal is as less as possible while ensuring good metallurgical bond between the bead weld and base metal. The inter-mixing of bead weld metal with base metal during welds is called dilution. Higher dilution leads to greater degradation in quality of weld joint. Better control over the dilution is achieved by reducing extent of melting of base metal using suitable welding procedure such preheating, welding parameter, welding process etc. For examples plasma transferred arc welding (PTAW) causes lesser dilution than SAW primarily due to difference in net heat input which is applied during welding in two cases. PTAW supplies lesser heat compared to other processes namely MIGW, SMAW and SAW. Bead welds are also used just to deposit the weld metal same as base metal so as to regain the lost dimensions. This process is called reclamation. The loss of dimensions of the functional surfaces can be due to variety of reasons such as wear, corrosion etc. These bead welds are subsequently machined out to get the desired dimensional accuracy and finish.

24.4 Plug welds

These welds are used for comparatively less critical applications. For developing plug weld first a through thickness slot (of circular/rectangular shape) is cut in one of plates and the same is placed over another plate to be welded then weld metal is deposited in the slot so that joint is formed by fusion of both bottom plate and edges of slot in upper plate.

24.5 Welding and weld bead geometry

For developing a fusion weld joint, it is necessary that molten metal from electrode/filler and base metal fuse and mix together properly. Heat of arc/flame must penetrate the base metal up to sufficient depth for proper melting of base metal and then mixing with fused filler/electrode metal to develop metallurgical weld joint. Heat generation in case of arc welding is determined by welding current, voltage and welding speed. An optimum value of all three parameters is needed for sound welding free from weld discontinuities.

24.5.1 Welding current

Low welding current results in less heat generation and hence increased chances of lack of fusion and poor penetration tendency besides too high reinforcement owing to poor fluidity of comparatively low temperature molten weld metal. On the other hand, too high welding current may lead to undercut in the weld joint hear the toe of the weld due to excessive melting of base metal and flattened weld bead besides increased tendency of weld metal to fall down during vertical, horizontal and overhead welding owing to high fluidity of weld meal caused by low viscosity and surface tension. Increase in welding current in general increases the depth of penetration/fusion. Therefore, an optimum value of welding current is important for producing sound weld joint.

24.5.2 Arc voltage

Similar to the welding current, an optimum arc voltage also plays a crucial role in the development of sound a weld as low arc voltage results in unstable arc which in turn results in poor weld bead geometry is obtained while to high voltage causes increased arc gap and wide weld bead and shallow penetration.

24.5.3 Welding speed

Welding speed influences both fusion of base metal and weld bead geometry. Low welding speed causes flatter and wider weld bead while excessively high welding speed reduces heat input which in turn lowers penetration & weld bead width and increases weld reinforcement and bead angle. Therefore, an optimum value of welding speed is needed for producing sound weld with proper penetration and weld bead geometry.

24.6 Design aspects of weld joint

Strength of weld joints is determined by not only the properties of weld metal but also characteristics of heat affected zone (HAZ) and weld bead geometry (due to stress concentration effect) as sometimes properties of HAZ are degraded to such an extent that they become even lower than weld metal due to increased a) softening of the heat affected zone and b) corrosion tendency of HAZ. Assuming that the effect of weld thermal cycle on properties of HAZ is negligible, suitable weld dimensions are obtained for a given loading conditions by weld joint design. Design of a weld joint mainly involves establishing the proper load resisting cross sectional area of the weld which includes throat thickness of the weld and length of the weld. In case of groove butt weld joints, throat thickness becomes equal to shortest length of the line passing across the weld (top to bottom) through the root of weld. Conversely, throat thickness becomes the minimum thickness of weld or thickness of thinner plate when joint is made between plates of different thicknesses. While in case of fillet welds, throat thickness is shortest length of line passing root of the weld and weld face. Any extra material (due to convexity of weld face) in weld does not contribute much towards load carrying capacity of the weld joint.

In practice, however, load carrying capacity of the weld is dictated not just by weld cross sectional area but also by properties of weld metal and HAZ and stress concentration effect induced by weld bead geometry and weld discontinuities under the static as well as fatigue loading conditions.

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Lecture 25

DESIGN OF WELDED JOINTS IV

This chapter describes basic principle and methodology of weld joints design for static and dynamic loading to develop groove and fillet weld joints besides the information required for developing said designs.

Keywords: Design of weld joint, static and dynamic loading, load resisting cross sectional area, allowable stress, throat thickness, leg length, class of weld, stress range

25.1 Design of weld joint for static loading

As mentioned in section 24.6 for designing of a weld joint, it is required to determine the throat thickness and length of the weld. Measurement of throat thickness is easier for groove butt weld joint than fillet weld joint because root is not accessible in case of fillet weld. Throat thickness of fillet welds is obtained indirectly (mathematically) from leg length: $2^{1/2}$X leg length. Leg length of fillet weld can be measured directly using metrological instruments. Further, for a particular plate thickness, minimum throat thickness values have been fixed by American welding society in view of cracking tendency of fillet weld due to tensile residual stresses in weld joints. Small fillet weld developed on thick plate exhibits cracking tendency appreciably due to inability of small fillet to sustain heavy residual tensile stresses which develop in small fillet weld. It is important to note that depending upon the expected service load, a weld joint can be designed by considering tensile, compressive and shear stresses.

A weldment joint design program starts with recognition of a need to design expected to be induced during the service.(new design or failure of existing design) a weld joints followed by main steps of weldment design procedure including:

1. Determination or estimation of expected service load on the weld joint
2. Collecting information about working condition and type of stresses
3. Based on the requirement identify design criteria (ultimate strength, yield strength, modulus of elasticity)
4. Using suitable design formula calculate length of weld or throat thickness as per need or data given
5. Determine length and throat thickness required to take up given load (tensile, shear bending load etc.) during service

Methodology

- Depending upon the service requirements, select the type of weld joint and edge preparation for design
- Establish the maximum load for which a weld joint is to be designed
- For a given thickness of the plate usually throat thickness is generally fixed. For full penetration fillet weld, throat thickness is about 0.707 time of leg length of the weld and that of groove weld generally is equal to thickness of thinner plate (in case of dissimilar thickness weld) or thickness of any plate (Fig. 25.1).
- Using suitable factor of safety and suitable design criteria determine the allowable stress for the weld joint.
- Subsequently calculate length of the weld using external maximum load, allowable stress, throat thickness and allowable stress.

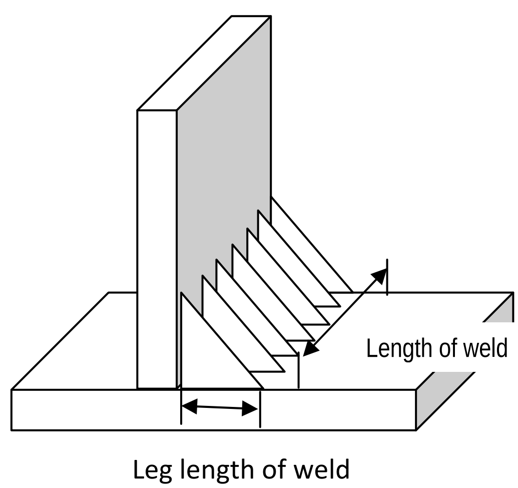
25.2 Design of fillet welds

(a) Stress on fillet weld joint can be obtained by using following relationship:

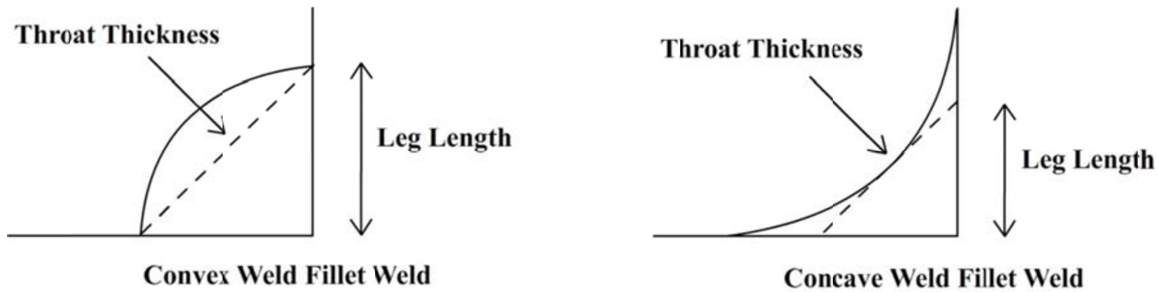
Load/weld throat cross sectional area

Load/(throat thickness X length of weld joint X number of welds)

Load/0.707 X leg length of the weld X length of the weld X number of welds



a)



b) c)

Fig. 25.1 Schematic diagram showing a) leg length and length of weld, b) throat thickness for convex and c) throat thickness for convex fillet welds

25.3 Design of butt weld joint

Stress on butt weld joint between equal thickness plates (Fig. 25.2) is obtained using following relationship: Stress: Load / weld throat cross sectional area= Load/(throat thickness X length of weld joint X number of welds)=Load/ thickness of any plate X length of the weld X number of welds

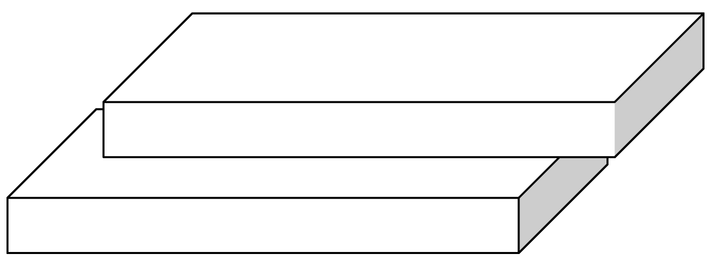


Fig. 25.2 Schematic diagram of butt weld between plates of equal thickness

Stress (σ) on the butt weld joint between plates of different thicknesses (T1 and T2) subjected to external load (P) experiences eccentricity (e) owing to difference in thickness of plates and T1 thickness of thinner plate of the joint (Fig. 25.3). Even axial loading due to eccentricity causes the bending stress in addition to axial stress. Therefore, stress on the weld joint becomes sum of axial as well as bending stress and can be calculated as under.

Stress in weld = Axial Stress + Bending Stress

$$\sigma_{total} = \frac{P}{T_1} + \frac{P.e.\frac{1}{2}.T_1}{\frac{T_1^3}{12}}$$

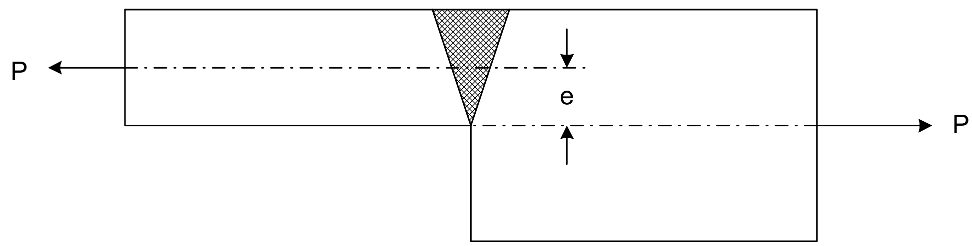
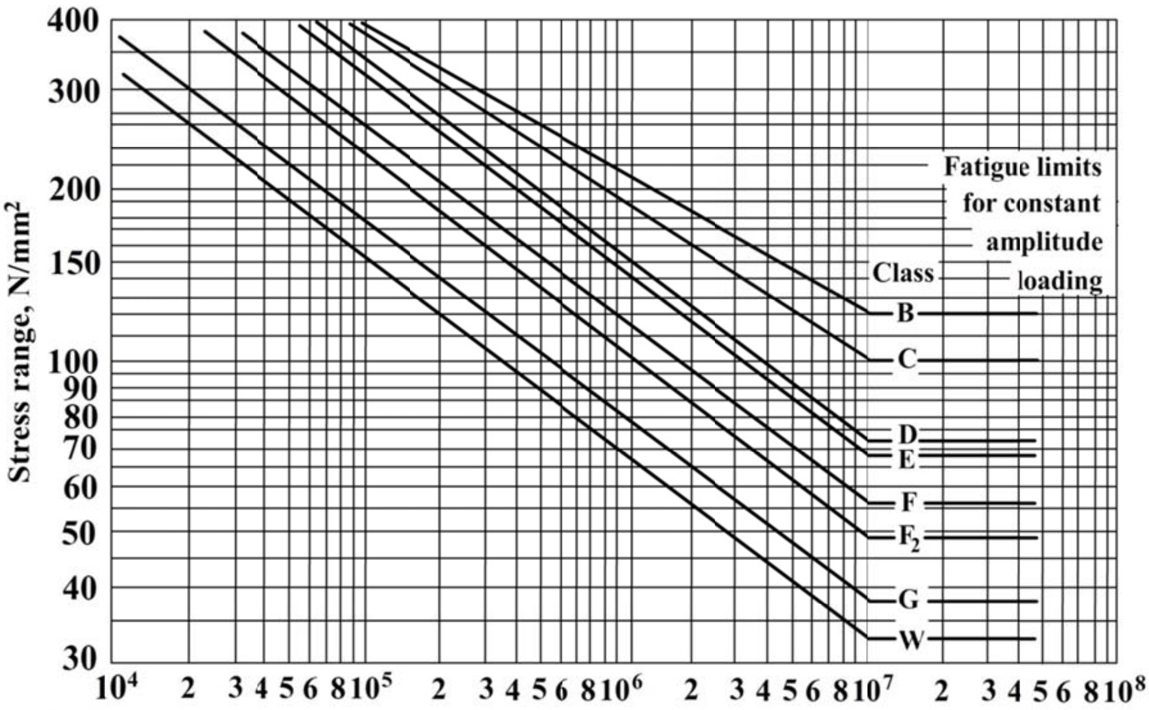


Fig. 25.3 Schematic diagram of butt weld when both the plates are of different thickness

25.4 Design of weld joints for fatigue loading

The approach for designing weld joints for fatigue load conditions is different from that of static loading primarily due to high tendency of the fracture by crack nucleation and growth phenomenon. A weld joint can be categorized in a specific class depending upon the severity of stress concentration, weld penetration (full or partial penetration weld), location of weld, type of weld and weld constraint. The class of a weld joint to be designed for fatigue loading is used to identify allowable stress range for a given life of weld joint (number of fatigue load cycles) from stress range vs. number of load cycle curves developed for different loading conditions and metal system (Fig. 25.4). Thus, allowable stress range obtained on the basis of the class of the weld and fatigue life of weld (for which it is to be designed) is used to determine the weld-throat-load-resisting cross-sectional area (throat thickness, length of weld and number of weld).



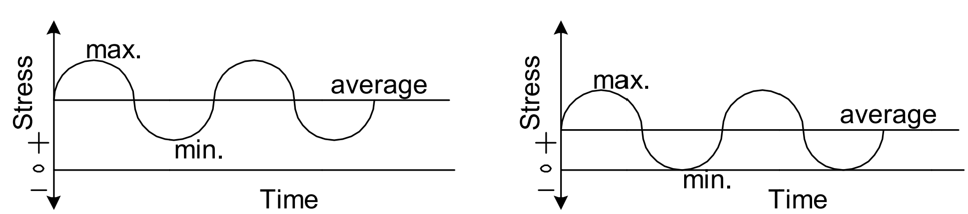
(a)

Fig. 25.4 S-N curves for different classes of weld joints (Madox, S K, 1991)

Procedure of weld joint design for fatigue loading

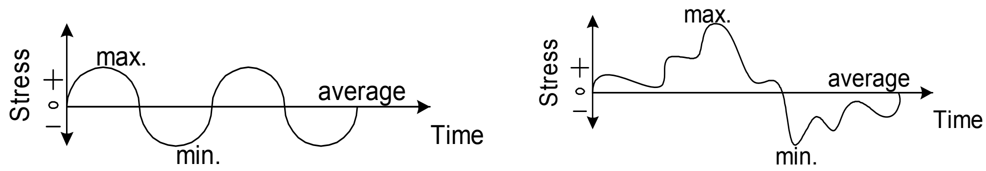
Weld joints for fatigue loading condition are designed using following steps:

- Identify the class of the weld joint based on severity of loading, type of weld, penetration and criticality of the joint for the success of the assembly
- For identified class of the weld joint, obtain a value of the allowable stress range using fatigue life (number of cycles) for which it is to be designed.
- The allowable stress range and service loading condition (maximum and minimum load) are used to determine load resisting cross sectional area of the weld joint (Fig. 25.5)



a) Tension-Tension

b) 0-Tension



c) Compression-Tension d) Fluctuating stress

Fig. 25.5 Common fatigue load patterns

- For given set of loading condition and identified class of the weld joint various details like throat thickness, length of weld joint and number of welds can be obtained from calculated load resisting cross sectional area desired.
- Generally, the maximum length of the weld becomes same as the length of the plate to be welded and maximum number of welds for butt welding is one and that for fillet weld can be two for uninterrupted welds. This suggests that primarily throat thickness of the weld is identified if length and number of weld are fixed else any combination of the weld parameters such as throat thickness, length of weld and number of welds can obtained in such a way that their product is equal to the required load resisting cross sectional area.
- Strength of weld metal doesn't play any big role on fatigue performance of the weld joints as under severe stress conditions (which generally exist in weld joint owing to the presence of notches and discontinuities) fatigue strength and life are marginally affected by strength of weld metal.

25.4.1 Information required for designing

- The fatigue life (number of load cycles) for which a weld is to be designed e.g. 2×10^6 cycles
- Class of the weld joint based on type and penetration and other conditions (Fig. 6)
- Allowable stress range on the basis of class of weld and life required from the figure
- Value of the maximum and minimum service load expected on weld joint

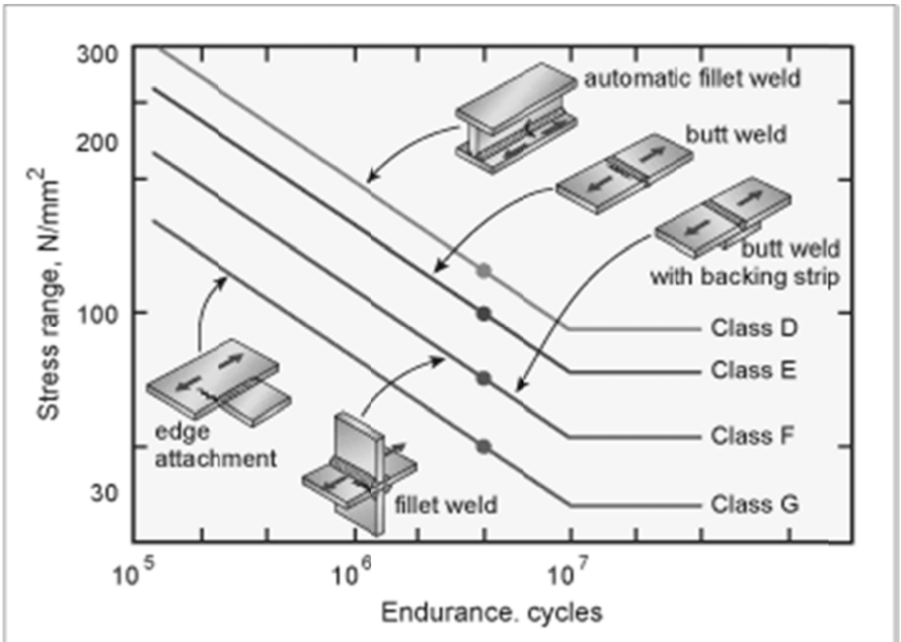


Fig. 25.6 Schematics of weld joints of different classes

Example

A T joint of steel plates is subjected to 350 kN load is developed using intermitted 4 double fillet welds of length each of 40 mm at an interval of 100 mm. Allowable shear strength of the weld metal is 100 MPa. Determine the leg length of the weld.

Solution

Weld load resisting cross sectional area: throat thickness X length of each weld X No. of weld

: weld throat thickness X 40 X 4 X 2

: weld throat thickness X 320

Load carrying capability: load resisting cross sectional area X allowable shear stress

350,000 : weld throat thickness X 320 X 100

Weld throat thickness: 350000/320 X 100

Weld throat thickness: 10.93 mm

Leg length of weld: weld throat thickness X (2)1/2

Leg length of weld : 10.92 X 1.414= 15.45 mm

Example

A full penetration butt weld joint made of two steel plates each of 10 mm X 100 mm X 300 mm is subjected load fluctuation from 150 kN to 350 kN load. Determine if weld is safe for 10^6 or 10^5 load cycle.

Solution

Assuming class of the weld for given service condition is E

Load resisting cross sectional area of weld: length X width: 10 X 100= 1000 mm 102

Assuming throat thickness of weld is equal to min. thickness of plate

Max stress: 350000/1000: 350 MPa

Min. stress: 150000/1000: 150 MPa

Stress range: 200 MPa

The allowable stress range for 106 and 105 load cycle for E class is obtained from standard table/plots: 180 and 260 MPa

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Lecture 26

DESIGN OF WELDED JOINTS V

This chapter presents fatigue of metals, stages in fatigue fracture and material characteristics affecting each stage of fatigue fracture. Further, relationship between the fatigue fracture and stress intensity factor has also been elaborated.

Keywords: Fatigue, stages of fatigue fracture, fatigue crack nucleation, stable fatigue crack growth, slip, stress intensity factor range, sudden fracture

The fluctuations in magnitude and direction of the load adversely affect the life and performance of an mechanical component compared to that under static loading condition. This adverse effect of load fluctuations on life of a mechanical component is called fatigue. Reduction in life of the mechanical components subjected to fatigue loads is mainly caused by premature fracture due to early nucleation and growth of cracks in the areas of high stress concentration occurring either due to abrupt change in cross section or presence of dis-continuities in form of cracks, blow holes, weak materials etc.

26.1 Fracture under fatigue loading

The fracture of the mechanical components under fatigue load conditions generally takes place in three steps a) nucleation of cracks or crack like discontinuities, b) stable growth of crack and c) catastrophic and unstable fracture. Number of fatigue load cycles required to complete each of the above three stages of the fatigue eventually determines the fatigue life of the component (Fig. 26.1). Each stage of fatigue fracture ranging from crack nucleation to catastrophic unstable fracture is controlled by different properties such as surface properties, mechanical and metallurgical properties of the components in question. Any of the factors related with material geometry of the component and loading condition which can delay the completion of any of the above three stages of the fatigue will increase the fatigue life.

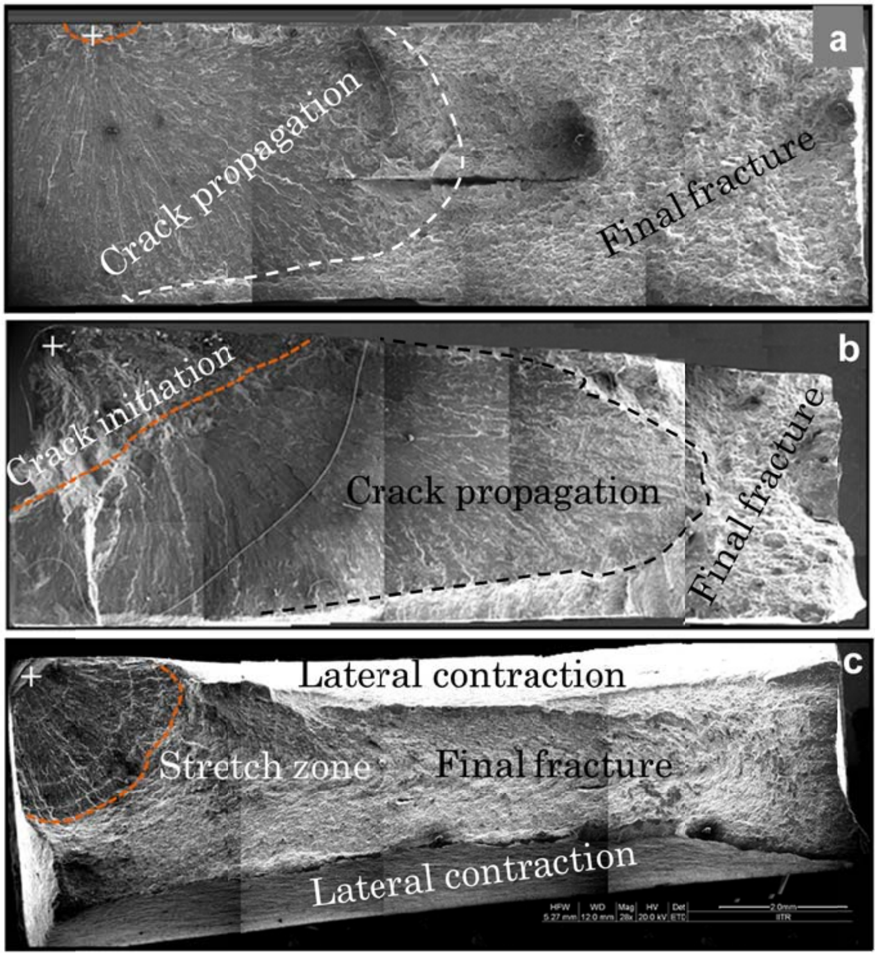

Fig. 26.1 Photograph of fatigue fracture surface of a weld joint

26.2 Factors affecting the stages of fatigue fracture

26.2.1 Surface crack nucleation stage

Surface crack nucleation stage is primarily influenced by surface properties such as roughness, hardness, yield strength and ductility of the engineering component subjected to fatigue provided there is not stress raiser causing stress localization. Cracks on the smooth surface of engineering component are nucleated by micro-level deformation occurring at the surface due to slip under the influence of fluctuating loads. Repeated fluctuation of loads results surface irregularities of micron level which act as stress raiser and site for stress concentration. Continued slip at certain crystauographic planes due to fluctuating load cycle finally produces crack like discontinuities at the surface. It is generally believed that first crack nucleation stage takes about 10-20% of total fatigue life cycle of the engineering component. Since the mechanism of fatigue crack nucleation is based on micro-level slip deformation at the surface therefore factors like surface irregularities (increasing stress concentration), high ductility, low yield strength and low hardness would facilitate the micro-level surface deformations and thereby lower the number of fatigue load cycles required for completing the crack nucleation stage (Fig. 26.2). Hence, for enhancing the fatigue life attempts are always made to improve the surface finish (so as to reduce stress concentration due to surface irregularities if any by grinding, lapping, polishing etc.), increase the surface hardness and yield strength and lower the ductility using various approaches namely shot peening, carburizing, nitriding, and other hardening treatment.

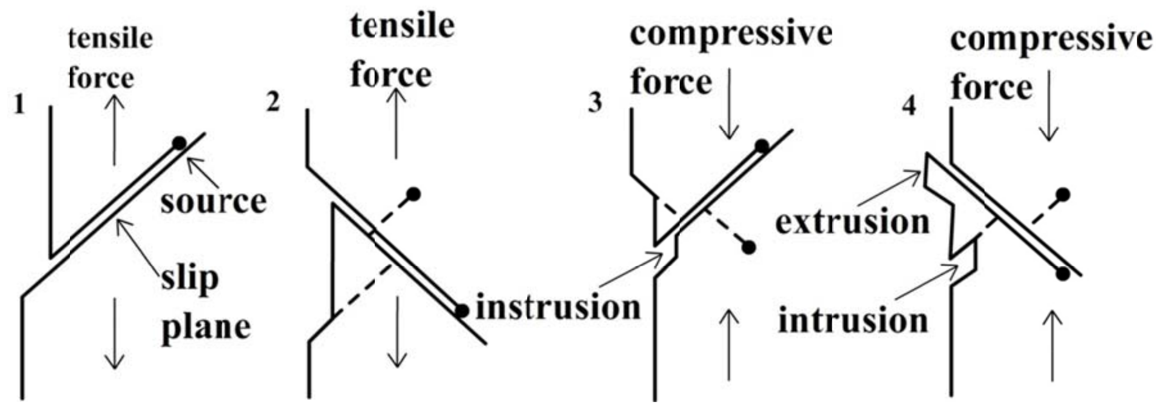

Fig. 26.2 Schematic of fatigue crack nucleation mechanism

Surface nucleation stage in case of welded joints becomes very crucial as almost all the weld joints generally possess poor surface finish and weld discontinuity of one or other kind which can act as a stress raiser. Further, the development of residual stresses in weld joints can also promote or discourage the surface nucleation stage depending upon the type of loading. Residual stresses similar to that of external loading facilitate the crack nucleation while that of opposite kind tends to discourage the crack nucleation. This is the reason why welding of base metal lowers the fatigue life up to 90% depending upon the type of the weld joints, loading conditions and surface conditions of weld.

26.2.2 Stable Crack Growth Stage

A crack nucleated in first stage may be propagating or non-propagating type depending upon the fact that whether there is enough fluctuation of load or not for a given material. A fatigue loading with low stress ratio (ratio of low minimum stress and high maximum stress) especially in case of fracture tough materials may lead to the existence of non-propagating crack.

However, growth of a propagating crack is primary determined by stress range (difference of maximum and minimum stress) and material properties such as ductility, yield strength and microstructural characteristics (size, shape and distribution of hard second phase particle in matrix). An increase in stress range in general increases the rate of stable crack growth in second stage of fatigue fracture. Increase in yield strength and reduction in ductility increase the crack growth rate primarily due to reduction in extent of plastic deformation (which reduces blunting of crack tip so the crack remains sharp tipped) experienced by material ahead of crack tip under the influence of external load. Increase blunting of crack tip lowers the stress concentration at the crack tip and thereby reduces the crack growth rate while a combination of high yield strength and low ductility causes limited plastic deformation at crack tip which in turn results in high stress concentration at the crack tip. High stress concentration at the crack tip produces rapid crack growth which reduces number of fatigue load cycle (fatigue life) required for completion of second stage of fatigue fracture of component.

All the factors associated with loading pattern and material which increase the stable crack growth rate, lower the number of fatigue load cycle required for fracture. High stress range in general increases the stable crack growth rate. Therefore, attempts are made by design and manufacturing engineers to design the weld joints so as to reduce the stress range on the weld during service (of possible) and lower the crack growth rate by developing weld joints of fracture tough material (having requisite ductility and yield strength).

The fracture mechanics principles have also been applied in fatigue studies to understand the conditions required for different stages of fatigue. The fracture mechanics considers the materials properties, crack size and applied stress condition for suggesting the conditions for growth of crack under fatigue condition. One of common terms in fracture toughness is stress intensity factor indicating the stress intensity near the tip of crack and is extensively used to predict the crack propagation and fracture conditions in case of homogeneous, linear elastic material for providing a failure criterion for brittle materials. Stress intensity factor (K) under uni-axial stress condition is given by $\sigma(\pi c)^{1/2}$. Where σ is applied stress (MPa), π is the constant, c is length (in m) of surface crack (half crack length of crack insides the body). For a given crack length, under varying load conditions stress intensity factor varies from max to min level as per externally applied stress. The variation in stress intensity factor is called stress intensity factor range (ΔK). A minimum stress intensity factor range needed for commencement of propagation of the crack is called threshold stress intensity factor (ΔK_{th}) as shown in Fig. 26.3. The Paris law shows the relationship between the stress intensity factor range (ΔK) and crack growth rate (dc/dN) per load cycle in second stage of fatigue fracture and is expressed as below.

Crack growth rate (dc/dN)= $C(\Delta K)^m$

Where c is the crack length, *N* is the number of load cycles and m is slope of curve in stage 2 of crack growth (Fig. 26.3).

26.2.3 Sudden fracture (Unstable crack growth)

Third of stage of fatigue fracture corresponds to unstable rapid crack growth causing abrupt facture. This stage commences only when load resisting cross sectional area of the engineering component (due to stable crack growth in second stage of fatigue fracture) is reduced to such an extent that it becomes unable to withstand maximum stress being applied during service. Hence, under such condition material failure occurs largely due to overloading of the remaining cross-section area. The mode of fracture at the third stage of fatigue failure may be ductile or brittle depending upon type of the material. Materials of high fracture toughness allow second stage stable crack growth (of fatigue fracture) to a greater extent which in turn delays the commencement of third stage unstable crack propagation (Fig. 26.3). Conversely for a given load, material of high fracture toughness (high strength and high ductility) can withstand to a very low load resisting cross sectional area prior to the commencement of third stage of fatigue failure than that of low fracture toughness matel.

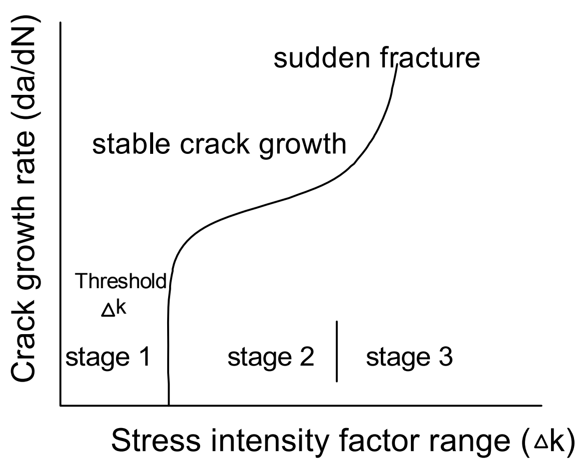

Fig. 26.3 Stage II stable fatigue crack growth rate vs stress intensity factor range in fatigue test.

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Lecture 27

DESIGN OF WELDED JOINTS VI

This chapter describes residual fatigue life concept and effect of various service load related parameters on fatigue performance of the weld joints. Further, relationship between crack growth and number of load cycle has also been elaborated.

Keywords: Crack growth, residual fatigue life, fatigue loading, maximum stress, type of stress, maximum stress, stress ratio, mean stress, loading frequency

27.1 Crack growth and residual fatigue life

Once the fatigue crack nucleated (after the first stage), it grows with the increase in number of fatigue load cycles. Slope of curve showing the relationship between crack size and number of fatigue load cycles indicates the fatigue crack growth rate doesn't remain constant (Fig. 27.1). The fatigue crack growth rate (slope of curve) continuously increases with increase in number of fatigue load cycles. Initially in second stage of the fatigue fracture, fatigue crack growth rate (FCGR) increase gradually in stable manner. Thereafter, in third stage of fatigue fracture, FCGR increases at very high rate with increase in number of fatigue load cycles as evident from the increasing slope of the curve.

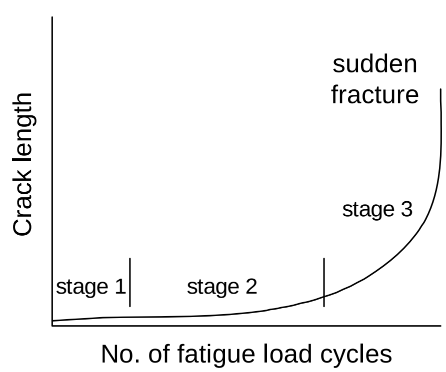


Fig. 27.1 Schematic of crack length vs. number of fatigue load cycles relationship

This trend of crack size vs. number of fatigue load cycle remains same even under varying service conditions of weld joints made of different materials. Moreover, the number of load cycles required for developing a particular crack size (during the second and third stage of fatigue facture) varies with factors related with service conditions, material and environment. For example, increase in stress range during fatigue loading of high strength and low ductility welds decreases the number of load cycles required to complete the second as well as third stage of fatigue fracture, conversely unstable fatigue crack prorogation (increasing FCGR) occurring in third stage of fatigue fracture is attained earlier. Increase in fatigue crack size in fact decreases the load resisting cross section (residual cross sectional area) of weld which in turn increases stress accordingly for given load fluctuations. Therefore, above trend of crack size vs. number of fatigue load cycles is mainly attributed to increasing true stress range for given load fluctuation which will actually be acting on actual load resisting cross section area at the any moment.

Residual fatigue life is directly determined by load resisting cross section area left due to fatigue crack growth (FCG) at any stage of fatigue life. Increase in crack length and so reduction in load resisting cross sectional area in general lowers the number of cycle required for complete fatigue fracture. Thus, left over fatigue life i.e. residual fatigue life of a component subjected to fluctuating load gradually decreases with increase in fatigue crack growth.

27.2 Factors affecting the fatigue performance of weld joints

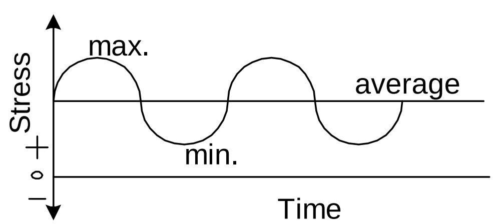
There are many factors related with service load condition, material and service environment affecting one or other stage (singly or in combination) of the fatigue fracture. The fatigue behavior of welded joints is no different from that of un-welded base metal except that weld joints need fewer number of load cycles due to many unfavorable features such as stress raisers, residual stresses, surface and sub-surface discontinuities, hardening/softening of HAZ, irregular and rough surface of the weld in as welded conditions (if not ground and flushed) besides in-homogeneity in respect of composition, metallurgical, corrosion and mechanical properties. Therefore, in general, fatigue performance of the weld joints is usually found offer lower than the base metal. However, this trend is not common in friction stir welded joint of precipitation hardenable aluminium alloys s these develop stronger and more ductile weld nugget than heat affected zone which is generally softened due to reversion in as welded conditions. The extent of decrease in fatigue performance (strength/life) is determined by severity of above mentioned factors present in a given weld besides the weld joint configuration and whether joint is load carrying or non-load carrying type. Reduction in fatigue performance of a weld joint can be as low as 0.15 times of fatigue performance of corresponding base metal depending up on the joint configuration and other welding related factors. Following section describe the influences of various service, material, environment and welding procedure related parameters on the fatigue performance of weld joints.

27.2.1 Service Load Conditions

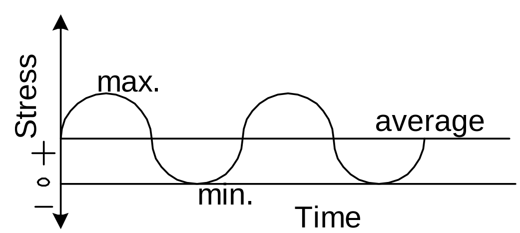
Service conditions influencing the fatigue performance of a weld joints mainly includes fatigue load and trend of its variation. Fluctuation of the load during the service can be in different ways. The fatigue load fluctuations are characterized with the help of different parameters namely type of stress, maximum stress, minimum stress, mean stress, stress range, stress ratio, stress amplitude, loading frequency etc. Following section presents the influence of these parameters in systematic manner on fatigue. These parameters help to distinguish the type of stresses and extent of their variation.

a) Type of stress

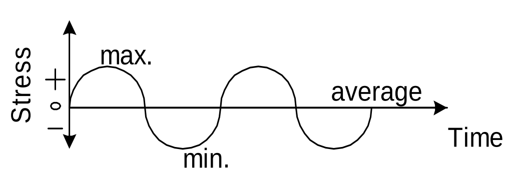
For nucleation and propagation of the fatigue cracks, existence of tensile or shear stress is considered to be mandatory. Presence of only compressive stress does not help in easy nucleation and propagation of the crack. Therefore, fatigue failure tendency is either reduced or almost eliminated when fatigue load is only of compressive type. As a customary, tensile and shear stress are taken as positive while compressive stress is taken as negative. These sign conventions play a major role when fatigue fluctuation is characterized in terms of stress ratio and stress range (Fig. 27.2).



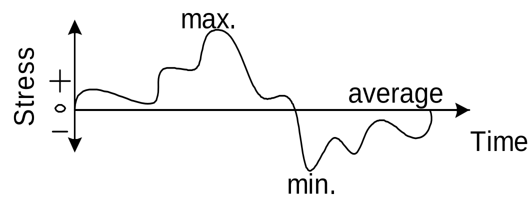
a) Tension-Tension



b) 0-Tension



c) Compression-Tension



d) Fluctuating stress

Fig. 27.2 Common fatigue load cycles

b) **Maximum stress**

It is maximum level of stress generated by fluctuating load and significantly influences the fatigue performance of the engineering component. Any discontinuity present in weld joints remains non-propagating type until maximum tensile/shear stress (due to fatigue loading) does not become more than certain limit. Thereafter, further increase in maximum stress in general lowers the fatigue life i.e. number of cycles required for fracture because of increased rate of crack growth in different stages of fatigue fracture occurring at high level of maximum stress leads to the reduction in number of load cycles required to completed each of the three stages of the fatigue fracture (Fig. 27.3).

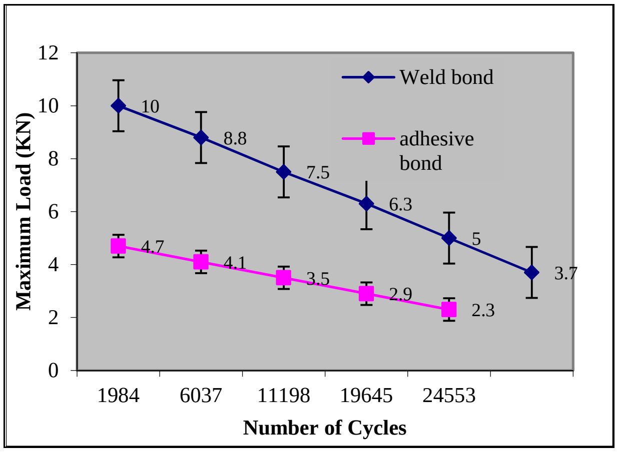


Fig. 27.3 effect of maximum load on fatigue life of weld bond and adhesive joints

c) Stress range

It is the difference between maximum and minimum stress induced by fatigue load acting on the engineering component of a given load resisting cross section area.

Difference of maximum and minimum stress gives the stress range directly if nature of stress remains same (tensile-tensile, compressive-compressive, shear-shear during loading. However, in case when load fluctuation changes nature of load from tensile and compressive, shear and compressive or vice versa then it becomes mandatory to use sign conventions with magnitude of stress according to the type of loading for calculating the stress range.

Zero stress range indicates that maximum and minimum stresses are of the same value and there is no fluctuation in magnitude of the load means load is static in nature therefore material will not be experiencing any fatigue. Conversely, for premature failure of material owing to fatigue it is necessary that material is subjected to enough fluctuations in stress during the service. The extent of fluctuation in stress (due to fatigue) is measured in terms of stress range. In general, increase in stress range lowers the fatigue life.

Most of the weld joint designs of real engineering systems for fatigue load conditions are therefore generally based on stress range or its derivative parameters such as stress amplitude (which is taken as half of the stress range) and stress ratio (ratio of minimum to maximum stress). In general, an increase in stress range decreases the fatigue life as evident from the fatigue behavior of friction stir weld joints in different temper conditions (Fig. 27.4)

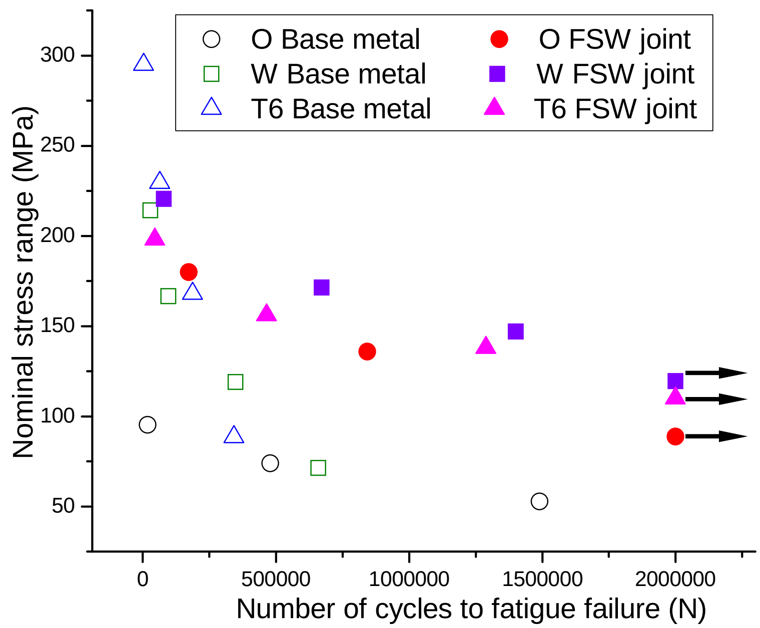


Fig. 27.4 Effect of stress range on fatigue life of friction stir weld joints

d) Stress ratio

It is obtained from ratio of minimum stress to maximum stress. Lower value of stress ratio indicates greater fluctuation in fatigue load. For example, stress ratio of 0.1, 0.2 and 0.5 are commonly used for evaluating the fatigue performance of weld joints as per requirement (Fig. 27.5). Stress ratio of 0.1 indicates that maximum stress is 10 times of minimum stress. Stress ratio of zero value suggests that minimum stress is zero while stress ratio of -1 indicates that the load fluctuates equally on tensile/shear and compressive side. The decrease in stress ratio for tensile and shear fatigue loads (say from 0.9 to 0.1) adversely affects the fatigue performance.

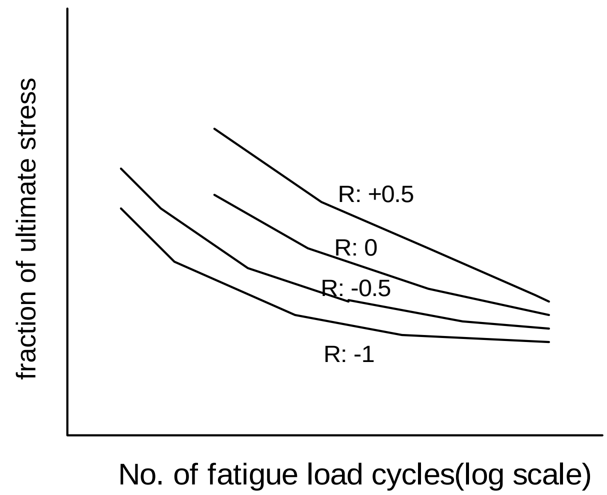


Fig. 27.5 Effect of stress ratio (R) on fatigue life (N) for given stress conditions

e) Mean stress

Mean stress is average of maximum and minimum stress. The influence of mean stress on the fatigue life mainly depends on the stress amplitude and nature of mean stress. Nature of mean stress indicates the type of stress. The effect of nature of mean stress i.e. compressive, zero, and tensile stress, on the fatigue life at low stress amplitude is more than that at high stress amplitude. It can be observed that in general mean tensile stress results in lower fatigue life than the compressive and zero mean stress (Fig. 27.6). Further, increase in tensile mean stress decreases the number of load cycle required for fatigue crack nucleation and prorogation of the cracks which in turn lowers the fatigue life.

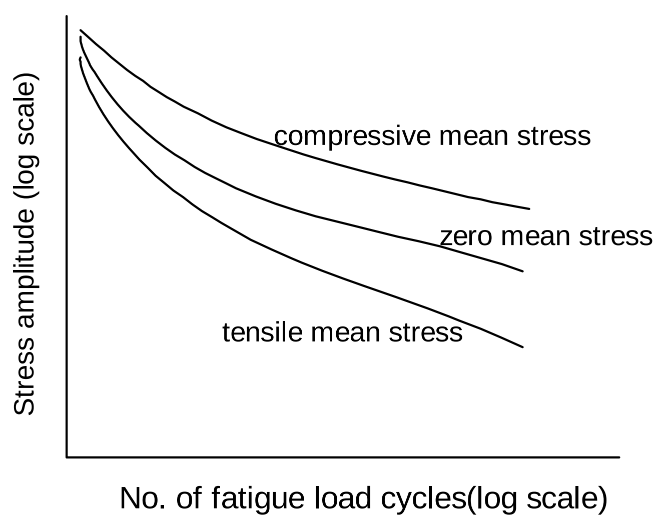


Fig. 27.6 Effect of type of stress on S-N curve

f) Frequency of fatigue loading

Frequency of the fatigue loading is number of times a fluctuating load cycle repeats in unit time and is usually expressed in terms of Hz which indicates the number of fatigue load cycles per second. Frequency of fatigue loading has little influence on fatigue performance.

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- R. Radaj, Design and Analysis of Fatigue Resistant Welded Structures, Woodhead Publishing, (1990)
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Lecture 28

DESIGN OF WELDED JOINTS VI

This chapter describes the influence of various physical, mechanical and metallurgical characteristics on fatigue performance of the weld joint. Further, the influence of environmental conditions namely temperature, vacuum and corrosion on fatigue behavior of the weld joint has also been elaborated.

Keywords: Melting point, thermal expansion coefficient, hardness, ductility, microstructure, morphology, aspect ratio, temperature, vacuum

28.1 Material Characteristics

The performance of an engineering component under fatigue load conditions is significantly influenced by various properties of weld / HAZ / base material such as physical properties, mechanical, corrosion and metallurgical properties.

a) Physical properties

Many physical properties such as melting point, thermal diffusivity and thermal expansion coefficient, of the base or filler metal can be important for development of sound weld. It is felt that probably thermal expansion coefficient of base metal is one of physical properties which can appreciably affect the fatigue performance of a sound weld joint as it directly influences the magnitude and type of residual stress developed due to weld thermal cycle experienced by the base metal during welding. Tensile residual stresses are usually left in weld metal and near-by HAZ which adversely affect the fatigue life of weld joint and therefore attempts are made to develop compressive residual stress in weld joints using localized heating or deformation based approaches.

b) Mechanical properties

Mechanical properties of the weld joint such as hardness, yield and ultimate tensile strength, ductility and fracture toughness significantly affect the fatigue strength of the weld. The extent of influence of an individual mechanical property on fatigue performance primarily depends on the way by which it affects the one or other stage of the fatigue fracture. For example, high ductility, low hardness and low yield strength lower the load cycle for the crack nucleation stage while low ductility, low tensile strength and high fracture toughness delay second stage of fatigue fracture i.e. lower stable crack growth rate and both these stages constitute to about 90% of the fatigue life.

It is generally believed that under the conditions of high stress concentration as in case of welded joints (especially in fillet weld and weld with severe discontinuities and stress raisers and those used in corrosive environment), the mechanical properties such as tensile strength and ductility don't affect the fatigue performance appreciably (Fig. 28.1). Therefore, design and production engineers should not rely much on tensile strength of electrode material for developing fatigue resistant weld joints. Moreover, in case of full penetration, ground, flushed, defect free butt weld joints, mechanical properties namely ductility, hardness tensile strength and fracture toughness can play an important role in determining the fatigue performance. Moreover, the effect of these properties on each stage of fatigue fracture has been described in respective sections (?) of fatigue fracture mechanism.

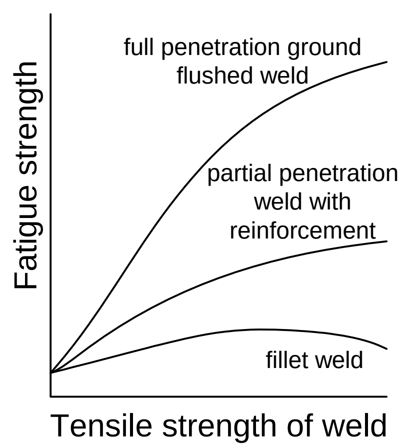
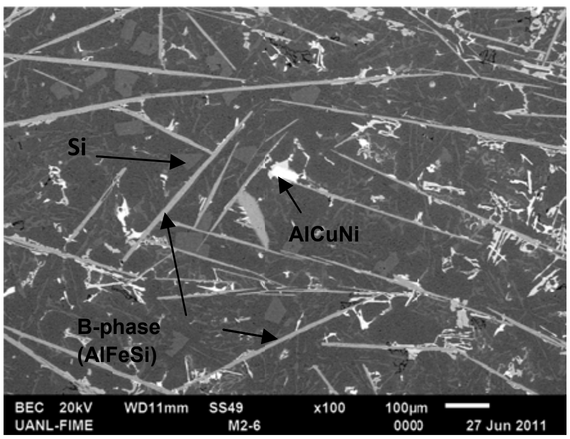


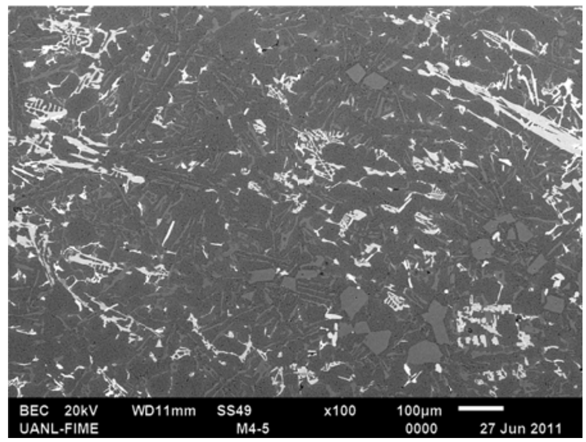
Fig. 28.1 Schematic diagram showing the fatigue strength vs. tensile strength relationship for different conditions of the weld

c) Metallurgical properties

Metallurgical properties such as microstructure and segregation of elements in weld influence the fatigue performance. Microstructure indicates the size, shape and distribution of grains besides the type and relative amount of various phases present in the structure. Due to varying cooling conditions experienced by weld metal and heat affected zone during welding severe structural in-homogeneity is observed in the weld metal. Therefore, the mode of weld metal solidification continuously varies from planar at fusion boundary to cellular, dendritic then equiaxed at weld center line which in turn results in varying morphologies of grains in weld metal. Similarly, size of grains also varies from coarsest at fusion boundary to finest at weld center line. Combination of welding process, welding parameters (deciding net heat input), section size and base metal composition eventually. Determines the final grain and phase structure. Needle shape phases lower the fatigue life more than spherical and cuboids shape micro-constituents (Fig. 28.2). In general, fine and equiaxed grains results in longer fatigue life than coarse and columnar dendritic grains as crack nucleation and stable crack grow stages of fatigue fracture are delayed. Therefore, attempts are made to have refined equiaxed grain structure using various approaches such as controlled alloying, external excitation forces, arc pulsation etc.



a)



b)

Fig. 28.2 Micrographs of aluminium-silicon alloy showing micro-constituents of different morphologies with a) long needles of Al-Si-Fe and b) fine and Chinese script morphologies

28.2 Environment

Fatigue performance of a weld joint is significantly governed by the service environments such as corrosion, high temperature and vacuum. In general, all these especial environments can effect the fatigue performance in either way (positively or negatively).

28.2.1 Corrosion fatigue

The performance of an engineering component which is exposed to corrosive media during the service and is also subjected to fluctuating load is terms as corrosion fatigue. Corrosion means localized removal of materials either from plane smooth surface or from the tip of pre-existing discontinuity. Localized corrosion from smooth surface facilitates easy nucleation of crack during first stage of fatigue fracture by forming small pits and crevices while removal of material from crack tip by corrosion accelerates the crack growth rate during second stage of fatigue fracture. A synergic effect of stable crack growth during second stage of stable crack growth and material removal from crack tip lowers the fatigue life drastically. Moreover, how far corrosion will affect fatigue life; it depends on corrosion media for a given metal of weld e.g. steel weld joints perform very more badly in saline environment (halide ions) than dry atmospheric conditions.

28.2.2 Effect of temperature

Effect of slight variation in temperature on fatigue performance of the weld joint is marginal. Low temperature generally increases the hardness and tensile strength and lowers the ductility. Increase in hardness and strength delays the crack nucleation stage during first stage of fatigue fracture, however; a combination of high strength and low ductility increases the stable crack growth rate in second stage of fatigue fracture. Carbon steel and mild steel weld joints below the ductile to brittle transition temperature lose their toughness which in turn increases the stable fatigue crack growth rate in second stage of the fatigue fracture. On the other hand, increase in temperature lowers the strength and increases the ductility. This combination of strength and ductility reduces the number of load cycles required for nucleation of the fatigue crack in first stage of fatigue fracture while crack tip blunting tendency increases due to easy deformation of the material ahead of the crack tip in turn lowers the second stage stable crack growth rate. Therefore, influence of slight increase in temperature on the fatigue life is not found to be very decisive and significant. However, too high or low temperatures can lower the fatigue performance appreciably due to large variation in material properties such as hardness, ductility and strength.

28.2.3 Effect of Vacuum

The fatigue performance of weld joints in vacuum is found much better than in the normal ambient conditions. This improvement in fatigue performance is mainly attributed to absence of any surface oxidation and other reactions with atmospheric gases.

References and books for further reading

- R. Radaj, Design and Analysis of Fatigue Resistant Welded Structures, Woodhead Publishing, (1990)
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Lecture 29

DESIGN OF WELDED JOINTS VII

This chapter presents the influence of various welding related parameters on fatigue behavior of weld joints. Attempts have been made to explain how (residual stress, mechanical properties and microstructure) fatigue performance is affected by variation in welding parameters.

Keywords: Welding parameters, welding procedure, edge preparation, welding process, welding consumable, cleanliness, flux, electrode diameter, post weld heat treatment

29.1 Parameters related with welding

There are many aspects related with welding which influence the fatigue performance of a sound (defect free) weld joint such as welding procedure, weld bead geometry, weld joint configuration and residual stress in weld joint. These parameters affect the fatigue performance in four ways a) how stress raiser in form of weld continuities are induced or eliminated, b) how do residual stresses develop due to weld thermal cycle experienced by the metal during the welding, c) how are mechanical properties such as strength, hardness, ductility and fracture toughness of the weld joint influenced and d) how is the microstructure of the weld and HAZ affected by the welding related parameters.

29.1.1 Welding procedure

Welding procedure includes the entire range of activities from edge preparation, selection of welding process and their parameters (welding current, speed), welding consumable (welding electrode and filler, flux, shielding gas), post weld treatment etc needed for development of a weld joint. Following sections describe effect of various steps of welding procedure on the fatigue performance of the weld joints.

Edge preparation

There are two main aspects of edge preparation which can influence the fatigue performance of a weld joint a) cleanliness of faying surface and b) cutting of faying surface of base metal to be welded by fusion arc welding process. Surface and edge of the plates to be welded are cleaned to remove the dirt, dust, paint, oil, grease etc. present on the surface either by mechanical or chemical methods. Use of chemical approach for cleaning the surface using hydrogen containing acid (sulphuric acid, hydrochloric acid etc.) sometimes introduce hydrogen in base metal which in long run can diffuse in weld and HAZ and facilitate crack nucleation & propagation (by HIC) besides making weldment brittle (Fig. 29.1). Further, improper cleaning sometimes leaves impurities on faying surface, which, if are melted or evaporated during the welding then these impurities can induce inclusions in weld metal. Presence of inclusions in weld metal acts as stress raiser for nucleation and growth of cracks and so weakens the joint and lowers fatigue performance. Cutting of hardenable steel plates by thermal cutting methods such as gas cutting also hardens the cut edge. These hardened edges can easily develop cracks in HAZ under the influence of the residual stresses caused by weld thermal cycle associated with welding.

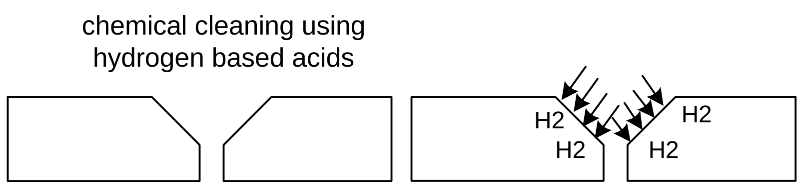

Fig. 29.1 Hydrogen based chemical cleaning can introduce hydrogen in weld

29.1.2 Welding process

Welding process affects the fatigue performance in two ways a) net heat input per supplied during welding affects cooling rate and the so weld-structure and b) soundness / cleanliness of the weld. Arc welding processes use heat generated by an arc for melting of the faying surfaces of the base metal. Heat generation from welding arc (VI) of a process depends on welding current (A) and welding arc voltage (V) while net heat supplied to base metal for melting is determined by welding speed (S). Therefore, net heat supplied to the faying surfaces for melting is obtained from ratio of arc heat generated and welding speed (VI/S). Net arc heat supplied to base metal falls over an area as determined by arc diameter at the surface of base metal. Net heat input per unit area of the base metal affects the amount of the heat required for melting. Higher the net heat input lower is cooling rate (Fig. 29.2). High cooling rate results in finer grain structure and better mechanical properties hence improved fatigue performance while low cooling rate coarsens the grain structure of weld which in turn adversely affects the fatigue life. However, high cooling rate in case of hardenable steel tends to develops cracks and harden the HAZ which may deteriorate the fatigue performance of the weld joints.

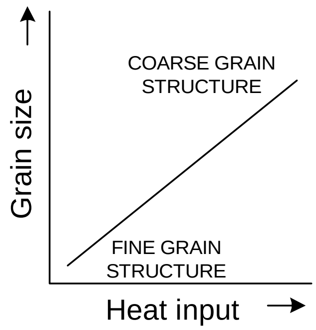

Fig. 29.2 Schematic diagram showing effect of heat input on cooling rate and grain structure of the weld

Each arc welding process offers a range for net heat input capacity which in turn affects the cooling rate and so the grain structure and fatigue performance accordingly. For example, shielded metal arc welding possess provides lower net heat input unit area than gas tungsten arc welding for developing sound weld joints.

Impurities in the form of inclusion in weld are introduced due to interactions between the molten weld metal and atmospheric gases. However, the extent of contamination of the weld metal by atmospheric gases depends on the shielding method associated with the particular welding process to protect the "molten weld". Each method has its own approach/mechanism of protecting the weld. GTA welding offers minimum adverse effect of weld thermal cycle and cleanest weld in terms of lowest oxygen and nitrogen content in the weld metal as compared to other welding process. On contrary SAW welding results in high oxygen concentration in weld while self shielded arc welding process produces weld joints with large amount of oxygen and nitrogen as impurities in the weld metal. These gases in turn result in inclusions and porosity in the weld and so degrades their fatigue performance. Therefore, selection of welding process affects the fatigue performance appreciably.

29.1.3 Welding consumables

Depending upon the welding process being used for fabrication of a fusion weld, variety of welding consumables such as welding electrode, filler wire, shielding gas, flux etc. are applied. The extent up to which the factors related with welding consumables influence the fatigue performance is determined by the fact that how following characteristics related with welding are affected by welding consumables:

a) net heat input

b) cleanliness of the weld metal
c) residual stress development
d) microstructure and chemical composition
e) mechanical properties of the weld joints

Effect of each of above aspects related with welding has already been described under separate headings in previous section. In following section, influence of welding consumable on each of the aspects will be elaborated.

a) Electrode

Electrode diameter, and its material affect the arc heat generation (due to variation in area over which is heat is applied and amount of heat generated (as per welding current and arc voltage) which in turn governs weld thermal cycle and related parameters such as cooling rate, solidification rate, peak temperature and width of HAZ. Large diameter electrodes use high welding current which in turn results in high net heat input. Composition of the electrode material affects the solidification mechanism of the weld metal, residual stress in weldment and mechanical properties of the weld metal. Electrode material similar to that of base metal results in epitaxial solidification and otherwise heterogeneous solidification through nucleation and growth mechanism is followed. The difference in thermal expansion coefficient and yield strength of electrode metal with respect to base metal determines the magnitude of residual stress in weld and HAZ region. Larger is the difference in thermal expansion coefficient of two (base metal and weld metal) higher will be the residual stresses. Further, low yield strength weld metal results in lower residual stresses than high yield strength metal. Development of tensile residual stresses in general lowers fatigue life of weld joints. Further, according to the influence of the solidification mechanism, microstructure and residual stress on mechanical properties of weldment, fatigue performance is governed. The equiaxed solidification mode, fine grain structure, compressive residual stresses improve the fatigue performance of the weld joints.

b) Coating material and flux

Presence of low ionization potential elements like Na, K, Ca etc. (in large amount) lowers the heat generation as easy emission of free electrons from these elements in coating material in the arc gap improve the electrical conductivity by increasing the charge particle density which in turn reduces the electrical resistance of arc column and so heat generation for a given current setting. Additionally, the basicity index of the flux or coating material on the electrode affects the cleanliness of the weld. In general, flux or coating material having basicity index greater than 1.2 results in cleaner weld than that of low basicity index. Thickness of the coating material on the core wire in SMA welding affects the contamination of the molten weld pool by influencing the shielding capability from atmospheric gases. Thicker is flux coating on the core wire better is protection due to release of large amount of inactive protective gases from thermal decomposition of coating materials and so cleaner is weld. However, increase in thickness of flux layer in SAW lowers the cooling rate of weld metal during the solidification and increases the protection from atmospheric contamination. Effect of both these factors on fatigue performance of the weld is expected to be different e.g. low cooling should adversely affect the mechanical properties and fatigue performance while cleaner weld should offer better fatigue performance owing to absence of stress raisers in form of inclusions.

c) Shielding gas

The effect of shielding gas (helium, argon, carbon dioxide, and mixture of these gases with oxygen, helium and hydrogen) on fatigue performance of the weld joint is determined by two factors:

a) **Effect of shielding gas on the arc heat generation**: The shielding gas affect the heat generation in the arc gap due to difference in ionization potential of different shielding gases. The variation in heat input in turn affects the cooling rate and so resulting microstructure and mechanical properties of the weld. High ionization potential shielding gas in general burns the arc hotter which in turn leads to lower net heat input higher cooling rate thus finer structure and improved mechanical properties produce enhanced fatigue performance of the weld joint. Addition of oxygen, hydrogen and helium in argon increases the arc heat generation and penetration capability of the arc.

b) **Effect of shielding gas on the cleanliness of the weld**: Shielding capability of each of the above mentioned gases to protect the molten weld pool from atmospheric gases is found different. Helium and argon provide more effective shielding than carbon di-oxide and other gases and hence they result in better fatigue performance of the weld joints. As carbon dioxide tends to decompose in arc environment to produce Co and O_2. Presence of oxygen arc zone can contaminate the weld metal.

29.1.4 Post Weld Heat Treatment

Weld joints are given variety of heat treatments (normalizing, tempering, stress relieving, Q &T, T6 treatment) for different purposes ranging from just relieving the residual stress to manipulating the microstructure in order to obtain the desired combination of the mechanical properties. In general, post weld heat treatment operation relieves the residual stresses and improves the mechanical properties; these in turn result in improved fatigue performance of the weld joints. However, improper selection of type of PWHT and their parameters like heating rate, maximum temperature, soaking time and then cooling rate, can deteriorate the microstructure and mechanical properties, induce unfavorable softening or hardening of HAZ, tensile residual stresses and cracking in HAZ. As a result, unfavorable PWHT can adversely affect the fatigue performance of the weld joint.

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Lecture 30

DESIGN OF WELDED JOINTS VIII

This chapter presents various approaches commonly used for enhancing the fatigue performance of weld joints namely reducing stress raiser, improving mechanical properties and inducing compressive residual stresses. Methods of improving fatigue behavior of weld joints based on above approaches have been elaborated.

Keywords: Improving fatigue performance, stress raiser, compressive residual stress, TIG dressing, shallow hardening, shot peening, overloading

30.1 Improving the fatigue performance of the weld joints

The performance of welded joints can be improved using multi-pronged approach which includes enhancing the load carrying capability of the weld by improving the mechanical properties of the weld, reducing the stress raisers, developing favorable compressive residual stresses. The basic principles of these approaches have been presented in following sections.

30.1.1 Increasing load carrying capacity of the weld

Load carrying capability of the weld joints can be enhanced by selecting proper electrode or filler metal and proper welding procedure so to obtain the desired microstructure and mechanical properties of the weld joints. Efforts are made to achieve the fine equiaxed grain structure in weld with minimum adverse affect of weld thermal cycle on the heat affected zone. These factors are influenced by electrode material composition, net heat input during welding and presence of nucleating agents in weld metal to promote heterogeneous nucleation so as to get refined equiaxed grain structure in the weld metal. Inoculation involving addition of the element like Ti, V, Al and Zr are commonly used in steel and aluminium welds to realize the fine equiaxed grain structure. Additionally, application of external excitation techniques such magnetic arc oscillation, arc pulsation and gravitational force method can also be used for grain refinement of weld metal. Selection of proper welding parameters (welding current, speed) and shielding gas also help to refine the grain structure of the weld by reducing the net heat input for developing weld joints. In general, fine equiaxed grain structure is known to enhance the load carrying capacity of weld joints and fatigue performance of the weld joints. Post weld heat treatment namely normalizing also helps to a) enhance fatigue performance of weld joints, b) refine the structure and c) relieve the residual stress. Surface and case hardening treatments like carburizing and nitriding also help to increase the fatigue performance of the weld joints in two ways a) increase the surface hardness up to certain depth and b) inducing compressive residual stresses.

30.1.2 Reducing stress raisers

First stage of fatigue crack nucleation is largely influenced by the presence of the stress raisers on the surface of engineering component subjected to fatigue loading. These stress raisers in the weld joints are mostly found in the form of ripples present on the surface of weld in as welded condition, sharp change in cross section at the toe of the weld, cracks in weld metal and heat affected zone, inclusions in weld, too high bead angle, excessive reinforcement of the weld bead, crater and under-fill (Fig. 30.1).

In order to reduce adverse effects of stress raisers on fatigue performance of weld joints, it is necessary that stress raisers in form of poor weld bead geometry and weld discontinuities are reduced as much as possible by proper selection of the welding parameters, consumable, manipulation of welding arc and placement of molten weld metal (Fig. 30.2). Presence of inclusions and defects in the weld metal can be reduced by re-melting of small amount of weld metal near toe of the weld using tungsten inert gas arc heat (Fig. 30.3). This process of partial re-melting weld bead to remove defect and inclusions especially near the toe of the weld is called TIG dressing. TIG dressing is reported to increase the fatigue life by 20-30% especially under low stress fatigue conditions. The TIG dressing also disturbs the system of residual stress by the re-melting a small portion of weld and HAZ.

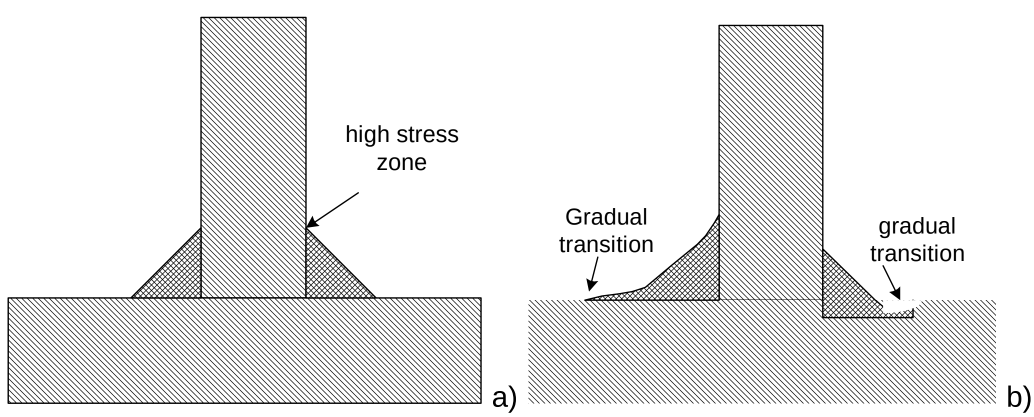

Fig. 30.1 Reducing stress concentration at toe of the weld a) toe with sudden change in cross section causing high stress concentration and b) providing some fillet at the toe of the weld by grinding

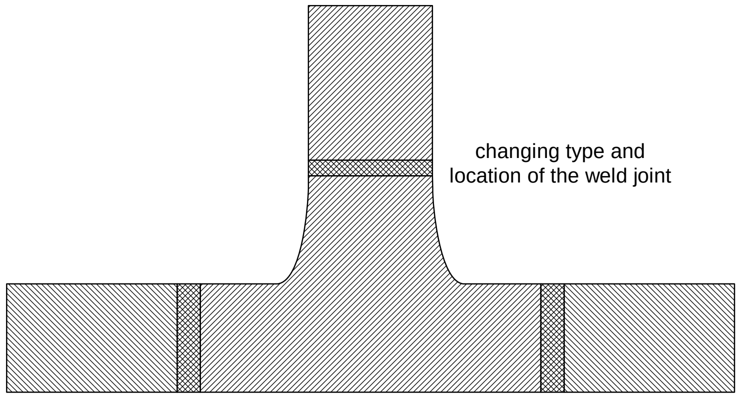

Fig. 30.2 Schematic diagram showing change on joint configuration from fillet to butt joints

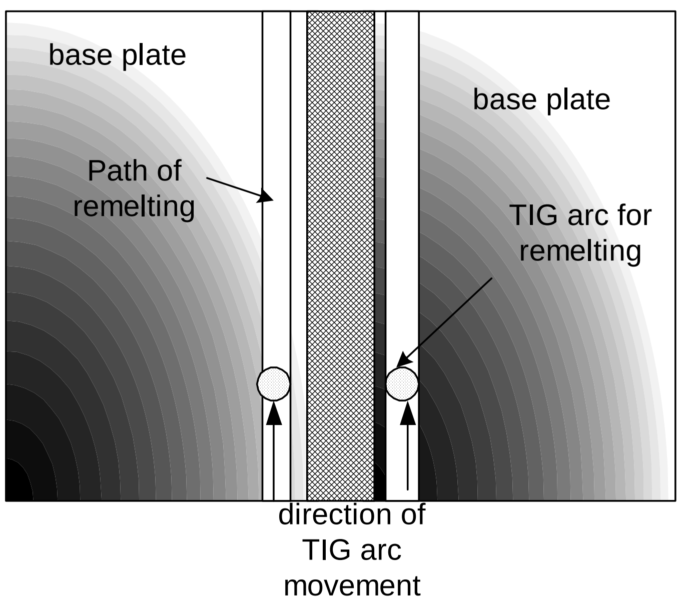

Fig. 30.3 Schematic of TIG dressing

Controlled removal of material from the toe of the weld by machining or grinding in order to give suitable fillet so as to avoid abrupt change in cross section of the weld is another method of enhancing the fatigue life of weld joints by reducing the severity of stress raisers.

Further, attempts should be made to reduce the weld bead angle as low as possible so that transition in cross-sectional area from the base metal to the weld bead is gradual to produce a weld joint without stress concentration (Fig. 30.1). Weld joints with machined, ground and flushed weld bead offer minimum stress concentration effect and hence maximum fatigue life. Additionally, efforts can be made to relocate the stress raisers away from the high stress areas by redesigning of components. For example, fillet weld can be replaced with butt weld by relocating the weld through redesign of component (Fig.30.2)

30.1.3 Developing compressive residual stress

This method of improving the fatigue performance of the weld joints is based on simple concept of lowering the effective applied tensile stresses by inducing compressive residual stress. This type of stress to some extent neutralizes/cancels the magnitude of externally applied tensile stress. Therefore, this method is found effective only when fatigue load is tensile in nature and its magnitude is lower than yield strength. Moreover, this method marginally affects the fatigue performance of the weld joints under low cycle fatigue conditions when fluctuating loads and corresponding stresses are more than yield strength of weld. Improvement in fatigue performance of the weld joint by this method can vary from 20-30%. There are many methods namely shot peening, overloading, spot heating, and post-weld heat treatment, which can be used to induce compressive residual stress. All these methods are based on principles of differential dimensional/volumetric change at the surface layer and core of the weld by application of either localizing heating or stresses beyond yield point.

a) Shot peening

In case of shot peening, high speed steel balls are directed towards the surface of the weld joint on which compressive residual stress is to be developed. Impact of shots produces indentation through localized plastic deformation at the surface layers of weld and HAZ while metal layers below the plastically deformed surface layers are subjected to elastic deformation. Material further deeper from the surface remains unaffected by shots and plastic deformation occurring at the surface. Elastically deformed layers tend regain their dimensions while plastically elongated surface layers resist any come-back. Since both plastically and elastically elongated layers are metallurgically bonded together therefore elastically elongated under-surface metal layer tends to put plastically elongated surface layer under compression while elastically elongated under-surface layers come under tension. Thus, residual compressive stresses are induced at shot peened surface. Presence of tensile residual stress below the surface is not considered to be much damaging for fatigue life as mostly fatigue failures commence from the surface.

b) Overloading

This method helps to reduce the residual stresses by a) developing the opposite kind of elastic stresses and b) relieving the locked in strain using plastic deformation by overloading the component under consideration.

c) Shallow hardening

Shallow hardening improves the fatigue performance in two ways a) increase in the hardness of surface and near surface layers which in turn delays crack nucleation stage of fatigue fracture and b) development of residual compressive stress at the surface reduces adverse effect of the external tensile stresses on all stages of fatigue fracture hence improve the fatigue performance. However, under external compressive loading conditions, residual compressive stresses will deteriorate the fatigue performance of welds.

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Lecture 31

INSPECTION AND TESTING OF WELD JOINT I

This chapter explains the need of inspection and testing of welded joints in different stages besides two broad categories of testing of weld joints. Further, three most common destructive testing methods namely tensile, hardness and bend test also have been described.

Keywords: Stages of inspection, weld testing, quality of weld, destructive testing, tensile test, bend test, hardness test

31.1 Introduction

To produce quality weld joints, it is necessary to keep an eye on what is being done in three different stages of the welding

- Before welding such as cleaning, edge preparation, baking of electrode etc. to ensure sound and defect free weld joints
- During welding various aspects such as manipulation of heat source, selection of input parameters (pressure of oxygen and fuel gas, welding current, arc voltage, welding speed, shielding gases and electrode selection) affecting the heat input and so melting, solidification and cooling rates besides protection of the weld pool from atmospheric contamination
- After welding steps, if any, such as removal of the slag, peening, post welding treatment

Selection of optimal method and parameters of each of above steps and their execution meticulously in different stages of production of a weld joint determine the quality of the weld joint. Inspection is mainly carried out to assess ground realties in respect of progress of the work or how meticulously things are being implemented. Testing helps to: a) assess the suitability of the weld joint for a particular application and b) to take decision on whether to go ahead (with further processing or accept/reject the same) at any stage of welding and c) quantify the performance parameters related with soundness and performance of weld joints.

Testing methods of the weld joint are broadly classified as destructive testing and non-destructive testing. Destructive testing methods damage the test piece to more or less extent. The extent of damage on (destructive) tested specimens sometime can be up to complete fracture (like in tensile or fatigue testing) thus making it un-useable for the intended purpose while in case of non-destructive tested specimen the extent of damage on tested specimen is either none or negligible which does not adversely affect their usability for the intended purpose in anyways.

Weld joints are generally subjected to destructive tests such as hardness, toughness, bend and tensile test for developing the welding procedure specification and assessing the suitability of weld joint for a particular application.

Visual inspection reflects the quality of external features of a weld joint such as weld bead profile indicating weld width and reinforcement, bead angle and external defects such as craters, cracks, distortion etc. only.

31.2 Destructive Test

31.2.1 Tensile test

Tensile properties of the weld joints namely yield and ultimate strength and ductility (%age elongation, %age reduction in area) can be obtained either in ambient condition or in special environment (low temperature, high temperature, corrosion etc.) depending upon the requirement of the application using tensile test which is usually conducted at constant strain rate (ranging from 0.0001 to 10000 mm/min). Tensile properties of the weld joint are obtained in two ways a) taking specimen from transverse direction of weld joint consisting base metal-heat affected zone-weld metal-heat affected zone-base metal and b) all weld metal specimen as shown in Fig. 31.1 (a, b).

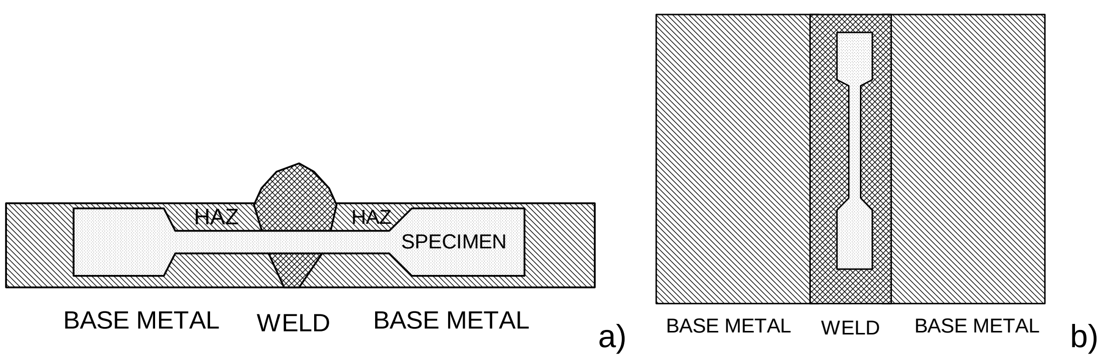


Fig. 31.1 Schematic of tensile specimens from a) transverse section of weld joints and b) all weld specimen

Tensile test results must be supported by respective engineering stress and strain diagram indicating modulus of elasticity, elongation at fracture, yield and ultimate strength (Fig. 31.2). Tests results must includes information on following point about test conditions

- Type of sample (transverse weld, all weld specimen)
- Strain rate (mm/min)
- Temperature or any other environment in which test was conducted if any
- Topography, morphology, texture of the fracture surface indicating the mode of fracture and respective stress state

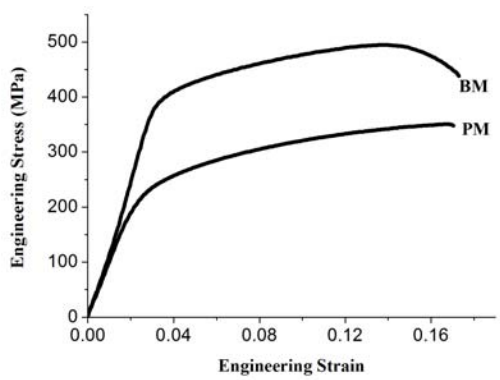


Fig. 31.2 Typical stress stain diagram for AA 7039 in as received (BM) and friction stir prcoessed (PM) condition

31.2.2 Bend test

Bend test is one of the most important and commonly used destructive tests to determine the ductility and soundness (for the presence porosity, inclusion, penetration and other macro-size internal weld discontinuities) of the weld joint produced using under one set of welding conditions. Bending of the weld joint can be done from face or root side depending upon the purpose i.e. whether face or root side of the weld is to be assessed. The root side bending shows the lack of penetration and fusion if any at the root. Further, bending can be performed using simple compressive/bending load and die of standard size for free and guided bending respectively (Fig. 31.3, 31.4). Moreover, free bending can be face or root bending while guided bending is performed by placing the weld joint over the die as needs for bending is better and controlled condition as shown in Fig. 31.4.

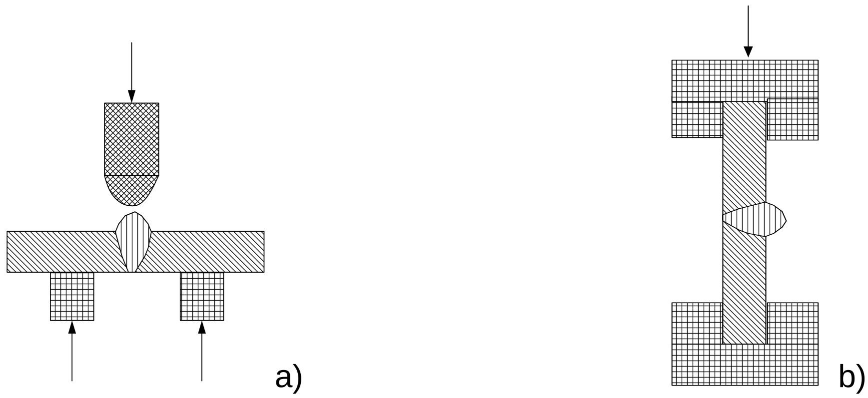
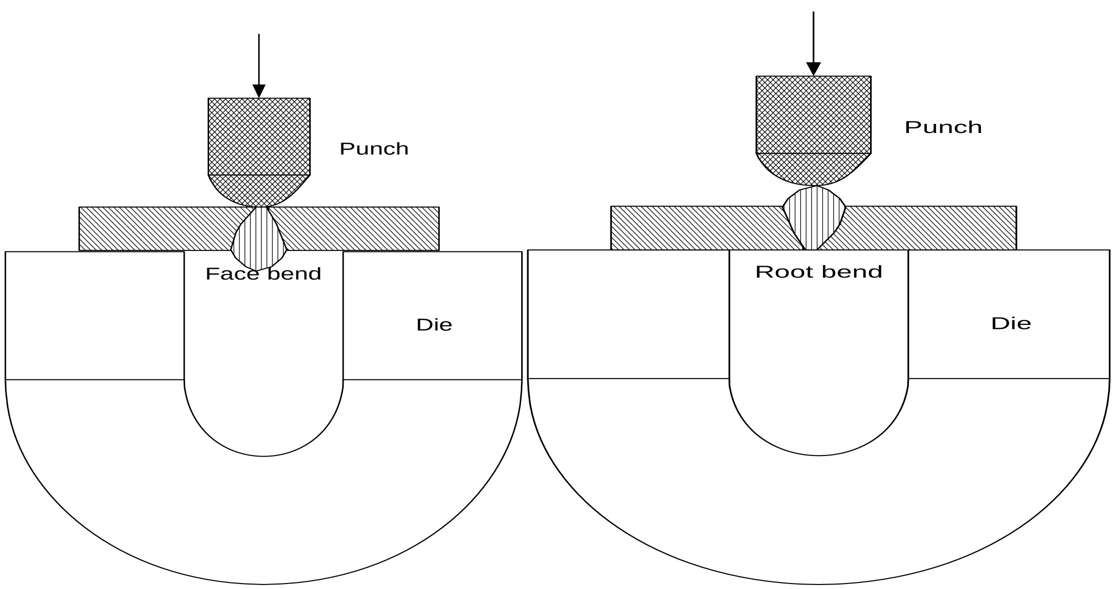


Fig. 31.3 Schematics of free bend tests



a) b)

Fig. 31.4 Schematics of guided bend tests a) face bend and b) root bend.

For bend test, the load increased until cracks start to appear on face or root of the weld for face and root bend test respectively and angle of bend at this stage is used as a measured of ductility of weld joints. Higher is bend angle (needed for crack initiation) greater is ductility of the weld. Fracture surface of the joint from the face/root side due to bending reveals the presence of internal weld discontinuities if any.

31.2.3 Hardness test

Hardness is defined as resistance to indentation and is commonly used as a measure of resistance to abrasion or scratching. For the formation of a scratch or causing abrasion, a relative movement is required between two bodies and out of two one body must penetrate/indent into other body. Indentation is the penetration of a pointed object (harder) into other object (softer) under the external load. Resistance to the penetration of pointed object (indenter) into the softer one depends on the hardness of the sample on which load is applied through the indenter.

All methods of hardness testing are based on the principle of applying the standard load through the indenter (a pointed object) and measuring the penetration in terms of diameter/diagonal/depth of indentation (Fig. 31.5). High penetration of an indenter at a given standard load suggests low hardness. Various methods of hardness testing can be compared on the basis of following three criteria 1) type of indenter, 2) magnitude of load and 3) measurement of indentation.

<table>
<tr><th>Parameter</th><th>Brinell</th><th>Rockwell</th><th>Knoop</th><th>Vickers</th></tr>
<tr><td>Load</td><td>500-2000 kg</td><td>Minor: 10 kg
Major: 60 to 200 kg as dictated by scale to be used (A-C)</td><td colspan="2">10 to 3000 g</td></tr>
<tr><td>Indenter</td><td>Ball</td><td>Ball or cone</td><td>Cone</td><td>Pyramid</td></tr>
<tr><td>Measurement</td><td>Diameter</td><td>Depth</td><td>Diagonal</td><td>Diagonal</td></tr>
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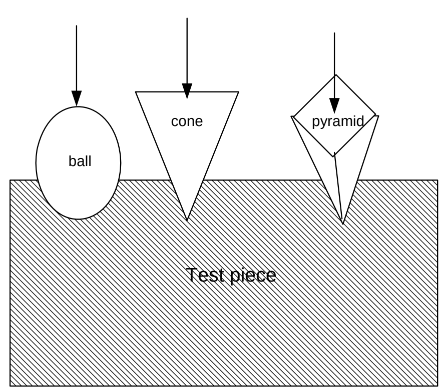

Fig. 31.5 Schematic diagram showing indentation using different indenters corresponding to different hardness test methods

Penetration due to applied normal load is affected by unevenness on the surface and presence of hard surface films such as oxides, lubricants, dust and dirt etc. if any. Therefore, surface should be cleaned and polished before hardness test. In case of Brinell hardness test, full load is applied directly for causing indentation for measuring hardness while in case of Rockwell hardness test, minor load (10 kN) is applied first before applying major load. Minor load is applied to ensure the firm metallic contact between the indenter and sample surface by breaking surface films and impurities if any present on the surface. Minor load does not cause indentation. Indentation is caused by major load only. Therefore, cleaning and polishing of the surface films becomes mandatory for accuracy in hardness test results in case of Brinell test method as major load is applied directly.

Steel ball of different diameters (D) is used as an indenter in Brinell hardness test. Diameter of indentation (d) is measured to calculate the projected area and determine the hardness. Brinell hardness test results are expressed in terms of pressure generated due to load (P). It is calculated by the ratio of load applied and projected contact area. Load in the range of 500 to 3000 kg can be applied depending upon the type of material to be tested. Higher load is applied for hardness testing of hard materials as compared to soft materials.

$$\mathrm{BHN} = \frac{2P}{\pi D[D - (D^2 - d^2)]^{1/2}}$$

In case of Rockwell hardness test first minor load of 10 kg is applied and then major load of 50-150kg is applied on the surface of the work-piece through the indenter and the same is decided by scale (A, B, C and D) to be used as per type of material to be tested. Minor load is not changed. Out of mainly scales, B and C scales are commonly used. Different indenter and major load are required for each scale. Steel ball and diamond cone are two types of indenters used in Rockwell testing. B scale uses hardened steel ball and major load of 90kg whereas C scale uses diamond cone and major load of 140kg accordingly hardness is written in terms of HRB and HRC respectively.

Vickers hardness test uses square pyramid shape indenter of diamond and load ranging from 1 to 120 kg. Average length (L) of two diagonals of square indentation is used as a measure of hardness. Longer is average diagonal length lower is hardness. Vickers hardness number (VHN) or diamond pyramid hardness (DPH) is the ratio of load (P) and apparent area of indentation given by the relation: $\mathrm{DPH} = \frac{1.854P}{L^2}$

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Lecture 32

INSPECTION AND TESTING OF WELD JOINT II

This chapter describes three important destructive testing methods of welded joints namely toughness test, fatigue test and fracture toughness testing. Additionally, concept of fracture toughness and conditions required for fracture toughness test for different stress conditions has also been presented. Further, non-destructive testing methods have also been presented.

Keywords: Impact test, Izod and Charpy test, fatigue test, endurance limit, fracture toughness, plain strain condition, CT specimen, three point bending specimen, Dye penetrant test, magnetic particle test, eddy current test and ultrasonic test

32.1 Toughness testing

In actual practice, engineering components during service are invariably subjected to various kinds of loads namely static and dynamic loads which are classified on the basis of the rate of change in magnitude of load and direction. Dynamic loads are characterized by high rate of change in load magnitude and direction. Reverse happens in case of static loads. In the hardness test and tensile tests, load is increased very slowly that corresponds to the behaviour of material under more or less static loading condition. Moreover, very wide range rate of loading (0.0001 to 1000mm/min) can be used in tensile test. Rate of loading governs the strain rate and so rate of hardening which can affect mechanical behavior of material. For example, material at low rate of loading showing the ductile behaviour can exhibit brittle behaviour under high rate of loading conditions.

The toughness test simulates service conditions often encountered by components of the system used in transportation, agricultural, and construction equipment. A material high impact resistance is said to be a tough material. Toughness is the ability of a material to resist both fracture and deformation. Toughness is the combination of strength and ductility. To be tough, a material must exhibit both fairly good strength and ductility to resist cracking and deformation under impact loading. Notches are made intentionally in impact test specimens to increase the stress concentration so as to increase tendency to fracture as most of the mechanical components have stress raisers. To withstand an impact force, a notched material must be tough.

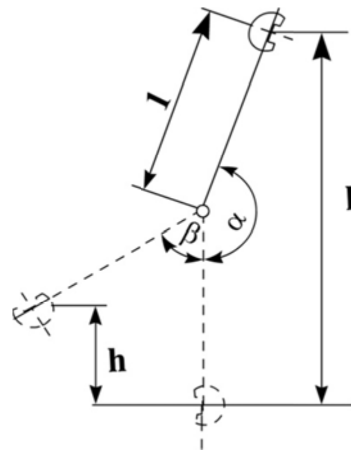


Fig. 32.1 Principle diagram of toughness test.

To study the behaviour of material under dynamic load conditions (at high rate of loading) toughness test is frequently conducted. There are two methods used for toughness testing namely Izod and Charpy test, based on the common principle of applying the load at high rate and measuring the amount of energy absorbed (kg m or Joule) in breaking the sample due to impact (Fig. 32.1). However, there are some differences also in these two methods in terms of sample size and shape, method of holding of the sample and maximum energy content of pendulum that hits the sample during the test.

Sr. No.	Toughness test	Sample	Holding
1	Izod	Held vertically on anvil as cantilever	Cantilever type and notch faces the pendulum
2	Charpy	Held horizontally on anvil as simply supported beam	Simply supported type and notch is opposite side of pendulum impact (not facing to pendulum)

Standard sample for both testing methods having a notch and is mounted on the machine in specific ways i.e. notch faces to pendulum in case Izod test while pendulum hits the sample from back of the notch in Charpy test (Fig. 32.2).

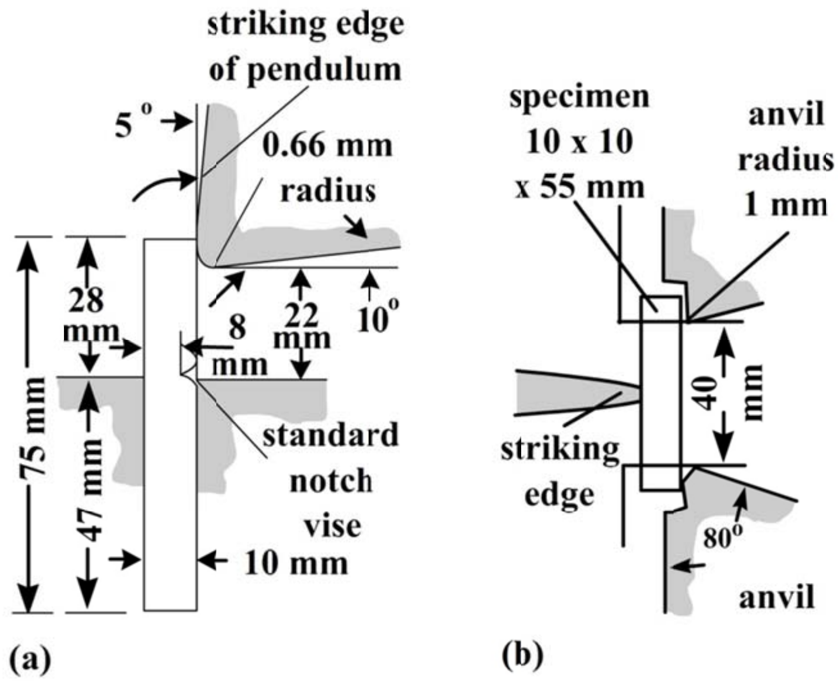


Fig. 32.2 Standard specimens for a) izod and b) charpy impact test

Since most of the engineering components are invariably designed with notch and stress raisers therefore, it becomes important to know about the behaviour of material with notch under impact loading. Hence, toughness test is usually conducted using sample with notch. Moreover, un-notched samples can also be used for the toughness test and the results are expressed accordingly.

Results of impact tests are expressed in terms of either amount of energy absorbed (Nm) or amount of energy absorbed per unit cross sectional area (Nm/cm^2) by standard sample. It may be noted that values of toughness are not directly used for design purpose but these only indicate the ability of the material to withstand against shock/impact load i.e. load applied at very high rate. These tests are useful for comparing the resistance to impact loading of different materials or the same material in different processing conditions such as heat treatment, procedure and mechanical working etc. Resistance to the impact loading of a material appreciably depends on the surrounding temperature (Fig. 32.3). Therefore, temperature at which toughness test is conducted must be reported with results.

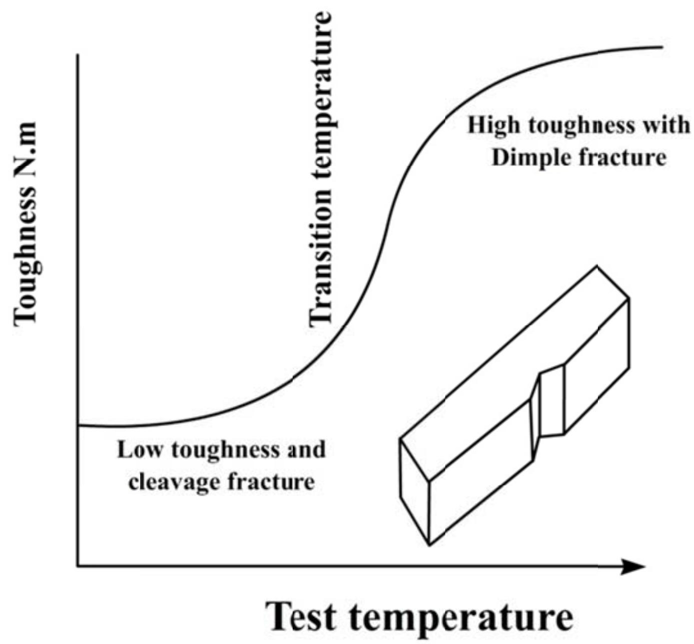
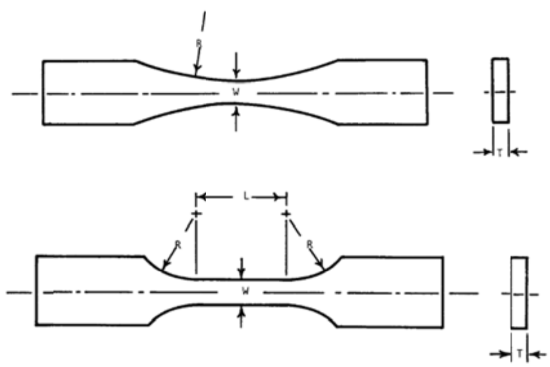


Fig. 32.3 Schematic diagram showing influence of test temperature on toughness

32.2 Fatigue behaviour of weld joint

The fatigue performance of the metallic components in general is determined in two ways a) endurance limit i.e. indicating the maximum stress, stress amplitude or stress range for infinite life (typically more than 20 million of load cycles) and b) number of load cycle a joint can be withstand for a set of loading conditions as desired. Two types of samples are generally prepared for fatigue studies as per ASTM 466 (Fig. 32.4 a, b). Reduced radius sample generally ensures fracture from weld joint or any specific location of interest (Fig. 32.5 a, b). The fatigue performance is appreciably influenced by the various variable related with fatigue test namely stress ratio, type of stress (tension-tension, reverse bending, tension-compression, zero-tension), maximum stress, stress range, loading frequency and surrounding environmental conditions such as temperature, corrosion, vacuum, tribological conditions. Each and every parameter to be used for the fatigue test must be carefully selected and recorded with results while reporting. The fatigue test results should include following.

- ➢ Test conducted according to ASTM E466 standard
- ➢ Type of loading: axial pulsating/reverse bending/tension-compression
- ➢ Maximum stress:
- ➢ Stress ratio (ratio of minimum stress to maximum stress)
- ➢ Temperature: ambient/vacuum/corrosion
- ➢ Frequency of pulsating load: load cycles per min
- ➢ Type of sample

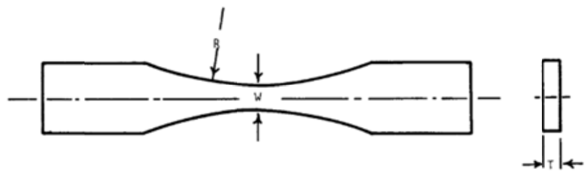


a) b)

Fig. 32.4 Standard specimen for fatigue testing

To conducting fatigue test, first step is conduct the tensile test on the weld joint for establishing the yielding strength of metal as maximum stress becomes 0.9 times of yield strength of material. For plotting the stress-number of cycle (S-N) curve, fatigue test is first conducted with maximum applied tensile load corresponding to 0.9 times of yield strength of weld joint under study to determine the number of load cycle required for fracture and then in the same way test is repeated at 0.85, 0.8, 0.75, 0.7 …. times of yield strength of weld joint until endurance limits or desired fatigue life is not achieved (Fig. 32.6). Typical dimensions of a standard specimen as per ASTM 466 are as-under.

- Continuous radius (R): 100mm
- Width (W): 10.3mm
- Thickness *T): 11mm (as received)
- Gripping length: 50mm



a)

b)

Fig. 32.5 Fatigue test sample a) Schematic diagram of standard fatigue test sample with continuous radius between ends and b) photograph of typical specimen

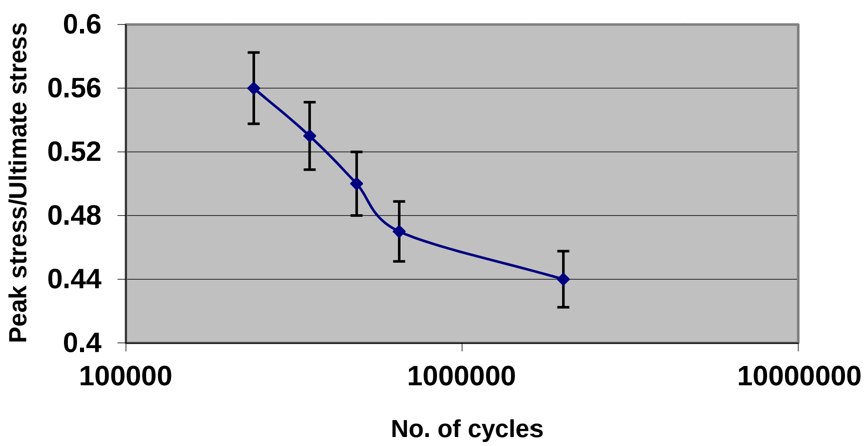
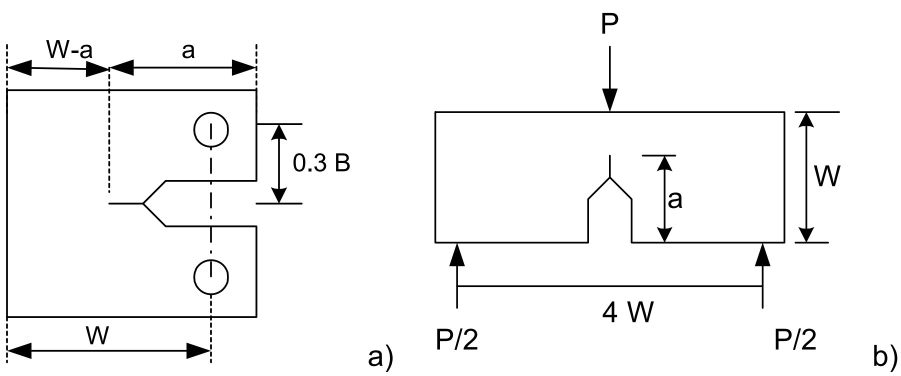


Fig. 32.6 Typical data on fatigue test showing peak stress/ultimate stress vs. number of cycle relationship for structure steel

32.3 Fracture toughness

The resistance to fracture conversely resistance to crack growth is known as fracture toughness and is measured using various parameters such as a) stress intensity around the crack tip (K), opening of crack mouth also called crack tip opening displacement (CTOD) and energy requirement for growth of crack (J or G). The mechanical properties namely yield strength and ductility and thickness of the weld joint under study primarily dictate the suitable parameter to be used for determining the fracture toughness. The fracture toughness parameter namely stress intensity factor (K) is commonly used for weld joint of heavy sections of high strength and low ductility material developing plain strain conditions, while crack tip opening tip displacement and energy based methods (G and J integral) are used for comparatively thinner sections made of low strength and high ductility material and those develop plain stress condition under external loading. Measurement of fracture toughness using any of above parameters is performed using two types of samples a) compact tension specimen (CT) and b) three point bending specimen (TPB). Schematics of two type of specimen are shown in Fig. 32.7. In general, in these tests, applied external load is increased until strain/crack opening displacement/energy vs. load relationship becomes non-linear. This critical value of load (P) is used for calculations of fracture toughness using relevant formulas.



W=2B, a=B, W-a=B and radius of hole r = 0.25B where B is plate thickness

Fig. 32.7 Schematic of fracture toughness specimens using a) compact tension and b) three point bending approaches

Although different standards have historically been published for determining K, CTOD and J-integral, the tests are very similar, and generally all three values can be established from one type of test.

In general, stress intensity factor (K) decreases with increase in specimen thickness. This trend continues up to a limit of thickness thereafter K becomes independent of the plate thickness. The corresponding value of K is called critical stress intensity factor (Kc) and occurs in *plane strain condition*. K_{IC} is used for the estimation of the critical stress need to apply to a specimen with a given crack length for catastrophic fracture to take place.

$$\sigma_C \leq K_{IC} /(Y(\pi a)^{1/2})$$

Where K_{IC} is the stress-intensity factor, measured in MPa*m½, σ_C is the critical stress applied to the specimen, a is the crack length for edge crack or half crack length for internal crack and Y is a geometry factor

32.4 Non-destructive testing (NDT)

To determine the presence of surface and surface imperfections, non-destructive testing of weld joints can be carried out using variety of techniques as per needs. Apart from the visual inspection, many non-destructive testing methods including dye penetrant test (DPT), magnetic particle test (MPT), eddy current test (ECT), ultrasonic test (UT), radiographic test (RT) etc. are used in manufacturing industry for assessing the soundness of weld joints. In following section, principle and capability of some non-destructive testing methods have been described.

32.4.1 Dye penetrant test

This is one of the simplest non-destructive testing methods primarily used for detecting the presence of surface defects only. In this method surface to be tested a thin low viscosity and low surface tension liquid containing suitable dye is applied (Fig. 32.8). The thin liquid penetrates (by capillary action) into fine cavities, pores and cracks, if any, present on the surface. Excess liquid present at surface is wiped out. Then suitable developer like talc or chalk powder is sprinkled over the surface. Developer sucks out thin liquid with dye wherever it is present inside the surface discontinuities present on the weld joints. Dye with liquid changes colour of developer and indicates location, and size of surface defects.

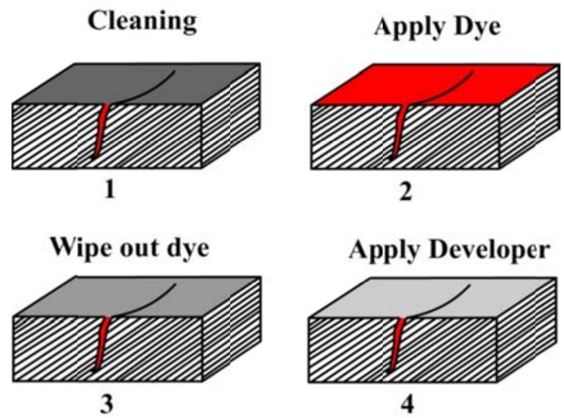


Fig. 32.8 Schematic showing four steps of dye penetrant test

32.4.2 Magnetic particle testing

This method is mainly used for assessing the surface and near surface defects in magnetic material. It is based on the simple principle of the flow of magnetic line of forces. Magnetic flux flows easily through metal from south to north-pole. The component to be evaluated is magnetized using electrical energy or suitable permanent magnetic. The electro-magnetization is performed using suitable yoke which is applied across the location / area to be tested. Presence of any dis-continuity in the form of crack, porosity, near surface defects in the path of flow of these lines results in leakage of magnetic flux forming two additional poles. The magnetic powder particles (in dry form or suspension form in thin liquid) are sprinkled over the surface of components to be tested. The magnetic particles tend to migrate toward the location wherever leakage of magnetic flux had taken place and then get piled up (Fig. 32.9). The particles align along discontinuities on the surface, near or shallow sub-surface discontinuities. The location and pattern of piled up magnetic powder particles suggest the location, size, type of discontinuity present on the surface or near surface region. Hazy pile of powder particle indicates the sub-surface defect. Formation of very thin line of powder particles suggests presence of crack with details of size and location of crack. However, this method of testing is found fit for ferromagnetic metal only.

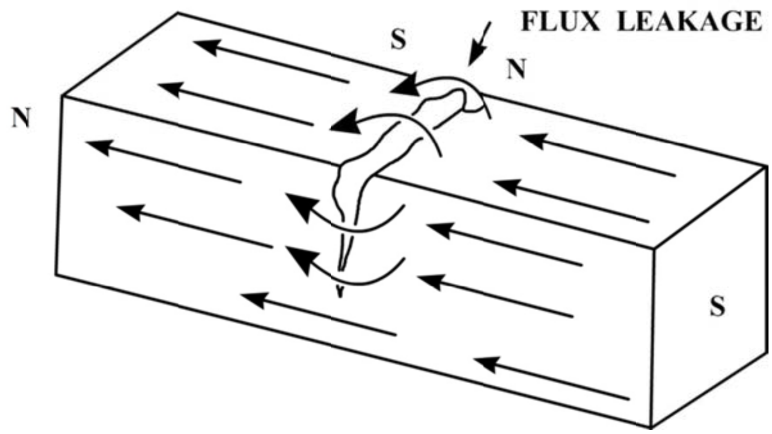


Fig. 32.9 Principle of magnetic particle test

32.4.3 Ultrasonic testing

This is one of the most popular, quick, cost effective and capable methods of NDT as it not only indicates the presence of discontinuities but also suggests their location using ultrasonic vibrations. Ultrasonic vibrations have capability to penetrate into the metals and are reflected as soon as they come across a change of medium e.g. metal to air, air to metal, metal to dis-continuities etc. This reflection characteristic of ultrasonic vibrations from the interfaces of change in medium is mainly exploited for detecting the presence or absence of discontinuities. Application of ultrasonic vibrations in a sound metal system at the sources produces two interfaces a) at top surface due to change of medium from air to metal and b) at the bottom surface due to change of medium from metal to air. The ultrasonic vibrations are used in two ways for NDT a) transmission and b) reflection of vibrations to evaluate the soundness of the weld joints in consideration. All these methods are very effective for parallel surface components e.g. plates, sheets.

Transmission approach

The transmission approach of ultrasonic testing uses two separate devices namely transmitter of vibration and receiver. Transmitting probe generates and sends the ultrasonic vibrations and receiver gets these vibrations at other end. Therefore, transmission approach needs access to both the sides of the components to be tested. Inputs from transmitting and receiving probes are given to oscilloscope (Fig. 32.10). Metal system without discontinuities shows the two peaks in oscilloscope i.e. one from the top surface and another from the bottom surface. In presence of discontinuity in the metal being tested, ultrasonic vibrations are reflected so they don't reach up to the receiving end and so no signal is received. Under this condition, only one peak in observed in the oscilloscope and absence of another peak from bottom surface suggests presence of discontinuity in the metal tested. One by one entire surface area of the component to be tested is scanned using transmitting and receiving probes. However, transmission approach is not very useful due to two reasons a) requirement of access to both sides of component to be tested and b) difficulty in placement of receiving probe in line of transmitting probe sending ultrasonic vibrations especially in case of components having thick sections.

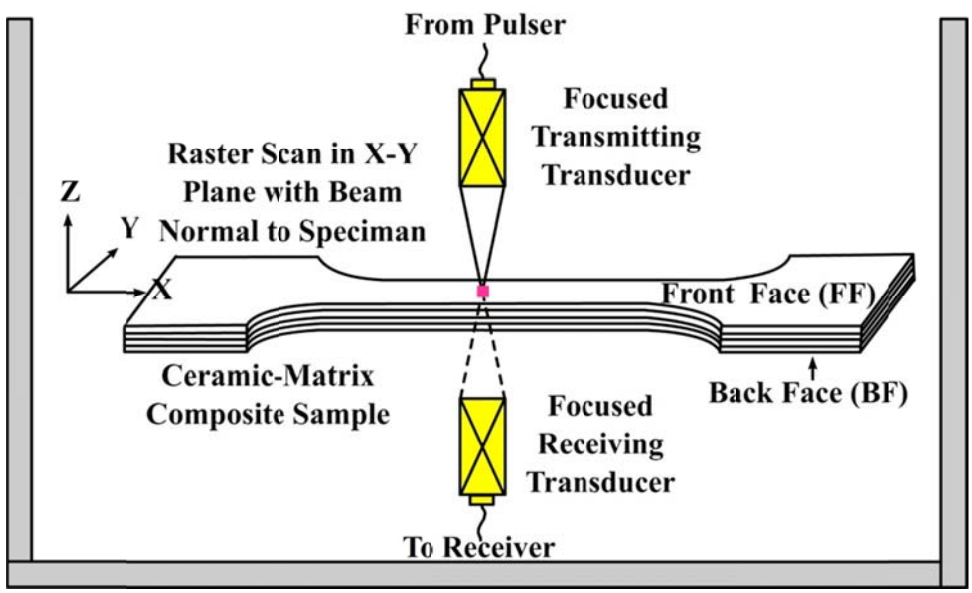


Fig. 32.10 Transmission type of ultrasonic testing

http://www.tms.org/pubs/journals/JOM/0301/Kim/Kim-0301.html

Reflection Approach

The reflection approach uses single probe which acts as a transmitter as well as receiver of ultrasonic vibrations. In metal system without discontinuities, application of ultrasonic vibrations results in the two peaks in oscilloscope i.e. one from the top surface and another from the bottom surface like transmission approach (Fig. 32.11). In presence of discontinuity in the metal being tested, ultrasonic vibrations are reflected. Vibrations reflected from the discontinuity shows additional peaks between the surface and bottom peaks in the oscilloscope. Relative location of the intermediate peaks (between the top and bottom surface peaks) suggests the distance of discontinuity from the surfaces. The reflection approach overcomes both limitations of transmission approach as it uses single probe so it does not require a) access of both sides of the component to be tested and b) alignment of transmission and receiving probes.

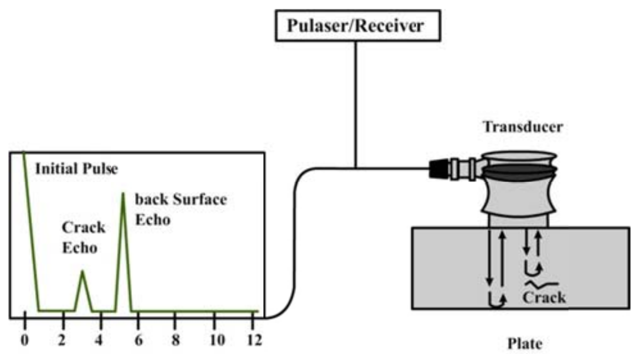


Fig. 32.11 Reflection type of ultrasonic testing

(http://ultrasonicinfo.blogspot.in/2007/11/basic-principles-of-ultrasonic-testing.html)

Pitch Catch method

In this method, ultrasonic vibrations are transmitted using 45 and 60 degree to the surface of the material to tested (Fig. 32.12). Reflected vibrations from the other reflecting surface or discontinuity are used to identify the presence and location of discontinuity in weld joints and other parallel sided surfaces.

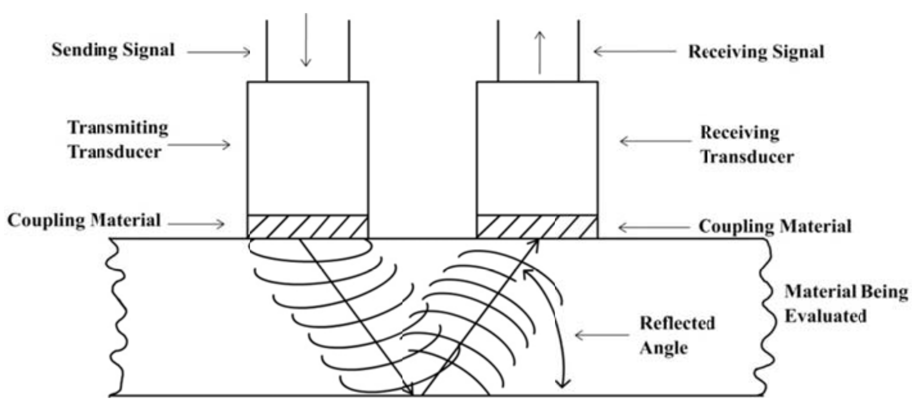


Fig. 32.12 Schematic of pitch catch method of ultrasonic testing

Coupler

For effective transmission of ultrasonic vibrations from the transmitting / source probe to the metal surface, generally a fluid mostly in the form of water or low viscosity liquid called coupler is used. The coupler ensures proper contact and transmission of vibration from source probe to metal surface with minimum losses. Water is considered as the best coupling media because it is readily available, low viscosity, and relatively safe to use with most construction materials. In the pitch-catch method, a water-based gel has proven to be the most practical coupling agent.

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Lecture: 33

Solidification of Weld Metal

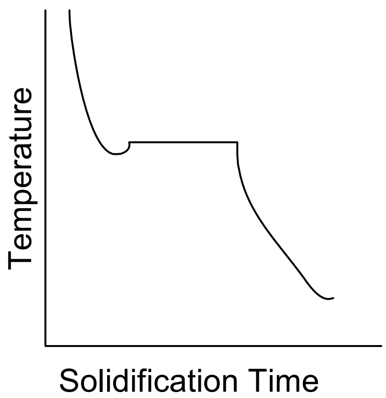
This chapter presents common solidification mechanisms observed in weld metal and different modes of solidification. Influence of welding speed and heat input on the grains structure of weld has been explained. Further, fundamental mechanisms used for grain refinement of weld metal and common methods of grain refinement have been described.

Keywords: Weld solidification, epitaxial solidification, actual temperature gradient (G), growth rate (R), axial and columnar grains, macrostructure, inoculation grain refinement, arc pulsation

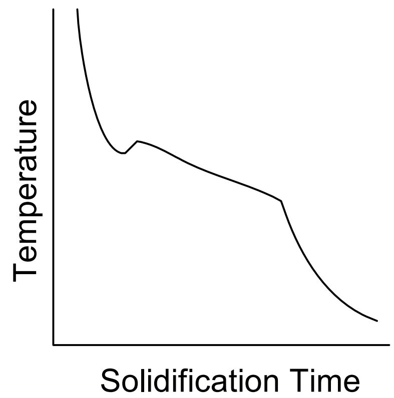
Fundamentals of solidification of metals

During the solidification of the liquid metal fast moving disordered atoms get arranged in a definite order to form crystal lattices such as BCC, FCC, and HCP etc. As soon as heat source moves away, gradually heat is lost to the base metal. Rate of heat loss depends on temperature of weld metal, weld pool size, thickness and thermal properties base metal etc.

On cooling, liquid metal losses energy in the form of latent heat and so the temperature is lowered which in turn decreases the average inter-atomic distance between mobile & disordered atoms. On further cooling, attractive forces between atoms prevent them moving away from one another and eventually completely liquid to solid transformation takes place. Solidification of pure metals begins with temperature arrest and then continues to take place at a constant temperature as shown in Fig. 33.1 (a) while alloys solidify over a range of temperature. The arrest in temperature is attributed to evolution of the latent heat of solidification on transformation from the liquid metal to solid state.



a)



b)

Fig. 33.1 Schematic of cooling curve for a) pure metal and b) alloy during the solidification

Total energy of the molten metal reduces during solidification. On the formation of a small nucleus e.g. cubical shape having side of length "a" two changes in free energies takes place a) free energy lost during the solidification and b) free energy required for creation of new surfaces of the cubical shape solid.

The freezing energy lost : $\Delta G_{LS} = a^3\ \Delta G_{LS}^*$

The surface energy needed for creation of new surfaces for a cube is : $6a^2\ \Delta G_I^*$

Where change in free energy per unit volume is ΔG_{LS}^* (on liquid to solid state transformation) and a is side of the cube. Therefore, volume of cube would be a^3. Where interfacial energy per unit area is ΔG_I^*

Thus, total change in free energy is the algebraic sum of above two energies $\Delta G = -a^3\ \Delta G_{ls}^* + 6a^2\ \Delta G_I^*$

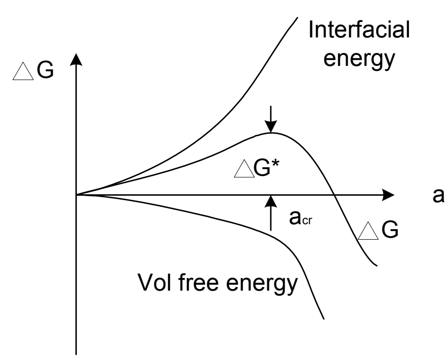


Fig. 33.2 Free energy vs grain size during the phase transformation

Above equation shows that total change in free energy will vary with change in size of nucleus (Fig. 33.2). There is a critical size a_{cr} for a nucleus to be stable, below which nucleus (called embryos) gets re-dissolved in the liquid metal. Figure (33.2) shows that reduction in free energy caused by liquid to solid phase transformation is more than increase in free energy due to creation of the new surfaces. This is the reason why under-cooling below the equilibrium transformation temperature is required, so that the condition of reduction in total energy is satisfied. Greater is the under cooling temperature smaller is the critical size. This explains the dependence of nucleation rate on under cooling temperature.

If liquid metal is already carrying solid particles then it will begin to crystallize on them at equilibrium temperature without under-cooling. This phenomenon forms the basis for the heterogeneous nucleation. Heterogeneous nuclei are physically and chemically different from the freezing liquid metal. Surface bonding and crystalline similarity for various particles in the liquid metal, are important factors to act as heterogeneous nuclei.

These particles may or may not be wetted by liquid metal depending upon the interface forces between them. Experimental investigations have established that two conditions should be satisfied by the heterogeneous particles to be an effective nucleant 1) crystalline similarity between the particles and solidified liquid metal and 2) difference in lattice size of two crystals should not be greater than 20%. However, these are not the only conditions for particles to be an effective nucleant.

Kinetics of liquid-solid interface is described by the ratio thermal gradient (G) and travel speed of liquid solid interface (R). Value of G and R are generally found in range of 100-1000K/m and 10^{-3} to 10^{3} m/s. Solidification mode generally varies as per prevailing G & R value for given solidification conditions. There can be four modes of the solidification (as per G and R value) namely a) planar (high G and low R), b) cellular, c) columnar dendritic, and d) equaixed dendritic (low G and high R). These four modes are shown in Fig. 33.3. Ratio of G and R determines the mode of solidification and product of two (G, R) indicates the cooling rate so these two parameters decide the fineness grain structure (Fig. 33.4).

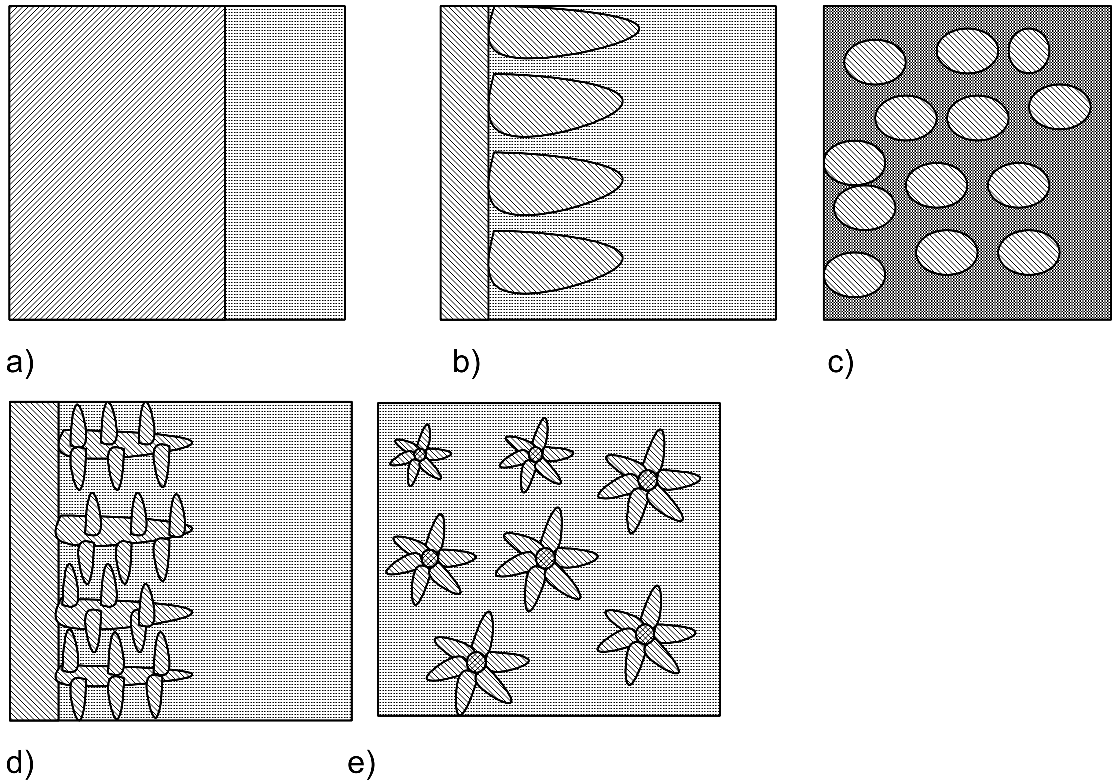


Fig. 33.3 Schematic of modes of the solidification a) planar, b & c) cellular, d) columnar dendritic and e) equiaxed dendritic

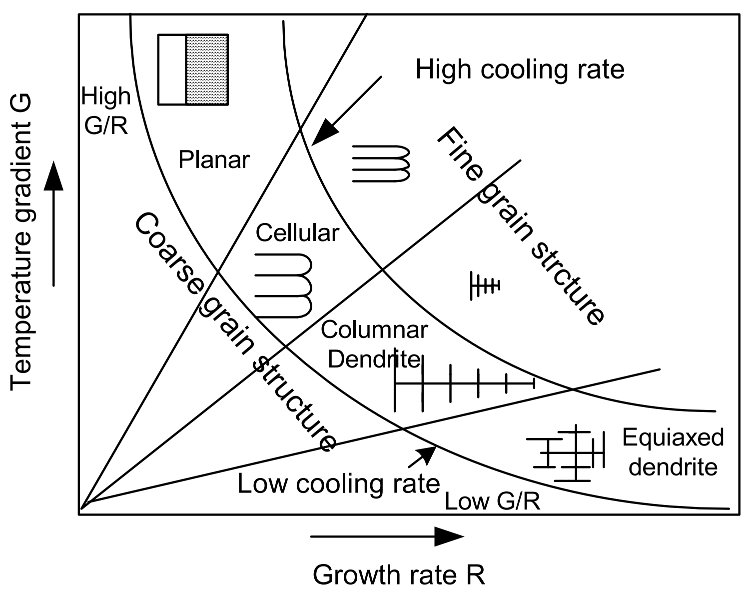


Fig. 33.4 Influence of G & R on mode of solidification and grain structure

Solidification of the weld metal can take place two ways a) epitaxial and b) none-epitaxial depending up on the composition of the weld metal. In a weld pool, temperature gradient is observed right from the center of the weld pool to fusion boundary of the base metal and iso-thermal temperature lines exist around the weld. These isotherms determine the boundaries of heat affected zone, mushy zone and liquid weld metal zone (Fig. 33.5). The peak temperature is found at the center of the weld and then decreases gradually on approaching towards weld fusion boundary. Grains grow from the fusion boundary towards the weld center. The growth generally occurs at a faster rate in the direction perpendicular to the fusion boundary and opposite to that of the heat flow than other directions.

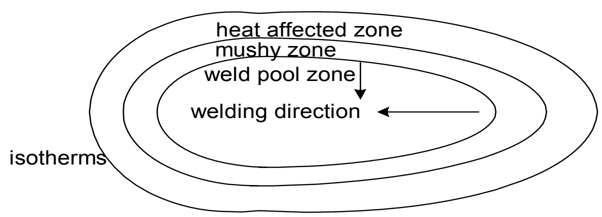


Fig. 33.5 Schematic showing different zones

33.1 Epitaxial solidification

The transformation of the molten weld metal from liquid to solid state is called solidification of weld metal and it occurs due to loss of heat from weld puddle. Generally, solidification takes place by nucleation and growth mechanism. However, solidification of weld metal can occur either by nucleation and growth mechanism or directly through growth mechanism depending upon the composition of the filler/electrode metal with respect to base metal composition. In case, when composition of the filler/electrode is completely different from the base metal, solidification occurs by nucleation and growth mechanism e.g. use of nickel electrode for joining steel. And when filler/electrode composition is similar to the base metal, solidification is accompanied by growth mechanism only on partially melted grain of the base metal which is commonly known as epitaxial solidification (Fig. 33.6). The growth of grain on either newly developed nuclei or partially melted grain of the base metal, occurs by consuming liquid metal i.e. transforming the liquid into solid to complete the solidification sequence.

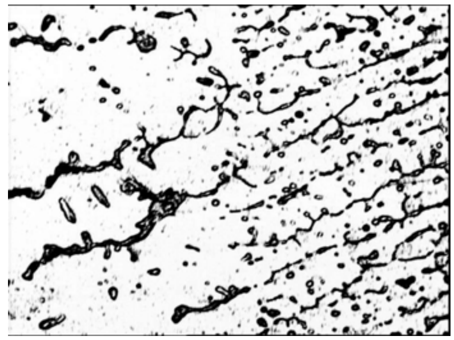


Fig. 33.6 Typical micrograph showing epitaxial solidification in Al weld joint

33.2 Modes of solidification

The structure of grain in growth stage is governed by mode of solidification. There are four type of grain commonly observed in solidified metal namely planar, cellular, dendritic, equiaxed corresponding to the respective modes of the solidification (Fig. 33.7). Moreover, the mode of solidification in weld depends on composition and cooling conditions experienced by weld metal at a particular location during the solidification. Thermal conditions during solidification are determined by heat transfer in weld pool affect the temperature gradient (G) at solid-liquid metal interface (^{0}C/mm) and growth rate of solidification front (R) as indicated from growth rate (mm/sec) of solid-liquid metal interface.

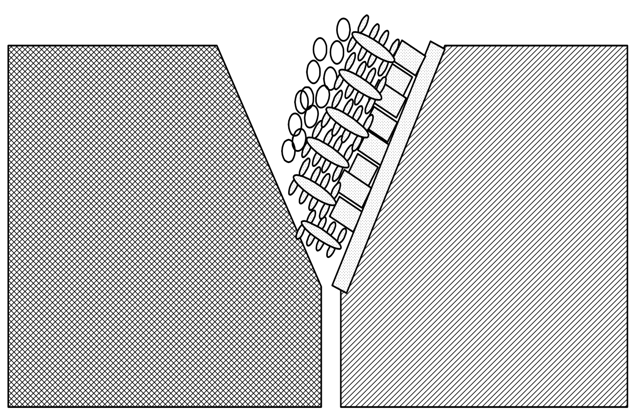


Fig. 33.7 Different modes of solidification a) planar, b) cellular, c) cellular, d) dendritic and e) cellular structure

The shape of solid-liquid metal interface determines morphology of microstructural features of the weld metal. A stable plane solid-liquid metal interface results in planar solidification. The condition for stability of plane solid liquid metal interface is given by $(G/R)>(\Delta T/D)$. Where G is the temperature gradient in liquid near solid liquid metal interface, R is growth rate of solidification front, ΔT is the solidification temperature range for a given composition and D is the diffusion coefficient of solute in liquid metal (Fig. 33.8).

Moreover, the stability of the solid-liquid metal interface is governed by thermal and constitutional supercooling condition prevailing in the liquid metal near the solid- liquid metal interface. Destabilization of solid-liquid metal interface results in the growth of interface in cellular or dendritic form. The constitutional super-cooling for instability of plane solid liquid metal interface is expressed by following relationship: $(G/R)>(\Delta T/D)$.

A combination of high actual temperature gradient (G) and low growth rate (R) results in planar solidification i.e. where liquid-solid interface is plane. A combination of low actual temperature gradient (G) and high growth rate (R) results in equiaxed solidification as shown in Fig. 33.8. A combination of intermediate G and R values results in cellular and dendritic mode of solidification. Product of G and R indicates the cooling rate. A high value of G.R produces finer grain structure than low G.R value. During welding, weld pool near the fusion boundary experiences high value of G and low value of R which in turn results in planar solidification and at the weld center reverse conditions of G and R exist which lead to the development of equiaxed grains. In fact, G and R varies continuously from the weld fusion boundary to the weld center therefore all common modes of the solidification can be seen in weld metal structure in sequence of planar at the fusion boundar, cellular, dendritic and equiaxed at the weld centre. In general, equiaxed grain structure is the most favourable weld structure as it results in best mechanical performance of weld. Therefore, attempts are made to achieve the fine equiaxed grain structure in the weld by different approaches namely inoculation, controlled welding parameters and application of external force such as electromagnetic oscillation, arc pulsation, mechanical vibrations etc. In following sections, these approaches will be described in detail.

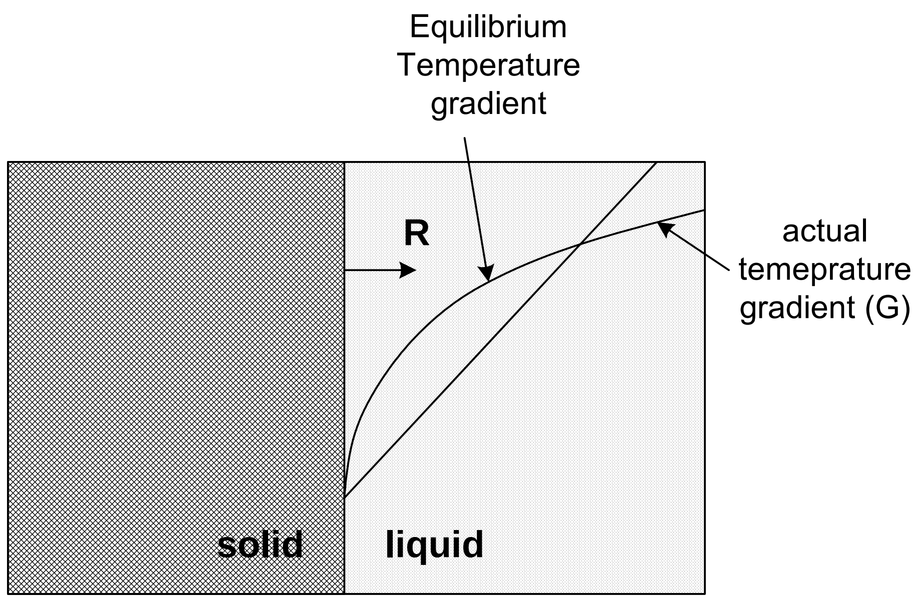


Fig. 33.8 Schematic of temperatures distribution during solidification near solid-liquid metal interface

In addition to microstructural variations in the weld, macroscopic changes also occur in weld, which are largely governed by welding parameters such as heat input (as determined by welding current and arc voltage) and welding speed. Macroscopic observation of the weld reveals of the two types of grains based on their orientation a) columnar grain and b) axial grain (Fig. 33.9). As reflecting from their names, columnar grains generally grow perpendicular to the fusion boundary in direction opposite the heat flow while axial grains grow axially in the direction of welding (Fig. 33.9). The axial grains weaken the weld and increase the solidification cracking tendency therefore effort should made to modify the orientation of axial grains.

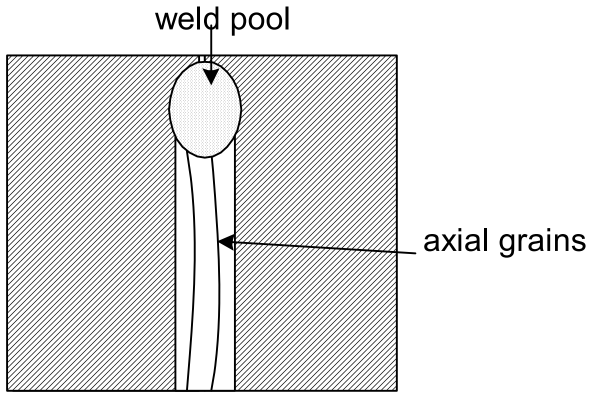


Fig. 33.9 Schematic of axial grain in weld joints

33.3 Effect of welding speed on grain structure of the weld

Welding speed appreciably affects the orientation of columnar grains due to difference in the shape of weld puddle. Low welding speed results in elliptical shape weld pool and produces curved columnar grain with better distribution of low melting point phases and alloying elements which in turn lowers solidification cracking tendency of the weld than weld produced using high welding speed (Fig. 33.10). At high welding speed, the shape of the trailing end of weld pool becomes like a tear drop shape and grains are mostly perpendicular to the fusion boundary of the weld. In this case low melting point phases and alloying elements are mostly segregated along the weld centerline,

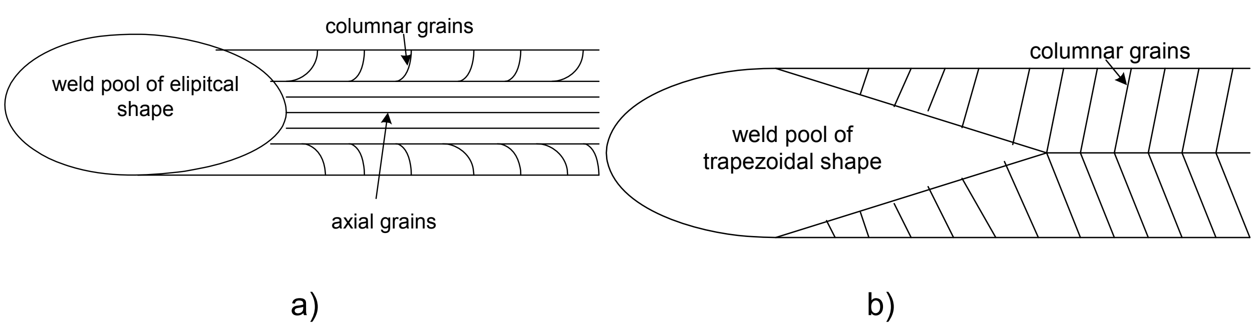


Fig. 33.10 Effect of wending speed on shape of weld pool and grain structure at a) low speed and b) high speed

33.4 Common methods of grain refinement

33.4.1 Inoculation

This method is based on increasing the heterogeneous nucleation at nucleation stage of the solidification by adding alloying elements in weld pool. These elements either them-self or their compounds act as nucleants. Increased number of nucleants in the weld metal eventually on solidification results in refinement of the grains in the weld (Fig. 33.11). It is understood that elements having a) melting point higher than the liquidus temperature of the weld metal and b) lattice parameter similar that of base metal can perform as nucleants. For aluminium, titanium and boron based compound as such TiB_2, TiC, Al-Ti-B, Al-Zr are commonly used as grin refiner. Addition of grain refiners in molten metal can lower the surface energy to facilitate the nucleation even with limited under-cooling. Increase in the nucleation rate facilitates the grain refinement. For steel, Ti, V and Al are commonly used grain refiners.

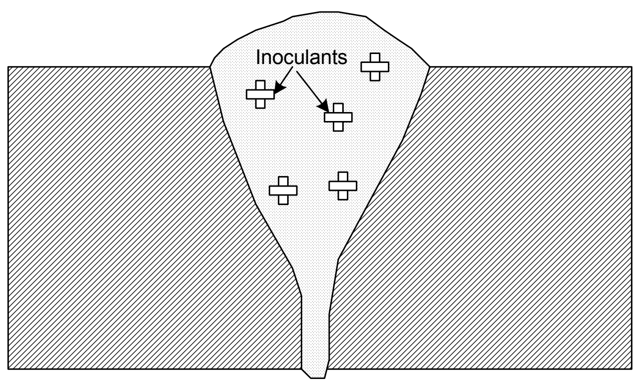


Fig. 33.11 Schematic of grain refinement by inoculation

33.4.2 Arc pulsation

The gas metal arc and gas tungsten arc welding process generally use constant voltage and constant current power source. Moreover, these processes sometime use a DC power source which can supply varying current called base current and peak current. Base current is the minimum current primarily used to have stable arc and supplies least amount of the heat to the weld; and solidification of the weld is expected to take place during the base current period (Fig. 33.12). While peak current is maximum current supplied by the power source to the weld arc to generate the heat required for melting of the faying surfaces. The cycle of alternate heating and cooling results in smaller weld puddle and so rapid cooling of the weld metal which in turn results in finer grain structure than the conventional welding i.e. without arc pulsation (Fig. 33.13). It is believed that abrupt cooling of the weld pool surface during base current period can also lead to development of few nucleants at the surface which will tend to settle down gradually and so making make their distribution uniform in the molten weld pool in the settling process. Increased availability of nucleants due to surface nucleation will also be assisting to get finer grain structure in weld.

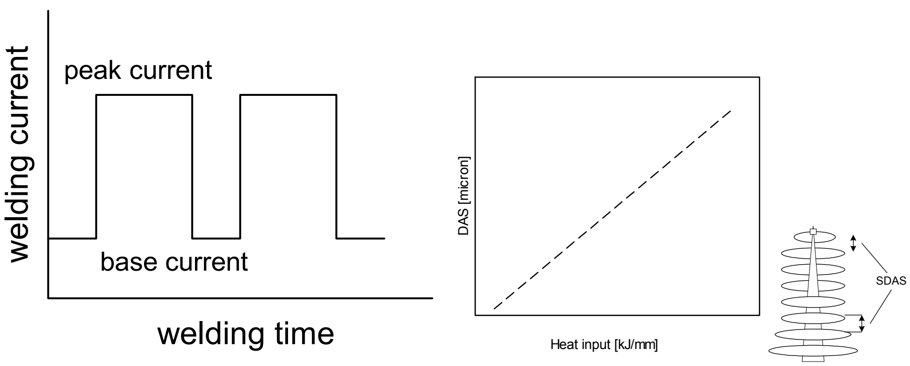
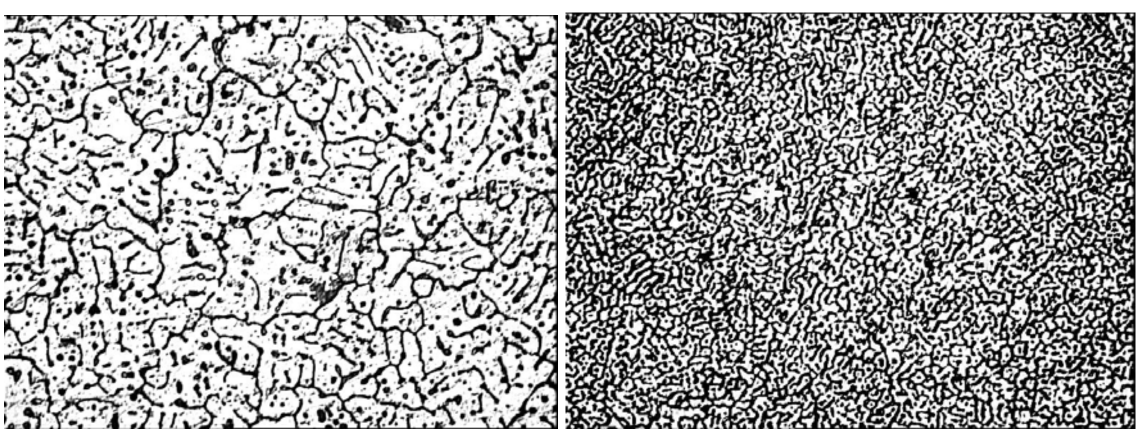


Fig. 33.12 Schematics of a) pulse current vs time welding and b) effect of heat input on dendrite arm spacing



a) b)

Fig. 33.13 Microstructure of aluminium weld developed a) without arc pulsation using 160 A current and b) arc pulsation between 120 and 160 A (200X)

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Lecture: 34

Solidification of Weld Metal

In this chapter, three grain refinement methods namely mechanical vibrations, electromagnetic forces, arc oscillation used for refining the structure of weld metal have been described. Further, two commonly observed metallurgical discontinuities in weld metal namely banding and segregation have also been explained.

Keywords: grain refinement, Mechanical vibration, magnetic arc oscillation, micro-segregation, banding,

34.1 Mechanical vibrations and Electro-magnetic force

Both these methods are based on use of external excitation force to disturb solidifying weld metal so as to create more number of the nucleants in weld metal. The external disturbance causes forced flow and turbulence in the viscous semi-solid weld metal carrying dendrites and nucleants which in turn can result in a) fracture of partially melted grains of the base metal, b) fragmentation of solidifying dendrites and c) improved distribution of chemical composition and the nucleants (Fig. 34.1). The fractured dendrites are pulled out of partially melted grains present in the weld and act as nucleants for solidifying weld metal as they are of the same composition in solid state.

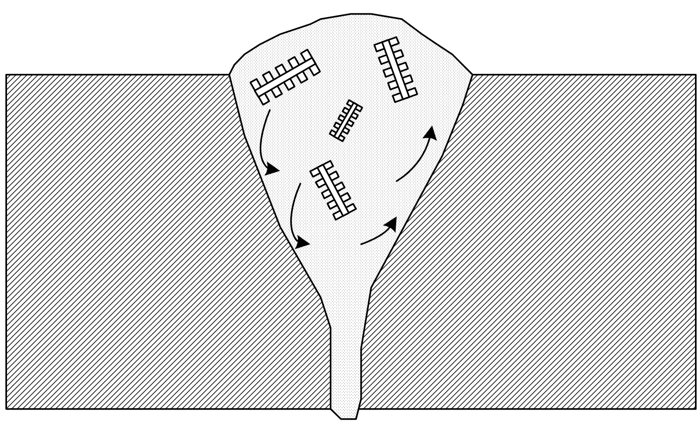

Fig. 34.1 Refinement using external excitation force

34.2 Magnetic Arc Oscillation

Arc composed of charged particles can be deflected using magnetic field. Arc oscillation affects the weld pool in two ways a) reduction in the size of weld pool and b) alternate heating and cooling of weld (similar to that of arc pulsation) as shown in Fig. (34.2). A combination of above two factors leads to rapid cooling which in turn reduces grain size owing to increased nucleation rate and reduced growth rate. As increase in cooling rate of the solidifying weld metal decreases the effective liquid to solid state transformation temperature which is known to increase the nucleation rate and lower the growth rate

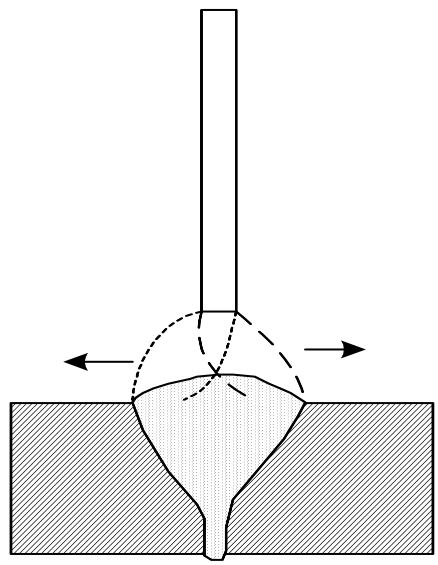

Fig. 34.2 Arc oscillation due to electromagnetic filed around welding arc.

34.3 Welding Parameter

Heat generated (kJ) by the arc is obtained from the product of welding current and arc voltage (V.I) for given welding conditions such as type, and size of electrode, arc gap, base metal and shielding gas (if any). While the exact amount of heat supplied to base metal for melting the faying surfaces is significantly determined by the welding speed. Increase in welding speed for a given welding current and voltage results in reduced heat input per unit length of welding (kJ/mm) which is also termed as net heat input for sake of clarity. Cooling rate experienced by the weld metal and heat affected zone is found inversely proportional to net heat input (Fig. 34.3). High the heat input lowers the cooling rate. Low cooling rate results in a) increased solidification time (needed to extract complete sensible and latent heat from the molten weld pool) and b) high effective solid to liquid state transformation temperature. Longer solidification time permits each grain to grow to a greater extent which in turn produces coarse grain structure. Further, high heat input causing high effective liquid solid transformation temperature produces low nucleation and high growth rate which in turn results in coarse grain structure. Increase in welding current or reduction in welding speed generally increases the grain size of weld metal as it increases the net heat input and lowers the cooling rate experienced by the weld metal during solidification.

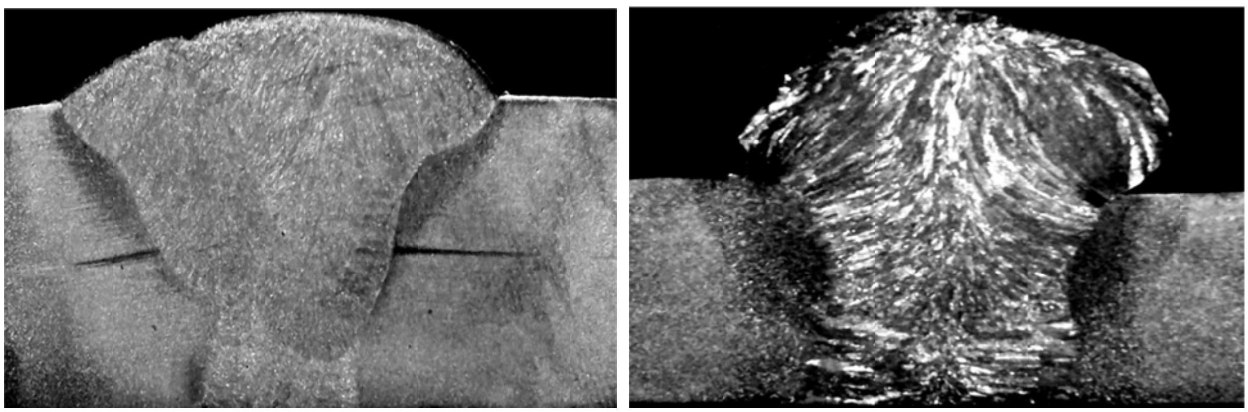

Fig. 33.4 Macro-photographs of weld joints produced using a) 3.0 kJ/mm and b) 6.0 kJ/mm heat input with help of submerged arc welding.

34.4 Typical metallurgical discontinuity of the weld

Due to typical nature of welding process, common metallurgical discontinuities observed in the weld are banding and micro-segregation of the elements. In the following section these have been described in detail.

34.4.1 Micro-segregation

Micro-segregation refers to non-uniform distribution of elements in the weld which primarily occurs due to inherent nature of solidification mechanism i.e. transformation of high temperature alpha phases first from liquid to solid by rejection of alloying elements into the liquid metal thereby lowering solidification temperature. Except planar mode, other modes of solidification namely cellular, dendrite and equiaxed involve segregation. Therefore, inter-cellular, inter-dendritic and inter-equiaxed region is generally enriched of alloying elements compared to cells (Fig 33.4).

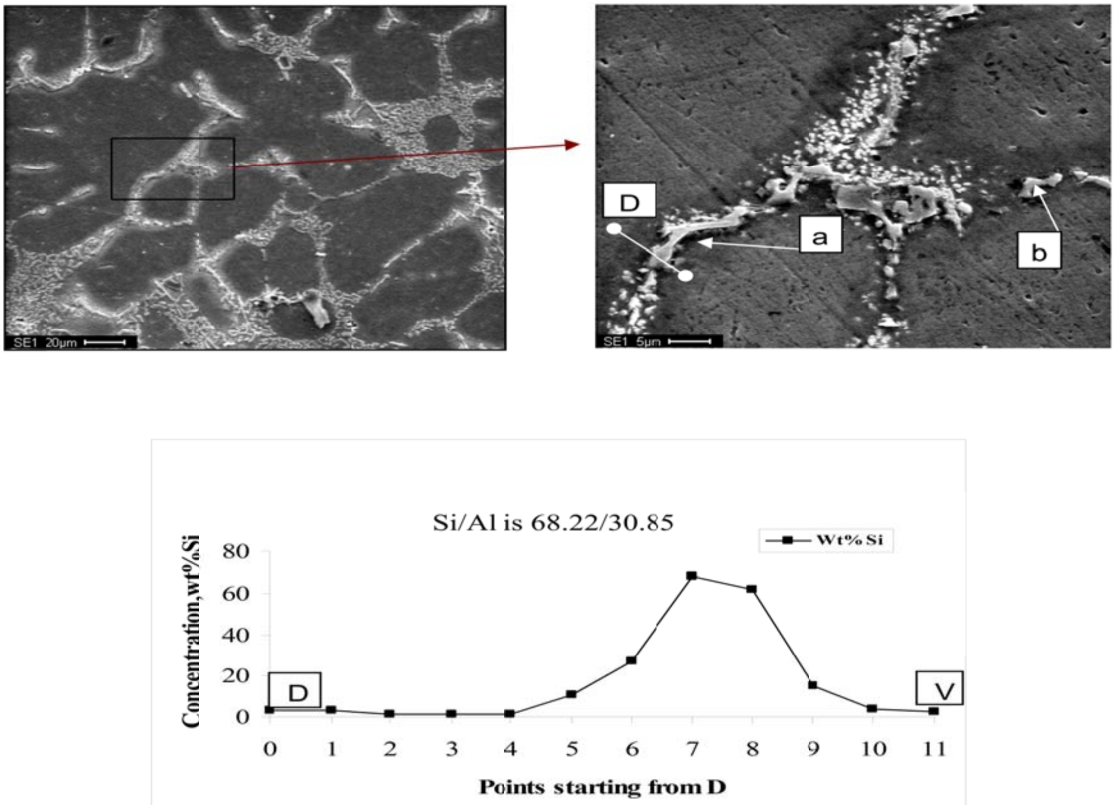

Fig. 34.4 Segregation of alloying elements at grain boundary

34.4.1 Banding

Welding arc is never in steady state as very transient heat conditions exit during arc welding which in turn lead to severe thermal fluctuations in the weld pool therefore cooling conditions varying continuously during the solidification. Variation in cooling rate of weld pool causes changing growth rate of the grain in weld and fluctuating velocity of solid-liquid metal interface. Abrupt increase in growth rate decreases the rate of rejection of alloying elements in liquid metal near the solid-liquid metal interface due to limited diffusion of alloying elements while low cooling rate increases the rejection of elements near the solid liquid metal interface as long time available for diffusion to occur. This alternate enrichment and depletion of alloying elements produces band like structure as shown in Fig 34.5. This structure is known to adversely affect fatigue and notch toughness properties of weld joints.

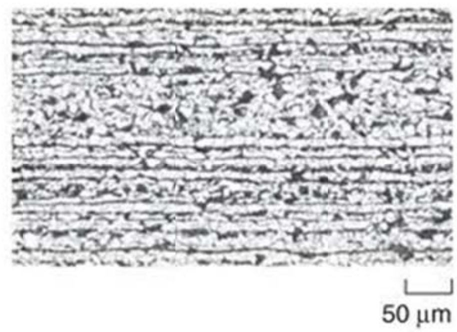

Fig. 34.5 Typical micrograph of steel showing banded structure (S Kou, 2003)

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Lecture 35

CHEMICAL REACTION IN WELDS I

This chapter presents the need of protecting the weld and rationale behind variations in cleanliness of the weld developed by different welding processes. The gas metal reactions and slag metal reactions have also been described besides their effect on elemental transfer efficiency.

Keywords: Cleanliness of weld, gas metal reaction, weld composition, oxides and nitrides, element transfer efficiency

35.1 Welding process and cleanliness of the weld

In fusion welding, the application of heat of the arc or flame results in the melting of the faying surfaces of the plates to be welded. At high temperature metals become very reactive to atmospheric gases such as nitrogen, hydrogen and oxygen present in and around the arc environment. These gases either get dissolved in weld pool or form their compound. In both the cases, gases adversely affect the soundness of the weld joint and mechanical performance. Therefore, various approaches are used to protect the weld pool from the atmospheric gases such as developing envelop of inactive (GMAW, SMAW) or inert gases (TIGW, MIGW) around arc and weld pool, welding in vacuum (EBW), covering the pool with molten flux and slag (SAW, ESW). The effectiveness of each method for weld pool protection is different. That is why adverse effect of atmospheric gases in weld produced by different arc welding processes is different (Fig. 35.1).

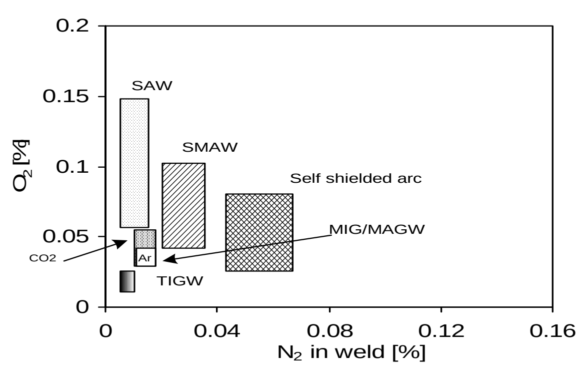

Fig. 35.1 Schematic diagram showing nitrogen and oxygen content in different welding processes

Amongst the most commonly used arc welding processes, the cleanest weld (having minimum nitrogen and oxygen) is produced by gas tungsten arc welding (GTAW) process due to two important factors associated with GTAW: a) short arc length and b) very stable arc produced by using non-consumable tungsten electrode. A combination of short and stable arc with none-consumable tungsten electrode results a firm shielding of arc and protection of the weld pool by inert gases restricts the entry of atmospheric gases in the arc zone. Gas metal arc welding (GMAW) also offers clean weld but not as clean as produced by GTAW because in case of GMAW arc length is somewhat greater and arc stability is poorer than GTAW. Submerged arc weld (SAW) joints are usually high in oxygen and less in nitrogen because SAW uses flux containing mostly metallic oxides. These oxides decompose and release oxygen in arc zone. The self shielded fluxed cored metal arc welding processes use electrodes having fluxes in core act as de-oxidizer and slag formers to protect the weld pool. However, weld produced by the self shielded fluxed arc welding processes are not as clean as those produced with GMAW.

35.2 Effect of atmospheric gases on weld joint

The gases present in weld zone (atmospheric or dissolved in liquid metal) affect the soundness of weld joint. Gases such as oxygen, hydrogen, nitrogen etc. are commonly present in and around the liquid metal. Both oxygen and hydrogen are very important in welding of ferrous and non-ferrous metals; these are mostly produced by decomposition of water vapours (H_2O) in high arc temperature. Oxygen reacts with carbon in case of steel to form CO or CO_2. These gases should escape out during the solidification; due to high solidification rate encountered in welding processes these gases may not come up to the surface of molten metal and may get trapped. This causes gaseous defects in the weldment, like porosity, blowhole etc. Chances for these defects further increases if the difference in solubility of these gases in liquid and solid state is high. Oxygen reacts with aluminium and form refractory alumina which forms inclusions and reduces the weldability. It's formation can be reduced by proper shielding of arc zone either by inert or inactive gases. Only source of nitrogen is atmosphere and it may form nitrides but it creates fewer problems. Hydrogen is a main problem creator in welding of steel and aluminium alloy due to high difference in liquid and solid state solubility. In case of steel, besides the porosity and blow holes hydrogen causes the problem of cold cracking even if it is present in very small amount, whereas in case of aluminium hydrogen causes pin hole porosity.

Oxides and nitrides formed by these gases if not removed from the weld, act as site of weak zone in form of inclusions which in turn lower the mechanical performance of the weld joint e.g. iron reacts with nitrogen to form hard and brittle needle shape iron nitride (Fe_4N) as shown in Fig. 35.2 (a, b). These needle shape micro-constituents offer high stress concentration at the tip of particle-matrix interface which under external tensile stresses facilitate the easy nucleation and propagation of crack, therefore fracture occurs at limited elongation (ductility). Similar logic can be given for reduction in mechanical performance of weld joints having high oxygen/oxide content. However, the presence of N_2 in weld metal is known to increase the tensile strength due to the formation of hardness and brittle iron nitride needles.

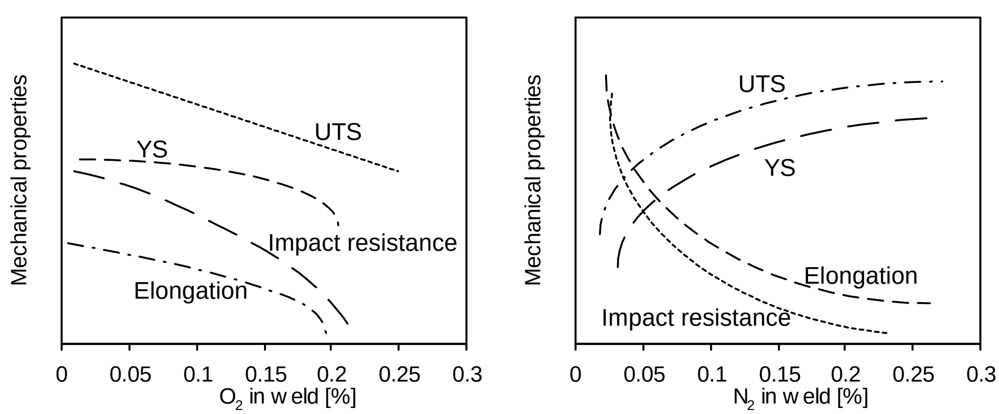

Fig. 35.2 Influence of oxygen and nitrogen as impurities on mechanical properties of steel weld joints

Additionally, these inclusions formed by oxygen, nitrogen and hydrogen break the discontinuity of metal matrix which in turn decreases the effective load resisting cross section area. Reduction in load resisting cross sectional area lowers the load carrying capacity of the welds. Nitrogen is also a austenite stabilizer which in case of austenitic stainless steel (ASS) welding can place crucial role. Chemical composition of ASS is designed to have about 5-8% ferrite in austenite matrix to control solidification cracking of weld. Presence of nitrogen in weld metal either from atmosphere or with shielding gas (Ar) stabilizes the austenite (so increases the austenite content) and reduces ferrite content in weld which in turn increases the solidification cracking tendency because ferrite in these steels acts as sink for impurities like P and S which otherwise increase cracking tendency of weld.

35.3 Effect on weld compositions

Presence of oxygen in arc environment not only increases chances of oxide inclusion formation tendency but also affects the element transfer efficiency from filler/electrode to weld pool due to oxidation of alloying elements (Fig. 35.3). Sometime composition of the weld is adjusted to get desired combination of mechanical, metallurgical and chemical properties by selecting electrode of suitable composition. Melting of electrode and coating and then transfer of the elements from the electrode across the arc zone causes the oxidation of some of the highly reactive elements which may be removed in form of slag. Thus transfer of especially reactive elements to weld pool is reduced which in turn affects the weld metal composition and so mechanical and other performance characteristics of weld.

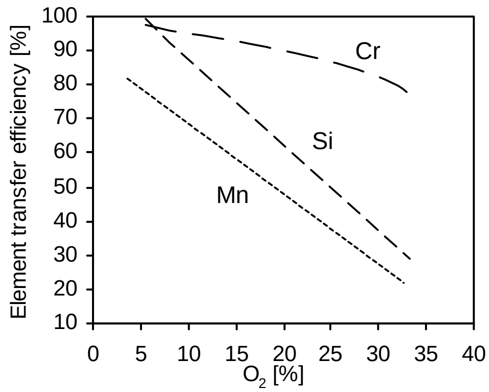

Fig. 35.3 Influence of oxygen concentration on element transfer efficiency of common elements

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Lecture 36

CHEMICAL REACTION IN WELDS II

This chapter presents influence of hydrogen in weld joints on the soundness and performance of weld joints. Further, different types of fluxes, their stability and effect on weld have been described. The concept of basicity index of the fluxes and its effect on weld has also been elaborated.

Keywords: Cold cracking, hydrogen induced porosity, sources of hydrogen, hydrogen solubility, basicity of flux, stability of oxides, acidic and basic fluxes

36.1 Effect of hydrogen on steel and aluminium weld joints

Hydrogen

Hydrogen in weld joints of steel and aluminium is considered to be very harmful as it increases the cold cracking tendency in hardenable steel and porosity in aluminium welds. Hydrogen induced porosity in aluminium welds is formed mainly due to high difference in solubility of hydrogen in liquid and solid state. The hydrogen rejected by weld metal on solidification if doesn't get enough time for escaping then it is entrapped in weld and results in hydrogen induced fine porosity. Welds made using different processes produce varying hydrogen concentration owing to difference in solidification time, moisture associated with consumable and protection of the weld pool from atmospheric gases, use of different consumables (Fig. 36.1). Hydrogen in steel and aluminium weld joint is found mainly due to high difference in solubility of hydrogen in liquid and solid state (Fig. 36.2).

Cold cracking is caused by hydrogen especially when hard and brittle martensitic structure is formed in the weld and HAZ of hardenable steel. Many theories have been advanced to explain the cold cracking due to hydrogen. Accordingly to one of hypothesis, hydrogen diffuses towards the vacancies, grain boundary area and other crystallographic imperfections. At these locations, segregation of the hydrogen results in first transformation of atomic hydrogen into gaseous molecules and then builds up the pressure until it is high enough to cause growth of void by propagation of cracks in one of directions having high stress concentration as shown in Fig. 36.3. Thereafter, process of building up of the pressure and growth of crack is repeated until complete fracture of the weld without any external load occurs. Existence of external or residual tensile stresses further accelerate the crack growth rate and so lower the time required for failure to occur by cold cracking. Presence of both of above discontinuities (cracks and porosity) in the weld decreases mechanical performance of weld joint. Hydrogen in arc zone can come from variety of sources namely:

- moisture (H_2O) in coating of electrode or on the surface of base metal,
- hydrocarbons present on the faying surface of base metal in the form of lubricants, paints etc
- inert gas (Ar) mixed with hydrogen to increase the heat input
- hydrogen in dissolved state in metal (beyond limits) being welded such as aluminium and steel

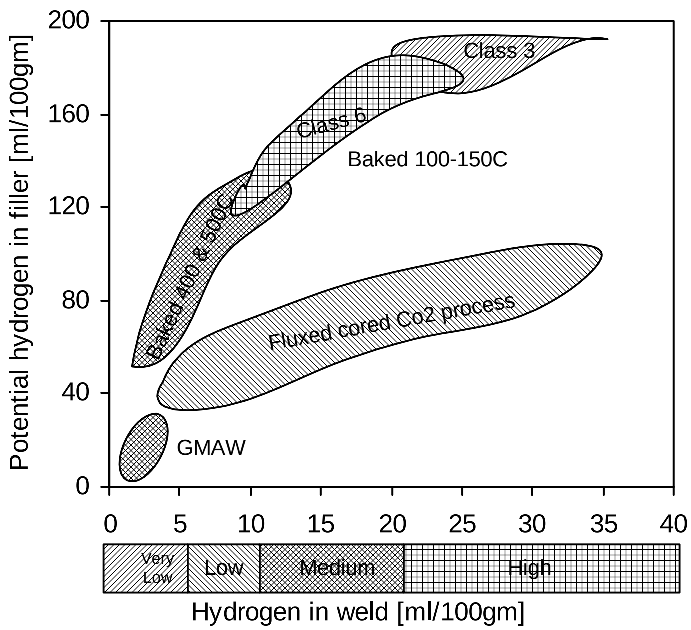


Fig. 36.1 hydrogen content in weld developed using different welding processes

It has been reported that proper baking of electrodes directly reduces the cold cracking tendency and time for failure delayed cracking. Therefore, attempt should be made to avoid the hydrogen from above sources by taking suitable corrective action.

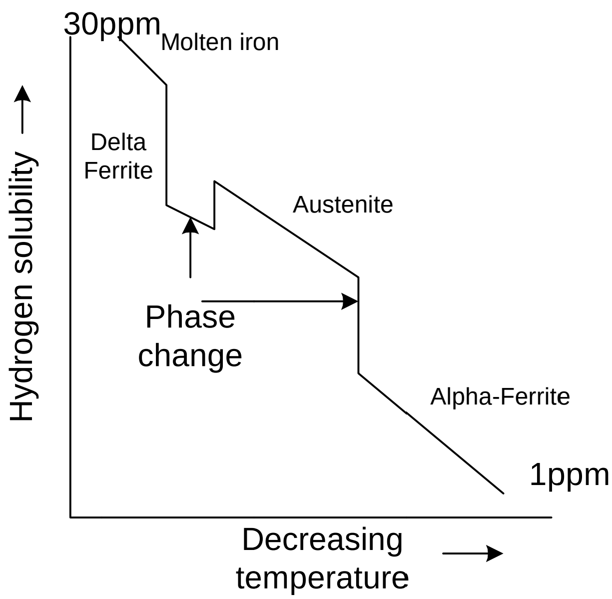


Fig. 36.2 Schematic of hydrogen solubility as a function of temperature of iron

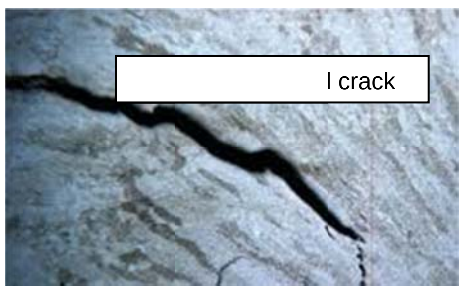


Fig. 36.3 Hydrogen induced crack

36.2 Flux in welding

Fluxes are commonly used to take care of problems related with oxygen and nitrogen. Variety of fluxes is used to improve the quality of the weld. These fluxes are grouped in three categories namely halide fluxes (mainly composed of chlorides and fluorides of Na, K, Ba, Mg) and oxide fluxes (oxides of Ca, Mn, Fe, Ti, Si) and mixture of halide and oxide fluxes. Halide fluxes are free from oxides and therefore these are mainly used for welding highly reactive metals having good affinity with oxygen such as Ti, Mg and Al alloys while oxide fluxes are used for welding of low strength and non-critical welds joints of steel. In general, calcium fluoride in flux reduces hydrogen concentration in weld (Fig. 36.4). Halide-oxide type fluxes are used for semi-critical application in welding of high strength steels.

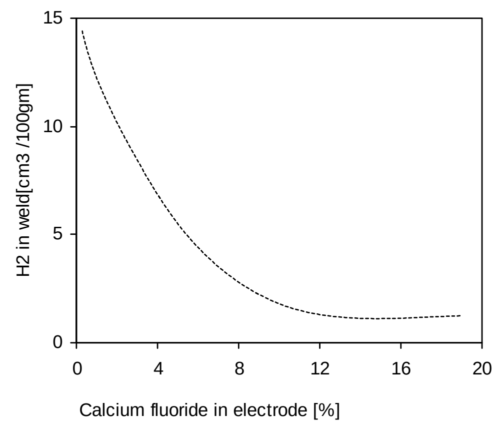


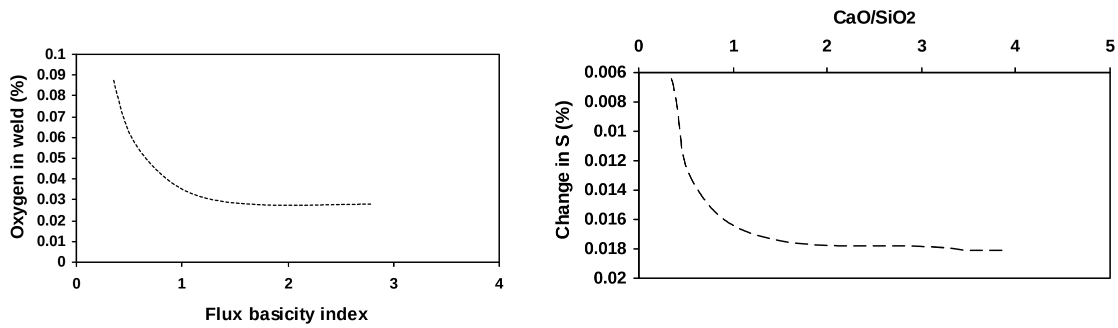
Fig. 36.4 Influence of calcium fluoride on hydrogen concentration in weld joints

36.2 Basicity of the flux

The composition of fluxes is adjusted so as to get proper basicity index as it affects the ability of flux to remove impurities like sulpher and oxygen from melt. The basicity index of the flux refers to ratio of sum of amount of all basic oxides and that of non-basic oxides. Basic oxides (CaO is most common) are donors of the oxygen while acidic oxides (such as SiO_2) are acceptor of oxygen. Common acidic and basic oxides are shown in table below. Flux having BI <1 is called acidic flux, neutral fluxes have 1<BI<1.2 while basic fluxes have BI>1.2. Increase in BI of the flux from 1 to 5 results in significant decrease in sulphur content of the weld. The basic oxides act de-sulphurizer as sulphur is removed from the weld in the form of SO_2 by reaction between oxygen released by basic oxides and S. Thus, the weld is de-suphurized.

Type of oxide	Decreasing Strength						
	1	2	3	4	5	6	7
Acidic	SiO_2	TiO_2	P_2O_5	V_2O_5			
Basic	K_2O	Na_2O	CaO	MgO	BaO	MnO	FeO
Neutral	Al_2O_3	Fe_2O_3	Cr_2O_3	V_2O_3	ZnO		

In general, an increase in basicity of the flux up to 1.5 decreases the S and oxygen concentration (from about 900 PPM to 250 PPM) in weld joints as shown in Fig. 36.5 (a, b). Thereafter, oxygen content remains constant at about 200-250 PPM level despite of using fluxes of high basicity index. Further, there is no consensus among the researchers on the mechanism by which an increase in basicity index decreases the oxygen content.



a) b)

Fig. 36.5 Influence of basicity of flux on a) oxygen and b) sulphur concentration in weld.

These oxides get decomposed at high temperature in arc environment. Stability of each oxide is different. Oxides with decreasing stability are as follows: (i) CaO, (ii) K_2O, (iii) Na_2O and TiO_2, (iv) Al_2O_3, (v) MgO, (vi) SiO_2, (vii) MnO and FeO. On decomposition, these oxides invariably produce oxygen and result-in oxidation of reactive elements in weld metal.

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Lecture 37

Weldability of Metals I

This chapter presents the concept of weldability of metals and factors affecting the same. Different parameters that are used as a measure of weldability have been elaborated. Attempts have been made to describe the relationship between carbon equivalent, hardenability and cracking tendency of weld joints of steel.

Keywords: Weldability, measures of weldability, carbon equivalent, cracking of HAZ, hardenability, austenitic electrode

37.1 Understanding weldability

Weldability is considered as ease of accomplishing a satisfactory weld joint and can be in determined from quality of the weld joint, effort and cost required for developing the weld joint. Quality of the weld joint however, can be determined by many factors but the weld must fulfill the service requirements. The characteristics of the metal determining the quality of weld joint includes tendency to cracking, hardening and softening of HAZ, oxidation, evaporation, structural modification and affinity to gases. While efforts required for producing sound weld joint are determined by properties of metal system in consideration namely melting point, thermal expansion coefficient, thermal and electrical conductivity, defects inherent in base metal and surface condition. All the factors adversely affecting the weld quality and increasing the efforts (& skill required) for producing a satisfactory weld joint will in turn be decreasing the weldability of metal.

In view of above, it can be said that weldability of metal is not an intrinsic property as it is influenced by a) all steps related with welding procedure, b) purpose of the weld joints and c) fabrication conditions. Welding of a metal using one process may show poor weldability (like Al welding with SMA welding process) and good weldabilitywhen the same metal is welded with some other welding process (Al welding with TIG/MIG). Similarly, a steel weld joint may perform well under normal atmospheric conditions and the same may exhibit very poor toughness and ductility at very low temperature condition. Steps of the welding procedure namely preparation of surface and edge, preheating, welding process, welding parameters, post weld treatment such as relieving the residual stresses, can influence the weldability of metal appreciably. Therefore, weldability of a metal is considered as a relative term.

37.2 Weldability of steels

To understand the weldability of steel, it important to look into the different phases, phase mixtures and intermetallic generally found in steel besides the changes in phase that can occur during welding due to heating and cooling cycles. All these aspects can be understood by going through following section presenting significance of Fe-C diagram, time-temperature-transformation diagram and continuous cooling transformation diagram.

Fe-C Equilibrium Phase Diagram

Fe-C diagram is also called iron-iron carbide diagram because these are the two main constituents observed at the room temperature in steel while the presence of other phases depends on the type and amount of alloying elements. It shows the various phase transformations as a function of temperature on heating / cooling under equilibrium conditions (Fig. 37.1).

Allotropy and critical temperatures

Change in crystal structure of an element with rise in temperature is termed as allotropy. Iron shows the allotropic behaviour at temperature 910^{0}C and 1390^{0}C. Iron changes its crystal structure first from BCC to FCC at 910^{0}C and then from FCC to BCC at 1390^{0}C. Therefore, solubility of carbon in iron varies with temperature especially above 910^{0}C and 1390 ^{0}C.

Isothermal Transformations in Fe-C diagram

Three are main reaction points in Fe-C diagram namely peritectic, eutectoid and eutectic, which are of great academic and practical importance. All three reactions take place at a fixed temperature and composition.

Peritecitc reaction

$$\text{Liquid metal} + \delta\text{-iron (B. C. C.)} \underset{}{\overset{1495\ ^0\text{C and } 0.18\%\ \text{C}}{\rightleftarrows}} \gamma\text{-iron (F. C. C.)}$$

Eutectic reaction

$$\text{Liquid metal} \overset{1130\ ^0\text{C and } 4.3\%\ \text{C}}{\rightleftarrows} \gamma\text{-iron (F. C. C.)} + Fe_3C$$

Eutectoid reaction

727 ^{0}C and 0.8% C

Solid (γ-iron) $\rightleftharpoons$ α-iron (B. C. C.) + Fe_3C

Proportions of various phases of these transformations can be obtained using lever rule. Fulcrum of the lever depends upon the alloy composition i.e. carbon content. Since these transformations take place at constant temperatures therefore it is easy to find the tie line. Terminal phases (and their compositions) can be obtained using the tie line and alloy compositions.

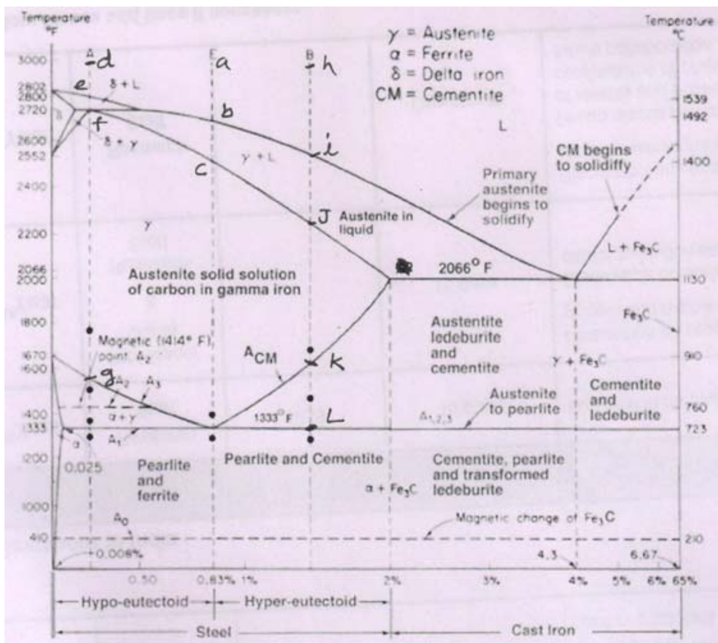

Fig. 37.1 Fe-C diagram (source: Materials Science and Metallurgy, 4th ed., Pollack, Prentice-Hall, 1988)

Phases appearing in Fe-C diagram are ferrite (α-Fe), austenite (γ-Fe), cementite (Fe_3C), δ iron and mixtures of phases such as pearlite (α-Fe + Fe_3C) and ledeburite (γ-Fe + Fe_3C). Pearlite and ledeburite are the result of eutectoid and eutectic reactions respectively. Details of these phases and their mechanical properties are presented in following section.

Ferrite

Ferrite is an interstitial solid solution of carbon in iron having B. C. C. structure. Solubility of carbon in iron having B. C. C. structure at room temperature is about 0.005% while that at eutectoid temperature (727^0C) is 0.025%. Ferrite is a soft, low strength, tough and ductile (50% elongation) phase.

Austenite

Austenite is an interstitial solid solution of carbon in iron having F. C. C. structure. This is not stable below eutectoid temperature (727^0C) in plain Fe-C system as it transforms into pearlite below this temperature. Solubility of carbon in iron having F. C. C. structure at temperature 1330^0C is 2.0% while that at eutectoid temperature (727^0C) is 0.8%. Austenite is a comparatively harder, stronger, tougher but of lower less ductility (%elongation) than the ferrite.

Cementite

Cementite is an inter-metallic compound of iron and carbon i.e. iron carbide (Fe_3C). Cementite contains 6.67% of carbon and has orthorhombic structure. It is the hardest amongst all phases appearing in Fe-C diagram. Its hardness is extremely high while strength is very poor.

Pearlite

Pearliteis a phase mixture of ferrite and cementite and is a result of eutectoid transformation. The pearlite has alternate layers (lamellas) of cementite and ferrite. Strength of pearlite is more than any of the individual phases of which it is made. Mechanical properties i.e. strength, ductility, toughness and hardness of pearlite depends on the inter-lamellar spacing. Thinner plates (layers) of alpha ferrite, Fe_3C results in better mechanical properties.

Ledeburite

Ledeburite is also a phase mixture of austenite and cementite and is formed as a result of eutectic transformation but is observed only above the eutectoid temperature in Fe-C diagram as below this temperature austenite of ledeburitetransforms into pearlite.

Effect of Phases on Mechanical Properties

It is important to note that every phase or phase mixture has its own mechanical properties. Some of the phases are very soft (ferrite) and some are extremely hard (cementite). Therefore, variation in proportions / relative amounts of these phases will affect the mechanical properties of steel as a whole. Increase in carbon content in steel linearly increases proportion of pearlite but at the cost of ferrite. Since ferrite is of low strength, soft and ductile while pearlite is hard, strong and of poor ductility and toughness, hence increase in percentage of pearlite increases strength, hardness and reduces the ductility and toughness of steel as a whole. Cementite appears as an individual phase only above eutectoid composition (steel having carbon > 0.8%). It tends to form a network along the grain boundary of pearlite depending upon carbon content. Complete isolation of pearlite colonies with the cementite (as a result of continuous network of cementite) decreases tensile strength and ductility because mechanical properties of the alloy / steel to a large extent depend upon the properties of phase which is continuous in alloy. Increase in the carbon content above the eutectoid compositions (0.8% C) therefore reduces the strength and ductility because in hypereutectoid steel, network of cementite is formed along the grain boundaries of pearlite and cementite has very low tensile strength (3.0MPa).

Phase Transformation

Steel having 0.8% carbon is known as eutectoid steel. Steels with carbon lesser than 0.8% are known as hypoeutectoid and those having more than 0.8% and less than 2% carbon are called hypereutectoid steels. Fe-C systems having carbon more than 2% are called cast irons. Cast iron having 4.3% carbon is known as eutectic cast iron. Cast irons with carbon less than 4.3 % are known as hypoeutectic and those having more than 4.3% are called hypereutectic cast iron.

STEEL

(a) Eutectoid steel

Transformation of eutectoid steel into various phases on cooling from molten state to the room temperature can be shown by drawing a vertical line through the composition point on E axis (called composition line). No phase transformation occurs until temperature of liquid metal goes down from point ‘a’ to ‘b’ on the liquidus. At the point ‘b’ solidification starts and first of all austenite (with 0.3%C) is formed. Further decrease in temperature results in formation of more and more proportion of austenite whose composition changes along the solidus whereas composition of liquid changes along the liquidus. It shows that carbon content in molten metal increases with the reduction in temperature until it goes down to the point ‘c’. On completion of solidification, steel attains the austenitic state thereafter no phase transformation takes place until it attains eutectoid temperature (723^0C). Reduction in temperature decreases the solubility of carbon in austenite. Austenite is supersaturated with carbon as temperature goes below the eutectoid temperature hence austenite rejects the excess carbon leading to the nucleation of cementite along the grain boundary. As rejection of carbon from austenite continues, cementite layer grows toward the center of austenite grain and a very small zone which is depleted of carbon is formed on both the sides of the cementite plate. As concentration of carbon in carbon depleted zone reduces to such an extent when it is enough to dissolve in iron having B. C. C. structure at that temperature austenite transforms into ferrite. Thickness of the cementite or ferrite plates depends on the rate of diffusion and time available for the transformation to take place. As this transformation occurs by nucleation and growth mechanism which is based on diffusion of atoms. Slower the cooling rate, greater is the time available for the transformation and phases to grow hence thicker cementite and ferrite plates are produced. This process continues until whole austenite is transformed into pearlite.

(b) Hypoeutectoid Steel

Transformation of 0.18%C steel during the cooling from molten state to the room temperature is shown by vertical line through the composition point. It is observed that no phase transformation takes place until temperature of liquid metal goes down from point ‘d’ to ‘e’ on the liquidus. At the point ‘e’ solidification starts and first of all δ iron (with 0.03%C) is formed. Further, decrease in temperature results in formation of more and more δ iron whose composition changes along the solidus whereas composition of liquid changes along the liquidus. Liquidusshows that carbon content in molten metal increases with the reduction in temperature. At the temperature of 1495^0C, liquid metal (with 0.5%C) and solid δ iron (0.1%C) the transformsinto austenite by peritectic reaction. On completion of solidification, steel attains the complete austenitic state thereafter no phase transformation takes place until it attains temperature corresponding to the point ‘g’ (i.e.850^{0}C). At about 850^{0}C, austenite transforms into the ferrite. Further, transformation of austenite into ferrite continues with reduction in temperature until eutectoid temperature is attained. During this transformation, the composition of austenite changes continuously with increase in carbon content in austenite. As eutectoid temperature is attained carbon content in austenite rises to 0.8% i.e. eutectoid composition. At this temperature, austenite of eutectoid composition transforms into pearlite as discussed above. Proeutectoid phase i.e. ferrite, is formed first from austenite in hypoeutectoid steel and subsequently austenite transforms into pearlite. Hence ferrite is found along the grain boundaries of pearlite. Continuity of ferrite network depends upon the carbon content in hypoeutectoid steel. Reduction in carbon content increases the continuity of ferrite network around the pearlite grains. Increase in carbon content reduces the amount of ferrite and increases the amount of pearlite.

(c) Hypereutectoid steel:

Transformation of hypereutectoid steel is similar to that of hypoeutectoid steel except that proeutectoid phase is cementite instead of ferrite. In this case no phase transformation takes place until temperature of liquid metal goes down from point ‘h’ to ‘I’ on the liquidus. At the point ‘i’ solidification starts and first of all austenite (with 0.8%C) is formed. Further, decrease in temperature results in formation of more and more amount of austenite whose composition changes along the solidus whereas composition of liquid metal goes along the liquidus . It shows that carbon content in molten metal increases with the reduction in temperature until it goes down to the point ‘j’. On completion of solidification, steel attains the austenitic state and thereafter no phase transformation takes place until it attains temperature corresponding to the point ‘k’ (1000^{0}C). At eutectoid temperature, austenite becomes supersaturated with carbon hence austenite rejects the excess carbon which leads to the nucleation of cementite along the grain boundary. Further, decrease in temperature results in formation of more and more cementite from the austenite whose composition changes along the kl. As eutectoid temperature is attained, carbon content in austenite decreases up to the eutectoid composition (0.8%C). At this temperature, austenite of eutectoid composition transforms into pearlite as discussed above. Proeutectoid phase i.e. cementite is formed first from austenite in hypereutectoid steel subsequently austenite transforms pearlite. Hence, cementite is found along the grain boundaries of pearlite.

Time Temperature Transformation (TTT) Diagram

This diagram shows the transformation of meta-stable austenite phase at constant temperature into various phases as a function of time (Fig. 37.2). Therefore, it is also known as isothermal transformation diagram.Transformation of austenite into various phases such as pearlite, bainite and martensite depends on the transformation temperature. Time needed to start the transformation of austenite into pearlite or bainite is called incubation period which is initially low at lower transformation temperature and then increases as transformation temperature increases. TTT Diagram for eutectoid C- steel has C shape due to variation in time needed to start and end the transformation of austenite at different transformation temperature This curve has a nose at about 550^0C. Transformation of austenite into pearlite takes place on exposure at any constant temperature above the nose. It is observed that higher the transformation temperature more is the time required for starting and completing the transformation. Transformation of austenite into pearlite or bainite occurs by nucleation and growth process. Hence, at high temperature high growth rate, low nucleation rate coupled with longer transformation time results in coarse pearlitic structure whereas at low transformation temperatures fine pearlitic structure is produced because of low growth rate, high nucleation rate and short transformation time. High transformation temperature lowers the strength and hardness of steel owing to the coarse pearliticstructure.

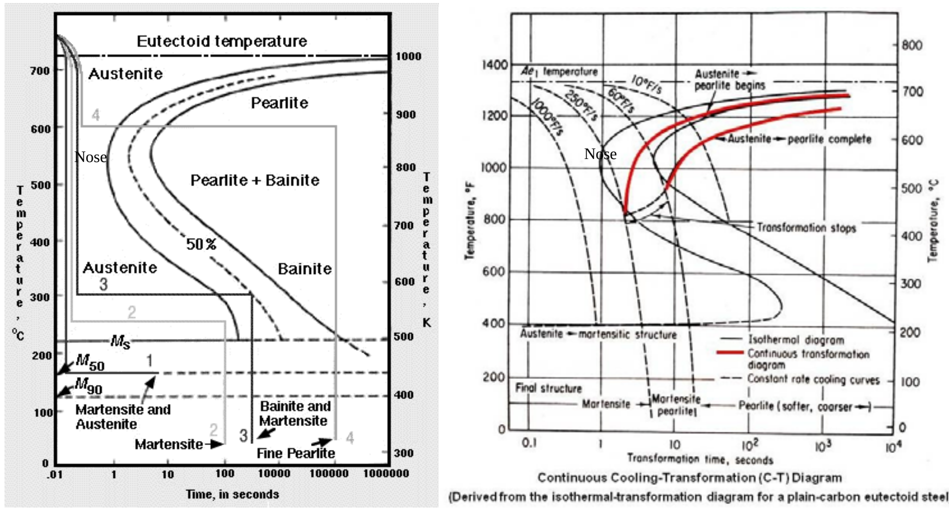

Fig. 37.2 Time-temperature-transformation diagram a) isothermal transformation and b) TTT diagram superimposed with different cooling curves

Transformation of austenite at a temperature below the nose of the curve results in bainitic structure. Bainite is a very fine intimate mixture of ferrite and cementite like pearlite. However, pearlite is a mixture of lamellar ferrite and cementite. That is why bainiteoffers much better strength, hardness and toughness than the pearlite. Degree of fineness of bainite also increases with the reduction in transformation temperature like pearlitic transformation. Bainite formed at high temperature is called feathery bainite while that formed at low temperature near the $M_S$temperatureis called acicular bainite.

Transformation of austenite at a temperature below the $M_S$temperatureresults in hard and brittle phase called martensite structure. Martensite is a supersaturated solid solution of carbon in iron having body centered tetragonal (B.C.T) structure. This austenite to martensite transformation is athermal transformation as it takes place by diffusionless process. Rapid quenching/cooling from austenitic temperature to a temperature below the ‘M_S’ prevents any kind of atomic diffusion. Therefore carbon atoms, which are easily accommodated within FCC unit cell (in austenite) at high temperature should be rejected at low temperature because of reduction in solid solubility. But at such a low temperature (below ‘M_S’) diffusion is prevented and that leads to formation of supersaturated solid solution of carbon in iron having BCC structure. This super-saturation of carbon in iron (BCC) causes the distortion of the BCC lattice structure and makes it BCT by increasing the c/a ratio more than 1. Degree of distortion is measured in terms of c/a ratio. This ratio depends up on the carbon content. Increase in carbon content up to 0.8%, increases the c/a ratio. The c/a ratio can be directly related with the increase in hardness, as there is linear relation between the two up to 0.8% carbon content.

Position of transformation lines and nose depends on steel composition, homogeneity of austenite and grain size. For each composition of steel, there will be just one TTT diagram. Steel other than eutectoid composition will have one more line initiating from the nose in TTT diagram corresponding to transformation of austenite into proeutectoid phase. In case of hypoeutectoid steel, first austenite forms ferrite as a proeutectoid phase, subsequently it transforms into pearlite whereas the proeutectoid phase for hypereutectoid steel is cementite.

Addition or reduction in carbon % in steel with respect to eutectoid composition shifts the nose of TTT diagram. For hypoeutectoid steels nose of the curve is shifted towards the left (reduced incubation time) whereas for hypereutectoid steels nose is shifted to right as compared to that for eutectoid steel. Temperature corresponding to start (M_s) and end (M_f) of martensite transformation is found a function of alloy compositions. Addition of alloying elements lowers these temperatures.

Continuous Cooling Transformation (C.C.T.) Diagram

CCT curve shows the transformation of austenite into various phases as a function of time at different cooling rates but not at constant temperature like in TTT diagram. This diagram is similar to that of TTT diagram except that under continuous cooling conditions (when temperature changes continuously) nose of the curve is shifted to right in downward direction and bainite transformation part as obtained in TTT diagram (below the nose) is absent in CCT diagram. Hence, continuous cooling diagram for eutectoid steel has only two lines above M_s,corresponding to the start and end of pearlite transformation (Fig. 37.3). Various linesAB, KN, QR, ZOshowing the reduction in temperature with time representing the different cooling rates called cooling curves. A very low cooling rate ‘AB’ results in the transformation of austenite into coarse pearlite starts at

T_{s1}temperature and ends at T_{s2} temperature. Therefore, transformation takes place over a range of temperature from T_{s1} to T_{s2}. Such low cooling rates are used for annealing of steels which increases the softness. At somewhat higher cooling rate (KN) the transformation of austenite into pearlite starts at T_{s3} temperature and ends at T_{s4} temperature. Therefore, effective transformation takes place over a range of temperature from T_{s3} to T_{s4}. Grain size depends on the transformation temperature. High transformation temperature produces coarse grain. Since the continuous cooling conditions result in transformation over a range of temperature say T_{s1} to T_{s2}hence the grain size also varies accordingly. Therefore, at start of transformation coarser pearlite grains are formed than that at end of transformation. High cooling rate reduces the effective transformation temperature hence fine grain structure is produced. Such cooling rates are used for normalizing of steel. Normalizing increases the strength, hardness and toughness due to finer grain structure.

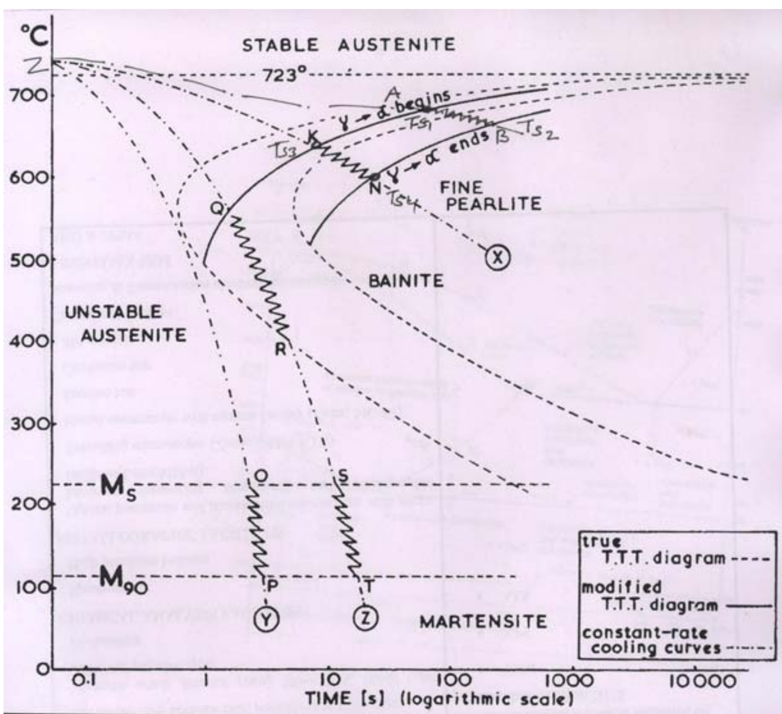

Fig. 37.3 Continuous cooling transformation diagram

Cooling curve ‘QR’ is tangential to 25% transformation line where 25% austenite has transformed into pearlite and 75% austenite is yet to transform. Thereafter, transformation of austenite stops and no further transformation takesplace until its temperature goes down to M_s. As austenite crosses the $M_s$temperature remaining 75% austenite begins to transform into the martensite. This transformation line is expected to result in about 75% of martensite and approx. 25 % pearlite.

Further, higher cooling rate line 'ZO', which is tangential to the nose of the CCT diagram does not cause any transformation of austenite into pearlite. Austenite remains stable until $M_s$temperature is reached. Further reduction in temperature transforms the austenite into the martensite. Moreover, complete transformation of austenite into martensite depends on the quenching temperature. If quenching temperature is below the 'M_f' then only whole austenite is expected to transform into the martensite; otherwise some un-transformed austenite is left in steel called retained austenite. Retained austenite is comparatively soft, therefore, its presence reduces the hardness of steel. Amount of retained austenite depends on the quench temperature between $M_s$and M_f. Lower the transformation temperature (between $M_s$and M_f), smaller is the amount of retained austenite in steel. There is non-linear relationship between the amount of austenite transforming into martensite and quenching temperature in range of $M_s$and M_f. Minimum cooling rate that ensures complete transformation of austenite into martensite and avoids the formation of soft phases/phase mixtures (like pearlite) is called critical cooling rate (CCR).

Critical cooling rate depends on the position of the nose, which is governed by the alloy composition, grain size and homogeneity of austenite. To take into account the effect of all alloying elements on the critical cooling rate, carbon equivalent is used.

High carbon equivalent lowers the critical cooling rate hence less drastic cooling is required for hardening. In general, presence of all alloying elements (except Co) shifts the nose of CCT diagram towards right (conversely increases the incubation period to begin transformation) which in turn reduces the critical cooling rate and increases hardenability. Reduction in carbon content increases the critical cooling rate and makes hardening of steel more difficult.

Fine grained austenite starts the transformation earlier so nose of curves is shifted to left (reduces the incubation period for transformation). This increases the critical cooling rate. On the other hand coarse grain structure reduces the critical cooling rate which in turn increases the hardenability. Similarly inhomogeneous austenite (due incomplete transformation/austenitizing during heating) also reduces the transformation time, shifting nose of CCT curve to left and so increases the critical cooling rate.

Weldability of steel and composition

Weldability of steels can be judged by two parameters (a) cleanliness of weld metal and (b) properties of HAZ. Cleanliness of weld metal is related with presence of inclusion in the form of slag or gases whereas HAZ properties are primarily controlled by hardenability of the steel. Proper shielding of arc zone and degassing of molten weld metal can be used to control first factor. Proper shielding can be done by inactive gases released by combustion of electrode coatings in SMA or inert gases (Ar, He, Co_2) in case of TIG, MIG welding. Hardenability of steel is primarily governed by the composition. All the factors increasing the hardenability adversely affect the weldability because steel becomes more hard, brittle and sensitive to fracture/cracking, therefore it needs extra care. So, more the precautions should be taken to produce a sound weld joint.

Addition of all alloying elements (C, Mn, Ni, W, Cr etc.) except cobalt increases the hardenability which in turn decreases the weldability. To find the combined effect of alloying elements on hardenability/weldability, carbon equivalent (CE) is determined. The most of the carbon equivalent (CE) equations used to evaluate weldability depends type of steel i.e. alloy steel or carbon steel.

- Common CE equation for low alloy steel is as under:

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

(elements are expressed in weight percent amounts)

- For low carbon steels and micro-alloy steels, CE is obtained using following equation: $CE = C + Si/25 + (Mn+Cr)/16 + (Cr+Ni+Mo)/20 + V/15$

- From the Welding Journal, for low carbon, micro-alloyed steels, Ito-Besseyo carbon equivalent:

$$Ceq = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5*B$$

Since the effect of different alloying elements on hardenability of steel is different therefore, their influence on weldability will also be different. In general, high the CE steel needshigh preheat temperature to produce crack free weld joint. Following point can be kept in mind as broad guidelines for welding steel.

- ❖ CE < 0.45 — No preheat required,
- ❖ 0.45<CE< 0.7 — 200-500^{0}C of preheat may be used
- ❖ CE > 0.7 — Can not be welded

Thickness of plate to be welded affects the cooling rate which in turn influences the hardening and cracking tendency. To take into account the thickness of plate above criteria is modified to get compensated carbon equivalent (CCE) relation.

CCE= CE + 0.00425t

Where t is the thickness of plate in mm

- ❖ CCE< 0.4 — No preheat required,
- ❖ 0.4<CCE< 0.7 — 200-500^{0}C of preheat may be used
- ❖ CCE> 0.7 — Cannot be welded

From the weldability point of view, steels can be placed in five categories based on chemical composition, mechanical properties, heat treatment conditions, and high temperature properties: a) carbon steel, b) high strength low alloy steel, c) quench and tempered steel, d) heat treatable steel and e) Cr-Mo steel. These steels need to be welded in different forms such as sheets, plates, pipes, forgings etc. In case of steel welding, it is important to consider thickness of base metal as it affects the heat input, cooling rate and restraint conditions during welding.

37.3 Different types of steel and welding

Carbon steel generally welded in as rolled condition (besides annealed and normalized one). The weldablecarbon steel is mostly composed of carbon about 0.25 %, Mn up to 1.65%, Si up to 0.6% with residual amount of S and P below 0.05%. High strength low alloy steel (HSLA) is designed to have yield strength in range of 290-550 MPa using alloying concentration lesser than 1% in total. These can be welded in conditions same as that of carbon steel. Quench and tempered (Q & T) steels can be a carbon steel or HSLA steel category that are generally heat treated to impart yield strength in range of 350 to 1030 MPa. Heat treatable steels generally contain carbon more than carbon steel or HSLA steels, to increase their response to the heat treatment (Kou, S welding metallurgy, John Willey, 2003). However, presence of high carbon in these steels increases the hardenability which in turn decreases the weldability owing to increased embrittlement and cracking tendency of heat affected zone. Further, PWHT of heat treatable steel weld joints is done to enhance their toughness and induce ductility because presence of high carbon in these heat treatable steels. Cr-Mo steels are primarily designed to have high resistance to corrosion, thermal softening and creep at elevated temperature (up to 700 ^{0}C). Therefore, these are commonly used in petrochemical industries and thermal power plants. Weld joints of Cr-Mo steels are generally given PWHT to regain ductility, toughness, and corrosion resistance and reduce the residual stresses.

37.4 Common problems in steel welding

37.4.1 Cracking of HAZ due to hardening

The cooling rate experienced by the weld metaland HAZ during welding generally exceeds the critical cooling (CCR)which in turn increases the chances martensitic transformation. It is well known from the physical metallurgy of the steels that this transformation increases the hardness and brittleness and generates tensile residual stresses. This combination of high hardness and tensile residual stresses makes the steel prone to the cracking.

37.4.2 Cold cracking

Another important effect of solid state transformation is the cold cracking. It is also termed as delayed/hydrogen induced cracking because these two factors (delay and hydrogen) are basically responsible for cold cracking. Applied/residual tensile stress vs. time relationship for failure by cold cracking is shown in Fig. 37.4. It can be observed that increase in stress decreases the time required for initiation and complete fracture by cold cracking.

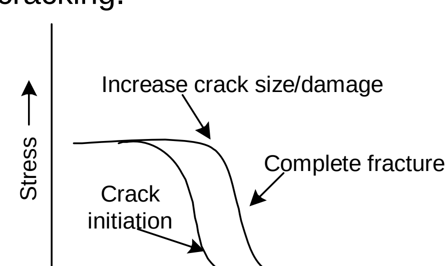

Fig. 37.4 Schematic diagram showing stress vs. time relationship for fracture by cold crack

Origin of this problem lies in the variation of solubility of hydrogen in the steel with the temperature. Reduction in temperature decreases solubility of hydrogen in solid state due to change in crystal structure from F. C. C. to B. C. C. High temperature transformation (like austenite to pearlite or bainite) allows escape of some of excess hydrogen (beyond the solubility) by diffusion. But in case of low temperature transformation (austenite into martensite), when rate of diffusion reduces significantly, hydrogen cannot escape and is trapped in steel as solid solution. Dissolved hydrogen has more damaging effect in presence of martensite and the same has been explained below.

Hydrogen dissolved in atomic state at low temperature tends to diffuse out gradually toward the vacancies and other cavities. At these locations atomic hydrogen converts into diatomic H_2 gas and with time, continued diffusion of hydrogen towards these discontinuities as this gas starts to build up pressure in the cavities (Fig. 37.5). If the pressure exceeds the fracture stress of metal, cavities expands by cracking. Cracking of metal increases the volume which in turn reduces the pressure. Due to continuous diffusion of hydrogen toward the cavities after some time again as pressure exceeds the fracture stress, and crack propagates further. This process of building up on pressure and propagation of cracks is repeated until compete fracture takes place without external load. Since this type cracking and fracture takes place after some time of welding hence it is called delayed cracking. Delay for complete fracture depends on the following factors:

- Hardenability of steel
- Amount of hydrogen dissolved in atomic state

❖ Magnitude of residual tensile stress

Hardenability of steel affects the critical cooling rate. Steel of high hardenability promotes the martensitic transformation therefore it has high hardness and brittleness. High hardness increases the cracking tendency whereas soft and ductile metals reduce it. Crack tips are blunted in case of ductile metals so they reduce the cracking sensitivity and increases the stress level for fracture. As a result crack propagation rate is reduced in case of ductile and low strength metal. Therefore, steels of low hardenability will therefore minimize the cold/delayed cracking.

Larger the amount of dissolved hydrogen faster will be the delayed/hydrogen induced cracking.

Remedy

❖ Use of low hydrogen electrodes.

❖ Preheating of plates to be welded.

❖ Use of austenitic electrodes.

Use of low hydrogen electrodes will reduce the hydrogen content in weld metal. Preheating of the plate will reduce the cooing rate, which will allow longer time for gases to escape during the liquid to solid state and solid-solid transformation. It may also reduce the cooling rate below the critical cooling rate so that martensitic transformation can be avoided and austenite can be transformed into softer phases and phase mixtures like pearlite, bainite etc. These soft phases further reduce the cracking tendency. Use of austenitic electrode also avoids the martensite formation and provides mainly austenite matrix in weld zone. Austenite is a soft and tough phase having high solubility (%) for hydrogen. All these characteristics of austenite reduce the cold/delayed cracking.

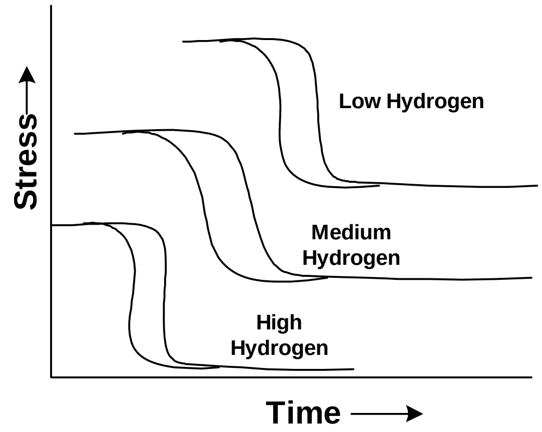

Fig. 37.5 Schematic diagram showing effect of hydrogen concentration on cold cracking at different stress levels

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Lecture 38

Weldability of Metals II

This chapter presents metallurgical aspects related with welding of aluminium alloys. Causes of common problems encountered during welding of aluminium alloys have been described. The mechanism of solidification cracking and its control has been elaborated in detail.

Keywords: Aluminium welding, heat treatable aluminium alloy, precipitation hardening, problems in aluminium welding, inclusion, gas and shrinkage porosity, solidification cracking, controlling solidification cracks

38.1 Need of aluminium welding

Welding of the aluminium is considered to be slightly difficult than the steel due to high thermal & electrical conductivity, high thermal expansion coefficient, refractory aluminium oxide (Al_2O_3) formation tendency, and low stiffness. However, increase in applications of aluminium alloys in all sectors of industry is a driving force for technologists to develop viable and efficient technologies for joining of aluminium without much adverse effect on their mechanical, chemical and metallurgical performances desired for longer life. The performance of weld joints of an aluminium alloys to a great extent is determined by its composition, alloy temper condition and method of manufacturing besides welding related parameters. All the three aspects are usually included in aluminium alloy specification. Aluminium alloy may be produced either only by cast or by casting and subsequent forming process (which are called wrought alloys). Welding of wrought aluminium alloys is more common and therefore in this chapter discussions are related to wrought aluminium alloys. Depending upon the composition, aluminium alloy are classified from 1XXX through 9XXX series. Some of aluminum alloys (1XXX, 3XXX, 4XXX and 5XXX) non-heat treatable and others (2XXX, 6XXX and 7XXX series) are heat treatable.

38.1.1 Strengthening of Non-heat treatable aluminium alloys and welding

The strength of the non-heat treatable aluminium alloys is mostly dictated by solid solution strengthening and dispersion hardening effects of alloying elements such as silicon, iron, manganese and magnesium. Magnesium is the most effective alloying element in solution strengthening therefore 5XXX series aluminium alloys have relatively high strength even in annealed condition. Most of the non heat treatable aluminium alloys are work hardenable. Heating of these alloys during welding (due to weld thermal cycle) lowers prior work hardening effect and improves the ductility which in turn can lead to loss of strength of HAZ. Moreover, high strength solid solution alloys of 5XXX series such as Al-Mg and Al-Mg-Mn are found suitable for welded construction structures as they offer largely uniform mechanical properties of the various zones of a welded joint.

38.1.2 Strengthening of heat treatable aluminium alloys and welding

The most of heat treatable aluminium alloys (2XXX, 6XXX and 7XXX series) are strengthened by solid solution formation, work hardening and precipitation strengthening depending upon the alloy condition and manufacturing history. Strength of these alloys in annealed condition is either similar or slightly better as compared to non-heat treatable alloys mainly due to presence of alloying elements such as copper, magnesium, zinc and silicon. Generally, heat treatable aluminium alloys are precipitation hardened. The precipitation hardening involves solutionizing followed by quenching and aging either at room temperature (natural aging) or elevated temperature (artificial aging).

Three most common precipitation hardenable aluminium alloys namely Al-Cu (2XXX series), Al-Mg-Si (6XXX series) and Al-Zn-Mg (7XXX series) are primarily hardened by forming phases namely Al_2Cu, Mg_2Si and Zn_2Mg respectively besides many complex intermetallic compounds developed during aging process. Therefore, presence and loss of these precipitates significantly affects the mechanical performance (hardness, tensile strength and % elongation) of weld joints of these alloys. However, the existence of theses hardening precipitates is influenced by weld thermal cycle experienced by base metal and weld metal during welding. In general, all factors decreasing the heat input (either due to low welding current, increase in welding speed or use of low heat input welding processes such as electron beam, pulse TIG) would reduce the width of heat affected zone associate adverse effects such as the possibility of partial melting of low melting point phases (eutectic) present at grain boundary, over-aging, grain growth, reversion or dissolution of precipitates or a combination few or all.

$$\text{Al–Cu–Mg (e.g., 2024):} \quad SS \rightarrow GP \rightarrow S' (Al_2CuMg) \rightarrow S (Al_2CuMg)$$
$$\text{Al–Mg–Si (e.g., 6061):} \quad SS \rightarrow GP \rightarrow \beta' (Mg_2Si) \rightarrow \beta (Mg_2Si)$$
$$\text{Al–Zn–Mg (e.g., 7005):} \quad SS \rightarrow GP \rightarrow \eta' (Zn_2Mg) \rightarrow \eta (Zn_2Mg)$$

In the solution heat treated condition, heat treatable alloys exhibit lower cracking tendency than in the aged condition mainly due to more uniform microstructure and lesser restraint imposed by base metal. Welding of heat treatable aluminium alloy in aged condition leads to reversion (loss/dissolution of precipitates) and over-aging (coarsening of precipitates by consuming fine precipitates) effect which in turn softens the HAZ to some extent. However, under influence welding thermal cycle, alloying elements are dissolved during heating and form heterogeneous solid solution and subsequently rapid cooling results in super-saturation of these elements in aluminium matrix. Thus, solutionizing and quenching influence the heat affected zone. Thereafter, aging of some of the alloys like Al-Zn-Mg occurs slowly even at room temperature which in turn help to attain strength almost similar to that of base metal while other heat treatable alloy like Al-Cu and Al-Mg-Si alloys don't show appreciable age hardening at room temperature. Hence, Al-Zn-Mg alloys are preferred when post weld heat treatment is neither possible nor feasible.

38.2 Weldability of aluminum alloys

Weldability of aluminium alloys like any other metal system must be assessed in light of purpose (application of weld joint considering service conditions), welding procedure being used and welding conditions in which welding need to be performed. Weldability of aluminium may be very poor when joined by shielded metal arc welding or gas welding but the same may be very good when joint is made using tungsten inert gas or gas metal arc welding process. Similarly other aspects of welding procedure such as edge preparation, welding parameters, preheat and post weld heat treatment etc. can significantly dictate the weldability of aluminium owing to their ability to affect the soundness of weld joints and mechanical performance. Thus, all the factors governing the soundness of the aluminium weld, the mechanical and metallurgical features determine the weldability of aluminium alloy system. In general, aluminium is considered to be of comparatively lower weldability than steels due to various reasons a) high affinity of aluminium towards atmospheric gases, b) high thermal expansion coefficient, c) high thermal and electrical conductivity, d) poor rigidity and e) high solidification temperature range. These characteristics of aluminium alloys in general make them sensitive from defect formation point of view during welding. The extent of undesirable affect of above characteristics on performance of the weld joints is generally reduced using two approaches a) effective protection of the weld pool contamination from atmospheric gases using proper shielding method and b) reducing influence of weld thermal cycling using higher energy density welding processes. Former approach mainly deals with using various environments (vacuum, Ar, He, or their mixtures with hydrogen and oxygen) to shield the weld pool from ambient gases while later one has led to the development of newer welding processes such as laser, pulse variants of TIG and MIG, friction stir welding etc.

38.3 Typical welding problems in aluminum alloys

38.3.1 Porosity

Porosity in aluminum weld joints can be of two types a) hydrogen induced porosity and b) inter-dendritic shrinkage porosity and both are caused by entirely different factors (Fig. 38.1). Former one is caused by the presence of hydrogen in the weld owing to unfavorable welding conditions such as improper cleaning, moisture in electrode, shielding gases and oxide layer, presence of hydro-carbons in form of oil, paint, grease etc. In presence of hydrogen porosity in the weld metal mainly occurs due to high difference in solubility of hydrogen in liquid and solid state of aluminum alloy. During solidification of the weld metal, the excess hydrogen is rejected at the advancing solid-liquid interface in the weld which in turn leads to the development of hydrogen induced porosity especially under high solidification rate conditions as high cooling rate experienced by the weld pool increases tendency of entrapment of hydrogen. Excessive hydrogen porosity can severely reduce strength, ductility and fatigue resistance of aluminum welds due to two reasons a) reduction in effective load resisting cross-sectional area of the weld joints and b) loss of metallic continuity owing to the presence of gas pockets which in turn increases the stress concentration at the weld pores. It also reduces the life of aluminum welds. Therefore, to control hydrogen induced porosity in aluminium following approaches can be used a) proper cleaning of surfaces, baking of the electrodes to drive off moisture and remove the impurities from weld surface b) addition of freon to the shielding gas, c) churning the weld pool during weld solidification using suitable electro-magnetic fields.

Inter-dendritic porosity in weld mainly occurs due to poor fluidity of molten weld metal and rapid solidification. Preheating of plates and increasing heat input (using high current and low welding speed) help in reducing the inter-dendritic porosity.

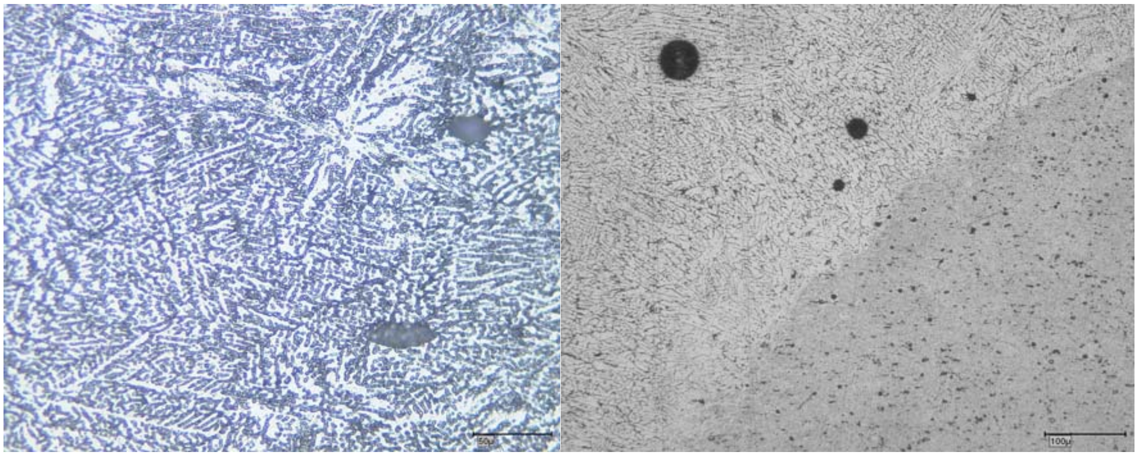


Fig. 38.1 Micrographs showing a) dendritic and b) gas porosity in aluminium welds (100X)

38.3.2 Inclusion

In general, presence of any foreign constituent (one which is not desired) in the weld can be considered as inclusion and these may be in the form of gases, thin films and solid particles. High affinity of aluminium with atmospheric gases increases the tendency of formation of oxides and nitrides (having density similar to that of aluminium) especially when a) protection of weld pool is not enough, b) proper cleaning of filler and base metal has not been done, c) shielding gases are not pure enough and therefore making oxygen and hydrogen available to molten weld pool during welding, d) gases are present in dissolved state in aluminium itself and tungsten inclusion while using GTA welding. Mostly, inclusion of oxides and nitrides of aluminium are found in weld joints in case of un-favourable welding conditions. Presence of these inclusions disrupts the metallic continuity in the weld therefore these provide site for stress concentration and become a source of weakness leading to the deterioration in mechanical and corrosion performance of the weld joints (Fig. 38.2). Ductility, notch toughness and fatigue resistance of the weld joints are very adversely affected by the presence of the inclusion. To reduce the formation of inclusion in weld it is important to give proper attention to a) avoid sources of atmospheric gases, b) developing proper welding procedure specification (selection of proper electrode, welding parameters, shielding gases and manipulation of during welding), and c) manipulation of GTAW torch properly so as to avoid the formation of tungsten inclusion.

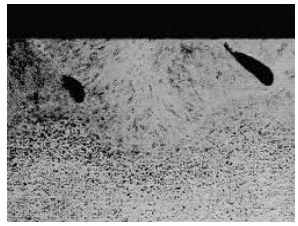


Fig. 38.2 Inclusions and other impurities in weld joints

38.3.3 Solidification cracking

This is an inter-dendritic type of cracking mostly along observed along the weld centerline in very last stage of solidification primarily due to two factors a) development of tensile residual stresses and b) presence of low melting point phases in inter-dendritic regions of solidifying weld is called solidification cracking (Fig. 38.3).

The solidification cracking mainly occurs when residual tensile stress developed in weld (owing to contraction of base metal and weld metal) goes beyond the strength of solidifying weld metal. Moreover, the contribution of solidification shrinkage of weld metal in development of the tensile residual stress is generally marginal. All the factors namely thermal expansion coefficient of weld and base metal, melting point, weld bead profile, type of weld, degree of constraint, thickness of work piece etc. affecting the contraction of the weld will govern the residual stresses and so solidification cracking tendency. The presence of tensile or shear stress is mandatory for cracking means no residual tensile stress no cracking. Residual stresses in weld joint can not be eliminated but can be minimized by developing proper welding procedure.

Increase in degree of restraint during welding in general increases solidification cracking tendency due to increased residual tensile stresses. Similarly, concave fillet weld bead profile results higher solidification cracking tendency than those of convex weld bead profile. In same line, other related materials characteristics of base metal such as increase in thickness of plate, high thermal expansion of coefficient and wider solidification temperature in general increases the residual stresses and so solidification cracking tendency.

Apart from the residual tensile stresses, strength and ductility of weld metal in terminal stage of solidification also predominantly determine the solidification cracking tendency. In general, all the factors such as composition of the weld metal, microstructure, segregation tendency, wider solidification temperature range and higher fluidity of low melting point phases (owing to reduction in surface tension and viscosity) of molten weld metal increase the solidification cracking.

Fig. 38.3 Solidification cracking in aluminium weld

38.3.3.1 Composition of aluminum alloy

Presence of all alloying element (silicon, copper, magnesium, zinc) in such a quantity that increases the solidification temperature range tends to increase the solidification cracking tendency. In general, addition of these elements in aluminum first widens the solidification temperature range then after reaching maximum it decreases gradually as evident from the Fig. 38.4. It can be observed that addition of these elements at certain level results in maximum range of solidification temperature and that corresponds to highest solidification cracking tendency. It can be noticed from the Fig. 38.4 that solidification cracking is lower with both very low and high concentration of alloying element owing to varying amount of low melting point eutectic and other phases. A very limited amount of low melting point phases obviously increases resistance to solidification cracking due to high strength of solidified weld metal in terminal stage of solidification while in case of aluminium alloy (such as eutectic or near to the eutectic composition) or those with high concentration of alloying elements having large amount of low melting point phases to facilitate healing of cracks by the backfill of incipient cracks which in turn decreases the solidification cracking tendency.

Therefore, selection of filler metal for welding of aluminum alloys is done in such a way that for given dilution level, concentration of alloying element in weld metal corresponds to minimum solidification temperature so as to reduce the solidification cracking possibility. In general, application of Al-5%Mg and Al-(5-12%) Si fillers are commonly used to avoid solidification cracking during welding of aluminum alloys.

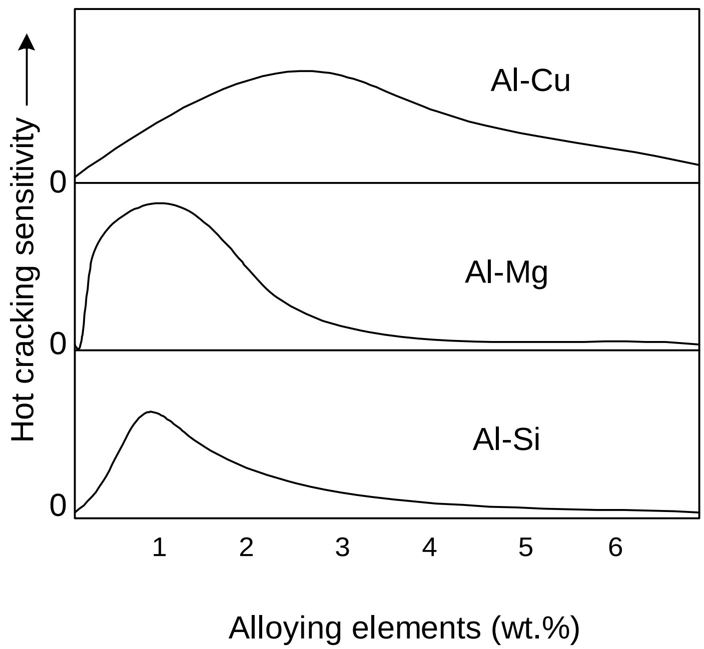
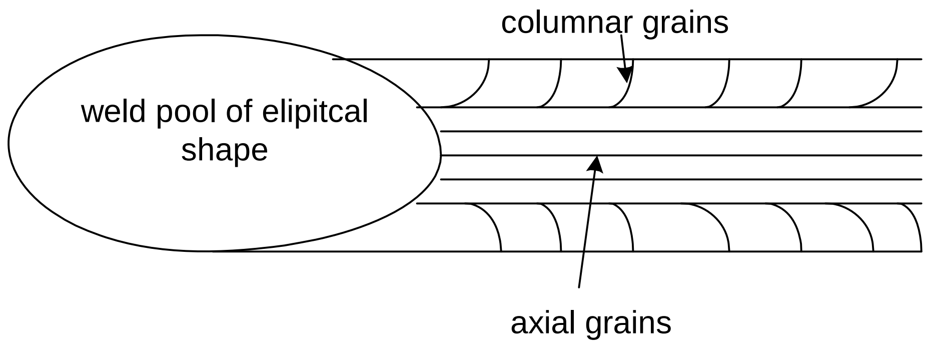
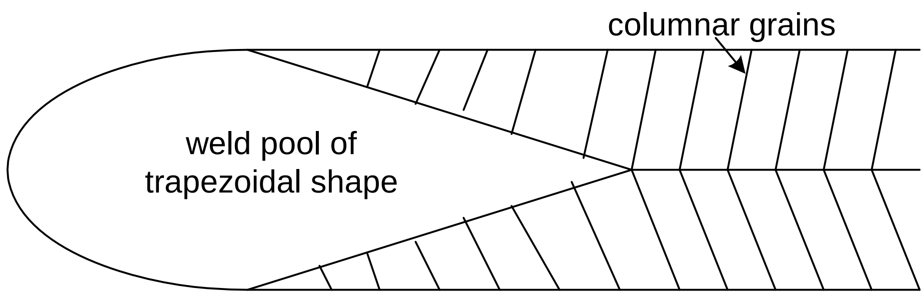


Fig. 38.4 Influence alloying elements on solidification cracking tendency

The influence of microstructure of weld metal on solidification cracking depends on the way it affects the segregation tendency owing to variation in size and orientation of grains. In general, fine grain structure results is large grain boundary area and hence more uniform distribution of low melting point phases and reduced segregation of alloying element. Further, fine equiaxed grain structure provides better heeling of incipient crack through back fill by liquid metal available at last to solidify due to improved fluidity of melt through the micro-channel present between already solidified metal. Conversely for a given solidification cracking sensitive alloy composition coarse columnar grain structure having abutting orientation encourages the cracking tendency as compared to fine equiaxed and axially grain (Fig. 38.5). Moreover, the morphology of low melting point phases as governed by their surface tension and viscosity in liquid state near last stage of solidification also affects the solidification cracking sensitivity. In general, low melting point phases having low surface tension and viscosity (so high fluidity) solidify in form of thin films and layer in inter-dendritic regions which are considered to be more crack sensitive than those of globular morphology formed in case of high surface tension and viscous low melting point phases.



a)



b)

Fig. 38.5 Schematic diagram showing influence of welding speed on weld pool and grain structure of weld a) low speed and b) high speed

38.3.3.2 Control of solidification cracking

- Changing composition of the weld metal so as to reduce the solidification temperature range and increase the amount of low melting point eutectic phases and phase mixtures to facilitate heating of incipient cracks.
- Refinement of the grain structure: The microstructure of weld metal can be controlled in many ways such as addition of grain refiner, use of external electromagnetic or mechanical forces and selection of proper welding parameters such as heat input (VI) and welding speed or use pulse current for welding. Addition of grain refiner (Ti, B, Zr etc) in aluminium weld metal so as to facilitate the development of fine and equiaxed grain structure and reduce columnar grain structure. Similarly, low heat input leads to development of fine equiaxed grains and low welding speed produces curved grain associated with pear drop shaped weld pool. Mechanical vibrations and electro-magnetic stirring of weld pool also help to refine the grain structure avoid the abutting columnar grains (Fig. 38.5 b).

- Reducing tensile residual stresses developing in weld joints using any of the approaches such as controlling weld bead geometry, selection of weld joint design, welding procedure and low strength filler can help in reducing the solidification cracking.

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Lecture 39

Failure Analysis and Prevention: Fundamental causes of failure

This chapter defines the failure and elaborates the conditions for failure of mechanical components. Further, the fundamental causes of failure associated with design, materials, manufacturing and service have been described in detail.

Keywords: Failure analysis, causes of failure, modes of failure, fatigue, creep, SCC, design deficiency, improper material, defective raw material, poor maintenance, improper processing, failure mechanism vs. design criteria

39.1 Introduction

The failure of engineering components frequently leads to disruption in services to the public at large. To avoid reoccurrence of the failure of engineering component during service, it is important that whenever failure occurs, the same is thoroughly investigated to establish primary factor and other important factors that led to failure so that suitable recommendations can be made to avoid similar failure in future. Failure analysis and its prevention needs a systematic approach of investigation for establish the important causes of the failure. Therefore, it is worth to familiarize with fundamental causes of failure of mechanical, general approach to be used for the failure analysis and failure analysis of welded joints.

39.2 Fundamental causes of the failure

In general, an engineering component or assembly is considered to have failed under any of the following three conditions when the component is a) inoperable, b) operates but doesn't perform the intended function and c) operates but safety and reliability is very poor. However, metallurgical failure of a mechanical component can occurs in many ways a) elastic deformation is beyond acceptable limit, b) excessive and unacceptable level of plastic deformation, c) complete fracture has taken place and d) loss of dimension due to wear and tear besides variety of reasons. In two chapters, failure analysis shall be oriented mainly towards the metallurgical failure of mechanical components.

39.2.1 Elastic deformation

Elastic deformation occurs when stiffness of the component is less and the same is primarily determined by modulus of elasticity and cross section. Elastic deformation can lead to the failure of mechanical components especially in high precision assemblies and machinery where even small elastic deformation under operating conditions is not acceptable.

39.2.2 Plastic deformation

Excessive plastic deformation of the mechanical components can lead to the failure in two conditions a) externally applied stress is beyond the yield strength limit and b) component is subjected to applied stress lower than yield stress but exposed to high temperature conditions enough to cause creep. Both the cases should be handled using different approaches. To avoid the failure by plastic deformation owing to externally applied stress more than yield strength, the cross section should be designed after taking proper factor of safety and considering the yield strength of materials of which component is to be made. For mechanical components that are expected to be exposed in high temperature creep resistant materials should be selected so that under identical load condition, low steady state creep rate of creep resistant materials can allow desired longer creep life.

39.2.3 Fracture

Fracture of mechanical components is usually caused by a) overloading, b) fatigue and c) stress rupture.

Failure due to overloading can occur in many ways such as accidental loading, gradual reduction in load resisting cross sectional area of component due to wear and tear, deterioration in mechanical properties of component due to unfavorable metallurgical transformations during service. To avoid failure due to overloading well thought out design should be developed in light prevailing technological understanding and stress calculations while regular monitoring the condition of component during the service should also be done using suitable techniques and proper inspection and testing schedules.

39.2.4 Fatigue, SCC and Creep

The catastrophic fractures due to fatigue take place without any plastic deformation. The fatigue fracture occurs only when the extent of variation of the load on the component in respect of the loading parameters like stress range, stress amplitude, range of stress intensity factor and maximum stress, is large enough and type of load is mainly tensile or shear. As first stage of fatigue, crack nucleation and subsequent table growth of the crack during fatigue can occur only under tensile and shear load by mode I and mode II or mode III respectively. Fatigue failure can occur not just in components with stress raiser and internal defects but also in well polished component having uniform cross-section. However, fatigue life of the components having stress raiser and defects is generally found lower than those of smooth surface and uniform cross section. Engineering components that are expected to experience the fatigue loading are designed for specific life e.g. 1 million load cycles, 2 million load cycles, 10 million load cycles and infinite life. The fatigue life (Number of load cycle) of a weld joint is primarily decided by the stress range for a given joint configuration. Accordingly, weld cross section is designed to have stress range within the specified limit for typical particular designed fatigue life. Fracture surface of a component failed by fatigue exhibits concentric circular arcs usually called beach marks.

Stress rupture is another mechanism causing fracture of those components which are subjected to high temperature exposure at high stresses. The stress rupture is third and last stage of the creep where creep takes place at increasing rate as function of time by grain boundary sliding mechanism that nucleates voids and subsequently coalescence of voids lead to fracture. Generally, the surface of a component subjected to stress rupture has many cracks and severe necking near the fracture surface which can be seen even by naked eyes.

39.2.5 Loss of Dimension

Loss of dimension takes placed primarily due to removal of the material from the functional surface by variety of wear mechanisms such as abrasion, adhesion, corrosion erosion etc. Gradual loss of the material from the functional surface eventually can lead to reduction in load resisting cross sectional area to such an extent that failure takes place by any of the above mentioned mechanisms like excessive elastic deformation, plastic deformation, overloading, fatigue, creep or stress rupture singly or in combination with other mechanisms. Moreover, the resistance to wear of materials by a particular mechanism is determined by a combination of mechanical and chemical properties of materials.

39.3 Fundamental Causes of failure

The failure of an engineering component in actual working conditions can occur due to very large of factors related with design, materials, manufacturing, service conditions etc. To have systematic understanding on various factors which can lead to metallurgical failure of engineering components, these can be groups under following headings:

- ☑ Improper design
- ☑ Improper selection of materials
- ☑ Defects and discontinuities in metal itself
- ☑ Improper processing of materials
- ☑ Poor service conditions
- ☑ Poor assembling
- ☑ Poor maintenance

39.3.1 Lack of Design

A deficient design frequently causes failure of engineering components under external load. The deficiency in design of a component can be in various forms such as presence of stress raisers owing to sharp change in cross section, changing the design without proper consideration of its influence on stress distribution especially in high stress areas of the component, duplicating a successful design for more severe loading conditions, design is developed without full knowledge of stress conditions owing to complexity of the geometry and inability to use proper criteria for designing the engineering components.

It is believed that in general more than 50% of the metallurgical failures of engineering components occur due to localization of the stresses in presence of stress raisers such as sharp fillets, notches, keyways, holes etc. Localization of the stress initiates the cracks and facilitates their propagation hence premature fracture is encouraged by presence of stress raisers. Fatigue failure is mostly triggered by these stress raisers present either at the surface or in sub-surface region.

Premature failures are also observed when management encouraged by excellent performance of an engineering component with one system decides to put the same component on some other similar kind of system but of higher capacity without giving full consideration to the stress analysis which will be developed in the component on the new system. In new conditions may not be compatible to the same components in respect of material, design, and service conditions etc. which can lead to premature failure.

Sometimes even slight modification in design made to facilitate the manufacturing at the shop floor either (in absence or ambiguity in design specification) can lead to excessive stress concentration and so the premature failure engineering components.

A deficient design can also results from important factors like inability to calculate the type and magnitude of stresses accurately and dependence of designer on under of tensile data for the design purpose which may not always be equally relevant. Designers frequently also come across the situation when accurate calculations and clear analysis of stress (under prevailing technological understanding and capabilities) is not practicable due to complexity in geometry of the component.

39.3.3 Improper selection of the materials

Selection of a material for developing the design of a mechanical component during service in light of operating conditions should be based on expected failure mechanisms such as ductile or brittle fracture, creep, fatigue, wear etc. For each type of expected failure mechanism a combination of the mechanical, physical and chemical properties should be possessed by the material to be selected for developing a design. For example, if failure of a component is expected to occur by excessive plastic deformation at room temperature and high temperature conditions then yield strength and creep respectively will be important criterion for design. Similarly, if failure of a component is expected to occur by fracture under overloads, fluctuating loads and impact loads then ultimate strength, endurance strength and impact strength respectively should be considered for design purpose. Deficient material selection can occur due to reliance on tensile data for selection of materials, and inability to select of metal in light of the expected failure mechanism and so as to develop suitable criteria for the design purpose. The problem of the materials selection is further complicated when the performance of materials varies as function of time e.g. creep, corrosion, embrittlement etc.

The selection of the material for design purpose is still being made on the basis of the tensile data available in metal hand books despite of the fact that tensile data does not correctly reflect the performance of the materials under different types of load and service conditions. The criteria for the selection of metal for designing a component for a particular service conditions must be based on the expected failure mechanism. Practically there are no fixed criteria for selection of metal while designing the component. Design criteria for working condition of each component should be analyzed carefully and then based expected failure mechanism suitable design criteria may be developed. Only as a guide following table shows few failure mechanisms and the corresponding design criteria that may be useful for designing of the engineering component.

S. No.	Failure mechanism	Design criteria
1	Ductile fracture	Yield strength (in tension, compression, shear as per type of load)
2	Brittle fracture	Fracture toughness (critical stress intensity factor K_{1c}), Izode / Charpy notch toughness, ductility, ductile to brittle transition temperature
3	Fatigue	Endurance limit / fatigue strength with stress raiser, hardness
4	Thermal fatigue	Ductility, peak plastic strain (under operating conditions)
5	Creep	Creep rate at given temperature
6	Plastic deformation	Yield strength
7	Stress corrosion cracking	K_{1SCC}, corrosion resistance to specific environment

39.3.3 Presence of defects and discontinuities in raw/stock metal

Metal being used for fabrication of an engineering component may be deficient in many ways depending upon the thermal and mechanical stresses experienced by it during manufacturing steps used for developing the stock. For example rods, plates, and flats produced by bulk deformation based processes like rolling, forging and extrusion may have unfavorable flow of grains, surface cracks etc. while castings may have blow holes, porosity and dissolved gases in solid state. Components developed using such raw materials and stocks having internal discontinuity and minute surface defects generally offer poor mechanical performance especially under fatigue load conditions as these discontinuities provide easy path for fracture. Therefore, raw materials away from fracture location and near the fracture surface of the failed part must be studied using suitable techniques. To identify the presence of such discontinuities in raw/stock material more attention should be paid to the location wherefrom cracks have grown to cause fracture.

39.3.4 Unfavorable manufacturing processing conditions

A wide range of manufacturing processes are used for obtaining the desired size, shape and properties in stock material which includes primary and secondary shaping processes such as castings, forming, machining and welding apart from the processes like heat treatment, case hardening, surface coating etc. that are primarily designed to impart the desired combination of properties either at the surface or core of the raw materials as dictated by the requirement of the applications. The selection of inappropriate combination of the process parameters for each of above mentioned manufacturing processes can lead to development of discontinuities, defects, unfavorable transformation and metallurgical changes and so deterioration in the performance of final product during the service. These imperfections and discontinuities are mostly process specific and can exist in variety of forms due to improper selection of manufacturing process and their parameters. Therefore, due care must be taken by failure analyst to investigate the presence of any defect, discontinuity or unfavorable features in end produced by manufacturing processes and failed prematurely during the service. Presence of any undesirable feature or discontinuity in failed component not just near the fracture surface but also in new one or at the location away from the fracture surface indicates selection of inappropriate manufacturing process conditions. Further, to establish the reason for development of discontinuities and defects, manufacturing process and its parameters should be analyzed carefully to see whether these were compatible with the raw material or not. Hence, the failure analyst or investigation team members must have expertise in materials and manufacturing process in question in order to establish the cause of failure owing to deficiency in manufacturing stage of material. Just to have an idea, few manufacturing processes along with commonly found defects and discontinuities that can be potential sources of the failure occurring due to abused manufacturing condition have been described in the following sections.

Forming and forging

These are bulk deformation based groups of manufacturing processes in which desired size and shape is obtained by applying mostly compressive, shear and tensile force to ensure the plastic flow of metal as per needs. In manufacturing of defect and discontinuity free formed/forged products, the ductility of the raw material plays a very crucial role. Forming/forging can be performed either at room temperature or elevated temperature according to the ductility and yield strength of the raw material. To increase the ductility and reduce yield strength so as to facilitate bulk deformation is commonly performed at high temperature. Apart from ductility and temperature, the rate of deformation also significantly determines the success of bulk deformation based processes. Lack of ductility owing to inappropriate stock temperature and excessively high rate of deformation can lead to cracks and other continuities in end product.

Machining

Machining is a secondary shaping process and is also considered as negative process as unwanted material is removal form stock materials to get the desired size and shape. Further, the material from the stock is removed in the form of small chips by largely shear mechanism. However in some of the advanced machining processes the application of the localized intense heat is also used for removing the material from the stock by melting and ablation. Improper machining procedure including unsuitable selection of machining process, tool, cutting fluid, process parameters etc. can lead to development of undesirable features such as feed marks, overheating, decarburization, residual stresses and loss of alloying elements from the surfaces of the machined components. These can act as a source of stress raiser and provide easy site for nucleation of the cracks, softening of materials due to loss of alloying element. In case, failure triggered by discontinuities generated during machining, the failure analyst should look into the compatibility of machining procedure for a given material to establish the cause of the failure and make suitable recommendations to avoid the reoccurrence of the similar failure.

Welding

The development of a joint by welding and allied processes like brazing and soldering, thermal spraying etc. generally involves application of localized heat, pressure or both, with or without filler. However, the weld joint itself is frequently considered as discontinuity owing to presence of heterogeneity in respect of the mechanical, chemical, structural properties and residual stress state a compared to the base metal or the components being joined besides the existence of weld discontinuities within the acceptable limit in form of notches, porosities, poor weld bead profile, cracks etc. Owing to presence of the above undesirable features in weld joints joint efficiency is generally found less than 100%. Therefore, weld joints are not considered very reliable for critical applications. The most of the weld discontinuities are welding process and base metal specific. If failure has been triggered by weld discontinuities then failure analysis must look into welding procedure specification and work man ship related aspects to establish the causes of failure.

Heat treatment

Heat treatment of many metal systems like iron, aluminium, magnesium, copper, titanium etc is a common industrial practice to obtain the desired combination of properties as per needs of the end application of the component. Heat treatment mostly involves a sequence of the controlled heating up to predetermined temperature followed by holding for some time (soaking) and then controlled cooling. Each step of heat treatment from heating to the controlled cooling is determined by the purpose of heat treatment, method of manufacturing, size and shape of the component. Thus, inappropriate selection of any steps of heat treatment namely heating rate, peak temperature, soaking time and cooling rate can result in unfavorable metallurgical transformation and mechanical properties that can eventually lead to failure. For example, overheating of hardenable steel components for prolong duration can cause oxidation, decarburization, excessive grain growth, dissolution of the fine precipitates, increased hardenability, high temperature gradient during quenching and thus increased cracking tendency. Similarly, unfavorable cooling rate can produce undesirable combination of the properties which may be lead to poor performance of the component during the service. Therefore, hardness test on the failed component is commonly performed to conform of heat treatment was done properly. In case, failure investigation indicating that it was triggered by unfavorable properties and structure generated during heat treatment, then failure analyst should look into the compatibility of heat treatment parameters with material, size and shape of the component to establish the cause potential of the failure and make suitable recommendations.

Chemical cleaning

Surface of the engineering components is frequently cleaned using mild hydrogen based chemical and acids. Sometimes, during the cleaning hydrogen gets diffused into the sub-surface region of the metal if the same is not removed by post cleaning heat treatment or followed by development of the coatings immediately then hydrogen is left in the subsurface zone which can subsequently be the cause of the failure by hydrogen embrittlement or cold cracking. If the failure investigation indicates the possibility of hydrogen embrittlement or cold cracking then failure analyst should look into the detailed procedure used for chemical cleaning of the failed engineering components besides measuring the hydrogen dissolved in subsurface region using suitable method.

39.3.5 Poor assembling

Error in assembly can result due to various reasons such as ambiguous, insufficient or inappropriate assembly procedure, misalignment, poor workmanship. Sometimes, failures are also caused by the inadvertent error performed by the workers during the assembly. For example, failure of nut and stud assembly (used for holding the car wheel) by fatigue can occur owing to lack of information regarding sequence of tightening the nuts and torque to be used for tightening purpose; under such conditions any sort of loosening of nut which is subjected to external load will lead to fatigue failure.

39.3.6 Poor service conditions

Failure of an engineering component can occur due to abnormal service condition experienced by them for which they are not designed. These abnormal service conditions may appear in the form of exposure of component to excessively high rate of loading, unfavorable oxidative, corrosive, erosive environment at high or low temperature conditions for which it has not been designed. The contribution of any abnormality in service conditions on the failure can only be established after thorough investigation regarding compatibility of the design, manufacturing (such as heat treatment) and material of the failed components with condition experienced by them during the service. To avoid any catastrophic failure of critical components during the service usually well planned and thought out maintenance plan is developed which involves periodic inspection and testing of the components that is crucial for uninterrupted operations of entire plant. For a sound maintenance strategy, it is important that procedure of inspection and testing methods developed in such a way that they indicate the conditions of the component from the failure tendency point of view by the anticipated and expected failure mechanism. Any inspection and testing that doesn’t give information about the condition of the components with respect to failure tendency by the anticipated failure mechanism should considered redundant. For example, a typical sound test is conducted in Indian railways on arrival training at each big station for indentifying the assembly condition; similarly, the soundness of the earthen pot is also assessed by sound test.

39.3.7 Poor maintenance strategy

The failure of many moving mechanical components takes place due to poor maintenance plan. A well developed maintenance plan indicating each and every important step to be used for maintenance such what, when, where, who and how for maintenance, is specified explicitly. Lack of information on proper schedule of maintenance, procedure of the maintenance, frequently causes premature failure of moving components. For example, absence of lubrication of proper kind in right quantity and conditions frequently leads to the failure of assemblies working under sliding or rolling friction conditions.

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Lecture 40

General Procedure of Failure Analysis

This chapter present basic approach of proceedings with failure analysis and care need to have useful findings about few most potential causes of the failure. Step by step approach of failure analysis of the mechanical components has been described. It is important to note that these steps need not to be followed strictly in sequence (given below) as findings of any stage of investigation will dictate further direction of failure analysis.

40.1 Introduction

In the field of engineering, mechanical components are made using variety of materials processed by different manufacturing processes and are used in extremely wide range of the service conditions. Potential causes of the failure of the components and their mechanism are also numerous. Therefore, procedure of the failure analysis of each failed component should be different and the same must be developed after giving proper thought on possible sequence of events before failure along with proper evaluation of the situation and consideration of material, manufacturing process, service history and actual working condition etc. Since the failure analysis involves lot of efforts, time and use of resources therefore at the end of analysis failure analyst should be in position to come up with few most potential causes of the failure so that suitable recommendations can be made to avoid reoccurrence of the similar failure. It has been observed that on receipt of failed components, failure analyst tends to jump into conclusions based on half information and try to prepare the samples for metallographic studies to look explore the deficiency in the material itself. This kind of quickness is uncalled for and in this process vital clues, evidence and information can be lost from the surface of the fractured components. In this chapter, general practice for metallurgical failure analysis of failed component has been described besides common features of various types of fractures and important tools and equipments available for analysis and characterization.

40.2 General step of failure investigation

As a broad guidelines, steps generally used in metallurgical failure analysis of mechanical components are described in the following section. These steps are generic and need not to be followed in the specified; moreover the sequence of steps will largely be determined by the findings of the investigation at any stage, with main objective of collecting evidences for potential causes of the failure so the sequence of events prior to the failure can be established and suitable recommendations can be made to prevent the similar failure in the future.

1. Collection of back ground information about failed components
2. Preliminary examination of failed components
3. Selection, preservation and cleaning of the sample
4. Assessing the presence of discontinuity and defect in failed component by non-destructive testing
5. Evaluation of the mechanical properties of the failed components
6. Macroscopic observation of fracture surfaces
7. Microscopic examination of fracture surfaces
8. Metallographic examination of failed components
9. Establishing the fracture mechanism
10. Failure analysis using fracture mechanics approach
11. Conducting test under simulated conditions if required
12. Analysis of findings of investigation
13. Report writing with recommendation

40.1 Collection of back ground information of failed components

Failure analysis should begin with collection of information mainly on manufacturing procedures used for development the failed components, design aspects and service conditions of the same with objectives to familiarize with components under investigation and to make an effort to develop the “draft sequence” of events which would have led to the failure. Depending upon the level of record keeping practices, the extent of information available on above aspects may vary appreciably.

Information collection on manufacturing aspects should include details of drawing, material, manufacturing process and process parameters, assembling method used for obtaining the desired size and shape. Since manufacturing steps used for developing various components of an assembly are found in the form of many processes therefore information collection can be grouped under three heading based on nature of manufacturing process a) mechanical processes such as forging, forming, machining etc. wherein external stresses are applied during manufacturing, b) thermal processes such as welding, brazing, heat treatment etc. that are based on the application of heat to control the structure and properties and c) chemical processes such as cleaning, electroplating, machining etc which use mixture of chemical solutions for variety of purposes. Segregation of the information on mechanical, thermal and chemical basis helps to estimate the structure, mechanical and chemical changes that can be experienced by materials during manufacturing which can produce desirable or undesirable changes in the end product.

The collection of information about past service conditions to a great extent depends how meticulously record keeping of working conditions has been maintained. The failure analyst should try to collect information about loading and environmental conditions, duration of service, temperature, maintenance plan etc. Sometimes, failure analyst gets only fragmented information on service conditions, in such case based on the experience and skill, failure analyst needs to estimate/guess the working conditions in order to establish the sequence of events that led to the failure. However, in absence of information any error in estimation can be totally misleading to the investigation hence failure analysts are cautioned against such kind of estimation if they are not confident.

40.2 Preliminary examination of failed components

This step involves observation of failed components, their fragments and position occupied them after failure. Detailed photographic record showing the condition and location/position of the failed components should be obtained. A detailed and systematic photographing is important in failure analysis because the failure which is appearing to be a common and casual accident, subsequent investigation may indicate serious implications and tampering possibilities. Schematic diagrams can also be used to locations wherefrom photographs have been taken for better representation of the failed components and their fragments as per needs.

40.3 Preservation, cutting and cleaning of the sample

Usually in post-accident scenario, failed components are found in very bad condition of shape, debris, impurities etc. Based on the preliminary examination failure analyst should take decisions on location wherefrom sample need to be collected from fractured components for further analysis. The sample may be taken from the near fracture surface or significantly away from the fracture zone keeping in mind collection of the evidence that would help in establishing the sequence of events besides indicating the potential causes of failure. The skill, experience and gut feeling of the failure analyst play very crucial role in decision making on areas/locations wherefrom samples need to be collected. Once decision is taken, next step would be to obtain the samples by cutting from the failed component or assembly which can be done using mechanical or thermal methods. Due care should be taken to avoid any chemical or mechanical damage when mechanical methods (machining, cutting) are used for cutting the sample. Thermal cutting methods like gas cutting is considered to be more damaging than mechanical methods because application of heat for cutting the samples by thermal methods can change the structure up to a greater distance than mechanical methods. Additionally thermal methods will have the possibility of falling of spatter on the fracture surface. Hence, sample cutting by thermal methods should be made at greater distance than mechanical methods.

Cleaning of the fractured specimen should be avoided as far as possible as cleaning will remove the foreign matters like oxide, paints, chemical etc. present on the fracture surface which can play an important role in establishing the root cause and sequence of events prior to the failure. If cleaning is necessary to proceed with investigations and to carry out studies then dry or wet cleaning can be applied as per requirement with due care to avoid any kind of damage to fractured specimens. Dry cleaning using jet of compressed dry air can be applied to remove the foreign particles while wet cleaning can be done using mild acidic or basic solution followed by rinsing in fresh water or acetone followed by drying before putting samples into desiccators.

Sometimes plastic replica method is also used for cleaning fractured surfaces. In this approach one softened acetate sheet of about 1mm thickness is pressed over the fracture surface and then taken off once the sheet is dried after curing for 8-12 hours. Removal of sheet from the fractured surface takes away some of the foreign matter present on the surface. The shape of sheet generally corresponds to that of fractured surface. These sheets with attached foreign matter can be preserved for record and further studies of fracture surface and foreign matter as per needs in future.

40.4 Assessing the surface and sub-surface imperfections using NDT

To determine the possibility of the failure caused by presence few surface and surface imperfections, non-destructive testing of fractured component especially near the fracture surface can carried out using variety of techniques as per needs. Common non-destructive testing methods includes dye penetrant test (DPT), magnetic particle test (MPT), eddy current test (ECT), ultrasonic test (UT), radiographic test (RT) etc. Each test has unique advantages and limitations which dictate their applications as indicated in table.

NDT test	Advantage	Limitation	Applications
DPT	• Simple, • cost effective • portable	• Not for subsurface defects • Difficult to assess fine cracks • Surface cleaning in important	Surface discontinuities cracks, fine porosities
MPT	• Easy to apply • Quick • Simple	• Only for near surface defects • Only for ferromagnetic materials • Chances of arcing at contact point • Difficult to assess deep sub-surface defects	Fine surface defects closed by impurities
ECT	• Very sensitive method • Continuous production • Simi-skilled worker can use	• Difficult to interpret the results as output is influenced by many factors • Only for ferromagnetic and electrical conducting materials	For surface and sub-surface defects in continuous and long slender shape products like shaft and gears
UT	• Very sensitive method • Precisely locates the defects	• Difficult to interpret the results and accuracy depends on many factors • Needs expertise and skill to interpret findings	For both surface and subsurface defects like porosity, internal defects etc.

RT	• Positive record of test is obtained • No limit on thickness of the material which can be evaluated	• Difficult to interpret the results and accuracy depends on many factors • Needs expertise and skill to interpret findings • Specially precaution is needed to handle radiations and protect operators	Internal defects can be located precisely

40.5 Destructive test in failure analysis

Destructive tests such as hardness, tensile, toughness, fracture toughness and tests under simulated conditions are extensively used in failure analysis for variety of purposes. In general, destructive tests are carried out to generate the data on mechanical performance of the specimen under investigation and to assess their suitability for given service load conditions. Additionally, destructive tests can also be use to a) indentify / confirm the manufacturing process used for developed the component under investigation, b) confirm if a particular heat treatment was performed properly. Hardness test is commonly carried out on small fractured specimen for evaluating heat treatment, estimating ultimate tensile strength and determines the extent of work hardening or decarburization occurred on the fractured component during the service, if any. Since it becomes difficult to find large amount of material from the failed components for tensile and fatigue tests therefore failure analysts mostly rely on hardness tests. However, sometime tensile, toughness, fatigue tests are conducted at low, high temperature and in specific environments to assess the performance under simulated conditions. Further, it is advised that care should be taken in interpretation of laboratory test results of mechanical properties and attributing the same to failure owing to minor difference in scale/size of material in laboratory test and real service conditions. Minor difference in actual and recommended value of mechanical properties in fact may not be responsible for failure. Tri-axial stress state and related embrittlement of material should not be overlooked during interpretation of tensile test results.

40.6 Macroscopic observation of fracture surfaces

Macroscopic observation of the fracture surfaces are generally carried out in range of 1-50 magnification with the help of lenses, stereoscope and optical microscope (with external lighting) and now more commonly used system is scanning electron microscope. Plastic replicas coated with gold layer of about 200^0A can also be used for macroscopic observation. A careful macroscopic examination can reveal important information on stress state under which failure has taken place, location wherefrom fracture had initiated, direction of crack growth and operational fracture mechanism during various stages of fracture.

The stress state under which failure has taken place can be plain stress and plain strain condition. The plain stress condition generally observed in ductile metals of thin section like sheet, wire and thin plates, and is recognized by slating fracture surface appearance while plain stain condition usually noticed with hard, brittle metals of heavy sections and is recognized by flat fracture surface largely normal to external applied stress. The fracture surface of a typical tensile test specimen of mild steel shows more commonly known cup and cone fracture involving a combination of flat fracture surface in central part corresponds to plain strain condition and slanting fracture surface near the outer surface belongs to the plain stress condition. Most of the fractures of real components generally occur under combined plain stress and plain strain condition.

Presence of chevron marks on the brittle fracture surface can easily indicate the location wherefrom fracture had initiated and direction of growth of crack. Cracks usually grow in the direction opposite of orientation of the chevron marks. Region where these marks converge indicates the site of fracture initiation. It is important to note here that above trend is common but always not true. The chevron marks can indicate the reverse trend also; conversely these can show last part of the fracture instead of starting part of the fracture surface.

Each fracture mechanism (such as fatigue fracture, stress corrosion cracking, hydrogen embrittlement, brittle fracture etc.) results in specific kind of fracture surface morphology in respect of surface roughness and texture. Macroscopic examination based on surface roughness and texture can reveal the extent and area where a particular fracture mechanism might have been operational during fracture. For example, typical fatigue fracture surface exhibits different roughnesses and textures in three areas of fatigue fracture namely fracture crack initiation, stable crack growth and sudden fracture zones.

40.7 Microscopic observation of fracture surfaces

The microscopic examination of the fracture surface helps to identify the operating micro-mechanism of the fracture and is usually carried out using devices like transmission electron microscope and scanning electron microscope. Both electron microscopes have different capabilities in terms of magnification and resolving power. The transmission electron microscope offers higher resolving power (up to 10^0A) and magnification (3×10^5) than the scanning electron microscope (up to 150 ^{0}A resolution and 1×10^5 magnification). Specimens are usually coated with thin layer of gold of about 50 ^{0}A to make them electrical conducting with better reflection. Scanning electron microscopy (SEM) is more popular as compared to transmission electron microscopy (TEM) due to two reasons related with sample preparation a) sample preparation for TEM is very tedious and time consuming and b) no sample preparation is needed for SEM except that it should be small enough to get accommodated in vacuum chamber.

Depending upon the type of materials and locating conditions, the fracture surface may reveal variety of microscopic fracture mechanisms such as dimple fracture, cleavage fracture, inter-granular fracture and fatigue fracture. The fracture based on macro-scale deformation of the material (before fracture) can be classified as ductile fracture and brittle fracture. Amongst the four microscopic mechanisms of the fracture, dimple fracture belong to ductile fracture while other three namely cleavage, intergranular and fatigue fracture corresponds to brittle fracture.

Dimple fracture is usually associated with extensive plastic deformation of materials prior to fracture which is indicated by the presence of conical shape deep cavities in one part of the fracture surface and corresponding conical shape protrusions in another opposite part fracture surface. Number, size and depth of dimple suggest the extent of plastic deformation and load carrying capacity.

Dimple fracture is considered as high energy fracture as it consumes lot of energy in causing plastic deformation prior to fracture. Fracture tough material of high load carrying capacity and good ductility predominantly exhibits dimple fracture.

Cleavage fracture is associated with brittle fracture and is characterized by the presence of typical river like pattern on the fracture surface that formed due to intermittent growth of crack and development of steps under the influence of external load. In cleavage fracture, cracks propagate through the grains that come across them conversely it is a result of trans-granular fracture. Cleavage fracture is considered as low energy fracture as it consumes little energy prior to fracture. The cleavage fracture usually offers low load carrying capacity and limited deformation prior to fracture.

Intergranular fracture is also associated with brittle fracture and material subjected to is characterized by the presence of typical flat surface ball shape grain on the fracture surface formed by de-cohesion of grains under the influence of external load owing to the presence of some poor or brittle phases/compounds at grain boundary. Since in the type of fracture, cracks propagate mostly along the grain boundaries to cause the fracture hence is termed as inter-granular fracture. Fracture occurring due to hydrogen induced cracking, stress corrosion cracking and sensitization of stainless steel etc. fall under the category of Intergranular fracture. Like cleavage fracture, Intergranular fracture is also considered a low energy fracture with poor load carrying capacity and limited ductility.

Fatigue fracture is mostly catastrophic and is generally characterized by the three distinct regions on the fracture surface corresponding to fatigue fracture initiation site, stable crack growth zone, and sudden fracture zone. Fracture owing to the fatigue typically exhibits concentric circles commonly termed as beach marks at low magnification and similar features observed at high magnification are called striations. These features are developed during second stage of fatigue fracture i.e. stable crack growth. According to the nature of material, third region correspond to sudden fracture may show either dimple or cleavage fracture.

40.8 Metallographic examination of failed components

Metallographic examination of the failed as well as new components is one of the most important tools available to the failure analyst as it is helps:

- to assess the class of the material (for the presence of desirable or undesirable features such as unfavorable orientation of grains, porosity etc.)
- to get idea about the suitability of composition
- to study the effect of service and aging conditions such as decarburization, excessive grain growth etc. if any
- to obtain the information about method of manufacturing and heat treatment carried out the on the failed component
- to determine the contribution of environmental effect on failure such as corrosion, oxidation, work hardening etc.
- to identify the microstructural constituents contributing to the crack nucleation and propagation, if any

It is practically not feasible to generalize the site wherefrom sample should be taken for metallographic studies from failed components for the failure analysis because each failure becomes unique and specific and therefore, needs different approach to establish the causes of failure. Moreover, few general guidelines for selection of sample for common failures can be given. The sample either from near fracture surface or away from it should be taken in such away that it represents to characteristics of the entire component correctly. Examination of crack tip near the fracture surface at high magnification can indicate if a) crack is growing in trans-granular or Intergranular manner and b) crack has some preferential path for growth in material.

Image analyzing software can be very useful to quantify the morphological characteristics of the micro-constituents that can be related with failure. The morphological features such as grain size, shape (aspect ratio, circularity, nodularity, form factor, shape factor etc.), number of particles per unit area, relative proportion of various phases and their distribution. Additionally, image analyzers can also help in measuring the geometrical dimensions of inclusion, cracks and proportions of various micro-mechanisms (such as dimple, cleavage etc.) present on the fracture surface.

40.9 Establishing the fracture mechanism

Using observations and data collected in so far from above stages of investigation, attempts are made to establish fracture mechanism and conditions which led to the failure during service. For this purpose, information collected from preliminary study of the failed component, macro and microscopy examination of fracture surface, metallographic study of samples, efforts should be made to establish the chain activities that have contributed to failure.

40.10 Failure analysis using fracture mechanics approach

In light of discontinuities if any found during investigation in failed component, fracture toughness & yield strength of material involved in failure, efforts should be made to analysis the situation using principle of fracture mechanics to establish that if presence of discontinuities in material have contributed to failure of the component under given service load conditions.

40.11 Conducting test under simulated conditions

Attempts can also be made to simulate the conditions under which a component has failed to understand what might have led to the failure if investigators are unable to find any logical reason for the failure of the component using normal investigation procedures on materials, manufacturing and service related aspects.

40.12 Analysis of findings of investigation

Analysis of all the information, facts, technical observations collected through the investigation is performed to establish the sequence of events that might have led to failure of a component. This can provide us an insight on few potential factors that have caused of failure of component.

40.13 Report writing with recommendation

The report of failure analysis of must include the following

- Few most potential causes of failure
- Sequence of events that have lead to failure

- Recommendation to take suitable steps so as avoid recurrence of the same kind of failure in future

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