Module-IV

4. Arc Welding

In this operation, electric arc is used to produce heat energy and the base metal is heated.

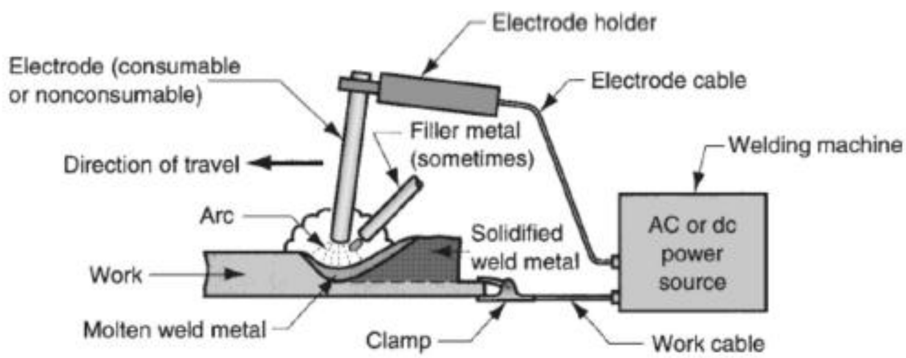
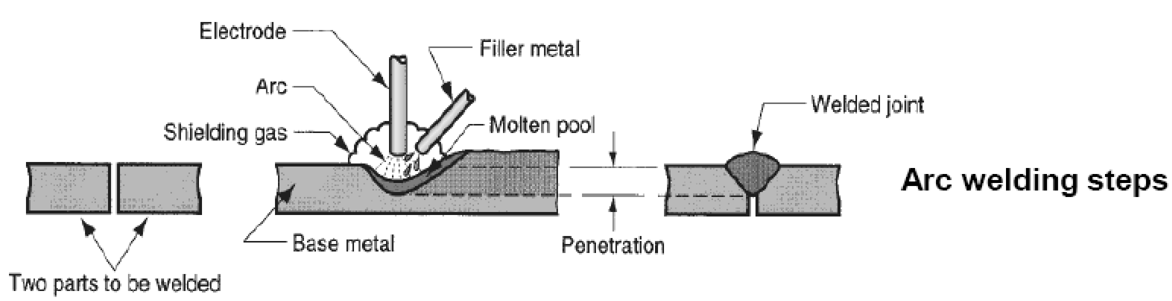


Fig. 4.1 Schematic view of an arc welding setup

In welding, the weld can be made by simply melting the edges of the two work pieces and allowing them to fuse together on cooling. This type of weld is referred to as an autogenous weld. The other method is to add extra material during the welding pro-process. In both cases, the welded area will have a microstructure and properties that are different from the parent metal. The three predominant zones in a fusion weld are the fusion zone, a heat-affected zone (HAZ), and the base metal as shown in figure below. The weld deposit itself will have a cast structure of often a complex composition. Between the weld deposit and the parent metal is an HAZ that did not melt during welding but reached very high temperatures. Grain growth due to the high temperatures is commonly encountered in the HAZ.



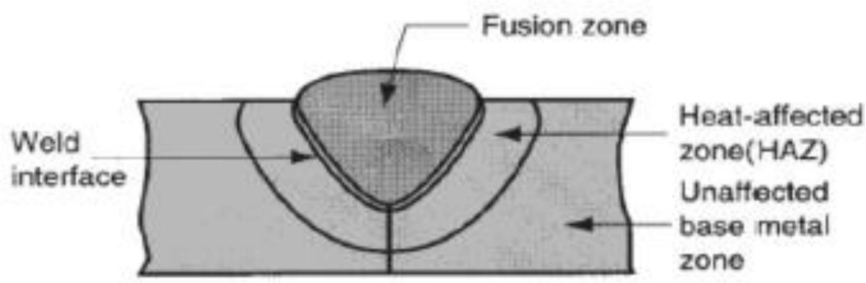


Fig. 4.2 different zones in fusion welding

For the proper penetration thick weld metal faces are prepared in different shape i.e. Square butt, single bevel, single –J, double bevel, double-J, single-V, single-U, double-V, double-U, flange type, tee type etc.

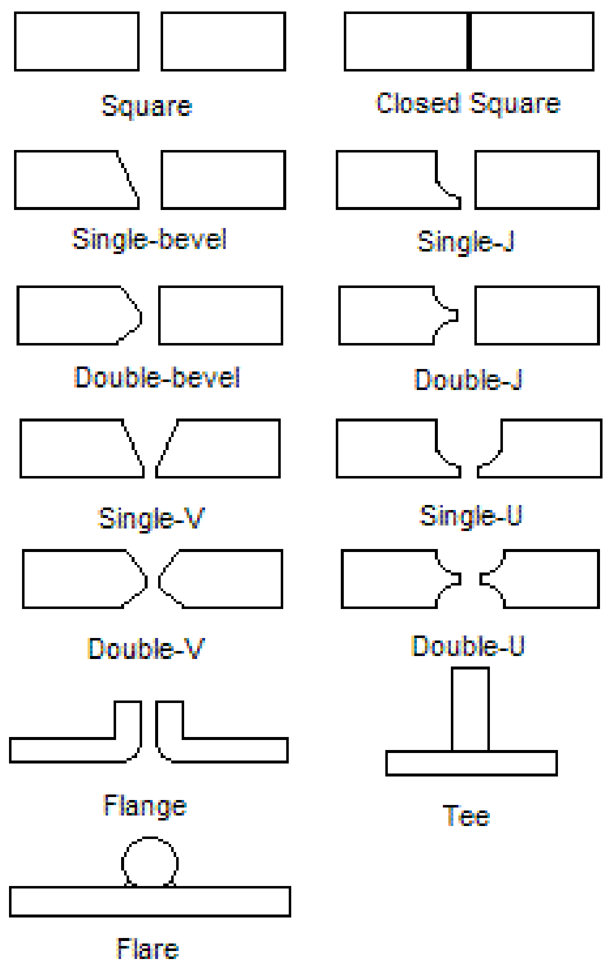
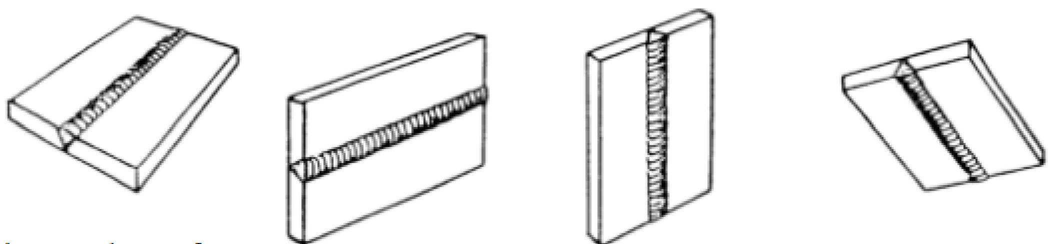


Fig. 4.3 Shape of different weld face

Welding is often done on structures in the position in which they are found. Techniques have been developed to allow welding in any position. Some welding processes have all-position capabilities, while others may be used in only one or two positions. All welding can be classified according to the position of the workpiece or the position of the welded joint on the plates or sections being welded.

There are four basic welding positions, which are flat, horizontal, vertical and overhead are shown below;

Flat Position — Horizontal Position — Vertical Position — Overhead Position



Plates and axis of weld horizontal — Plates vertical and axis of weld horizontal — Plates vertical and axis of weld vertical — Plates and axis of weld horizontal

4.1 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.

❖ 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. 4.3 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.

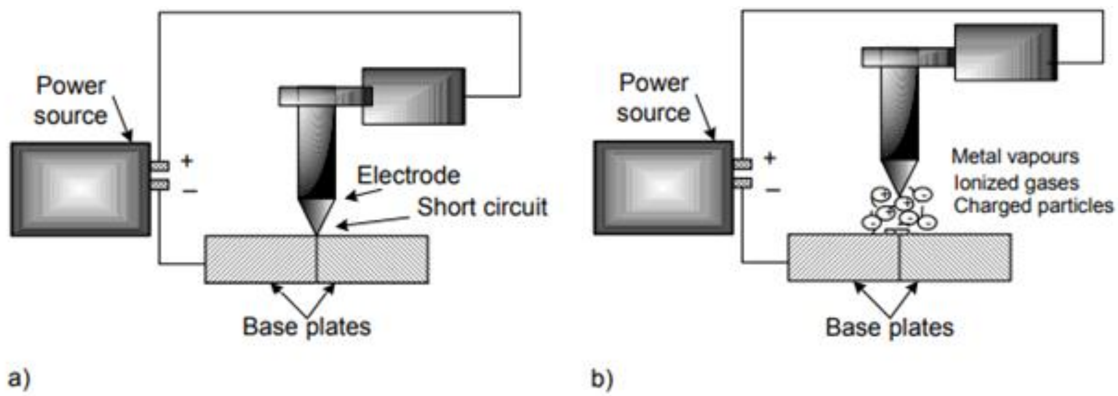


Fig. 4.3 Schematic diagram showing mechanism of arc initiation by touch start method a) when circuit closed by touching electrode with work piece b) emission of electrode on putting them apart

❖ Field Start

In this method, high strength electric field (107 V) is applied between electrode and work piece so that electrons are released from cathode electro-magnetic field emission (Fig. 4.4). 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.

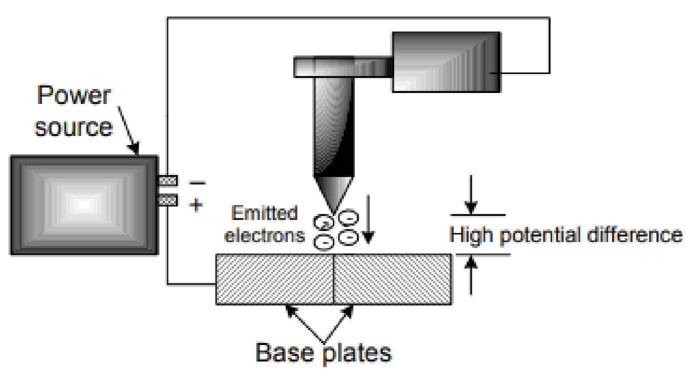


Fig. 4.4 Schematic diagram showing the field-start method of arc initiation

4.2 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.4.5 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.

- **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.4.5a). While in case of overhead welding it prevents the detachment.

Gravitational force (F_g)=ρVg

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).

- **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.4.5b). Accordingly, flux/electrode composition for oddposition welding purpose must be designed to have viscous and high surface tension weld metal/slag.

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

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.

- **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.4.5c). This force can be measured by following equation

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

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

- **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.4.5d).

- **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.4.5 e1-e4).

- **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.4.5 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)= (μ X I^2)/8π

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

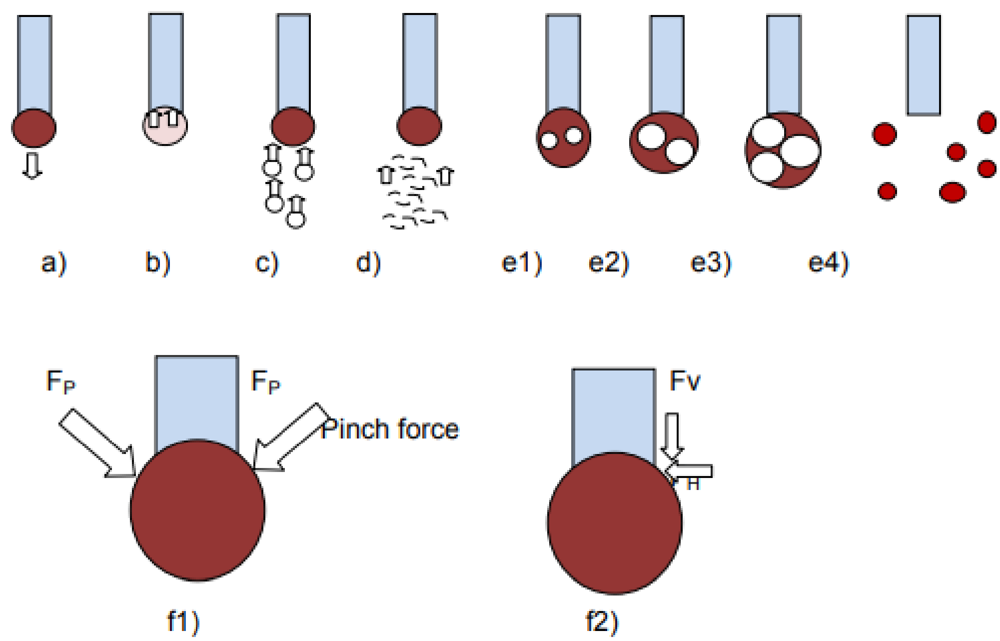


Fig.4.5 Schematic diagram showing different arc forces a) gravitational force, b) surface tension force, c) force due to impact of charge particles, d) force due to metal vapours, e1 to e5) stages in force generation due to gas eruption and f1&f2) electromagnetic pinch force

4.3 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 :

a. distribution of heat generated by welding arc at anode and cathode,
b. stability of the arc and
c. cleanliness of weld

a. 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.

b. 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.

c. 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.4.1 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

4.4 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.

a. Thickness of plate/sheet to be welded: DC for thin sheet to exploit better control over heat
b. 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
c. Ease of arc initiation and maintenance needed even with low current: DC preferred over AC
d. Arc blow: AC helps to overcome the arc blow as it is primarily observed with DC only.
e. Odd position welding: DC is preferred over AC for odd position welding (vertical and overhead) due to better control over heat input.
f. Polarity selection for controlling the melting rate, penetration and welding deposition rate: DC preferred over AC
g. AC gives the penetration and electrode melting rate somewhat in between that is offered by DCEN&DCEP. In DCEN maximum heat is generated at workpiece so the penetration is more but in DCEP maximum heat is generated near electrode.

DC offers the advantage of polarity selection (DCEN&DCEP) which helps in controlling the melting rate, penetration and required welding deposition rate. 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.

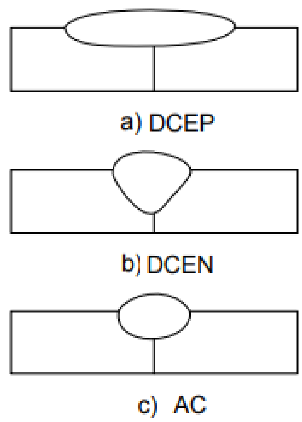


Fig. Schematic diagram showing effect of welding current and polarity

❖ 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. 4.6 a-b-c).

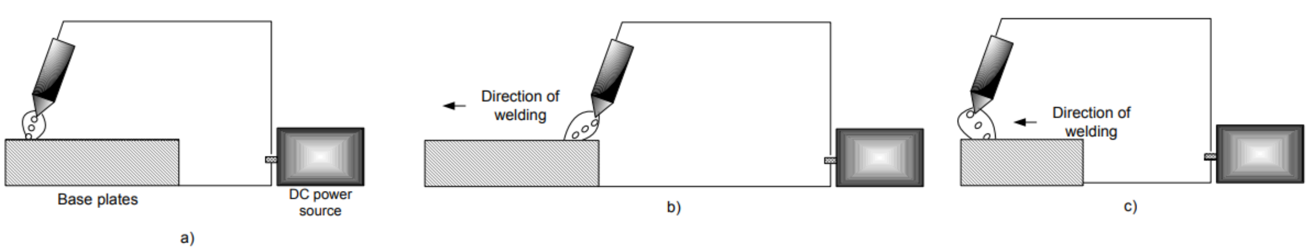


Fig. 4.6 Schematic diagram showing welding a) without arc blow, b) with forward arc blow and c) with backward arc blow

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:

i. 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 .

ii. 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 edge of the plate.

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 centre of wire (r) and magnitude of current (i). In general , the increase in current and decrease the distance from the wire, increase the intensity of electromagnetic field.

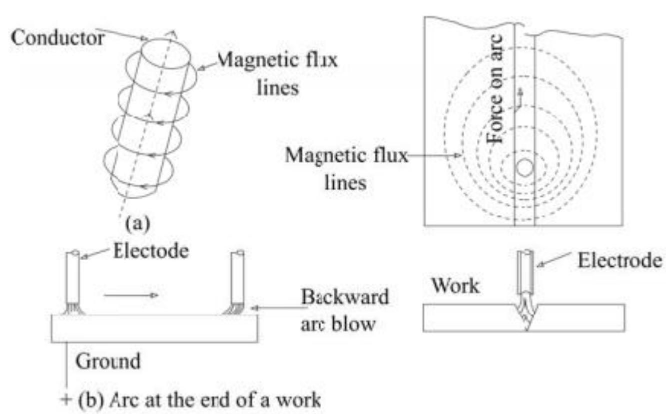


Fig. Schematic diagrams showing generation of electromagnetic force around the welding arc & electrode causing arc blow

The welding arc tends to deflect away from area where electromagnetic flux concentration more. 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 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. 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
- Shifting from D.C. 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.

4.5 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. 4.7). 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 (VC), plasma (Vp) and anode drop regions (Vp) 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.

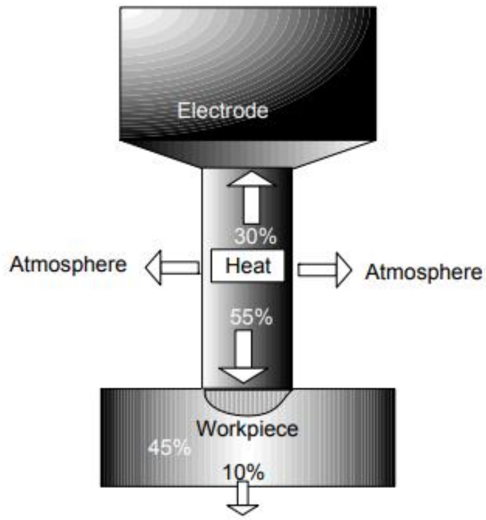


Fig. 4.7 Distribution of heat from the welding arc in DCEN polarity

❖ 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. 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%).

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.

$q_a = [\phi + V_a]\ I$

where q_a= is the heat at anode

ϕ is work function of base metal at temperature T = [(ϕ_0 +1.5 kT)

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 $q_p = V_p\ I$

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

So arc efficiency = total heat used / total heat generated in arc

$$= [q_a + m\ (V_p\ I)]/VI$$

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_pI)}/VI}]

Where q_c is the heat generated in cathode drop zone.

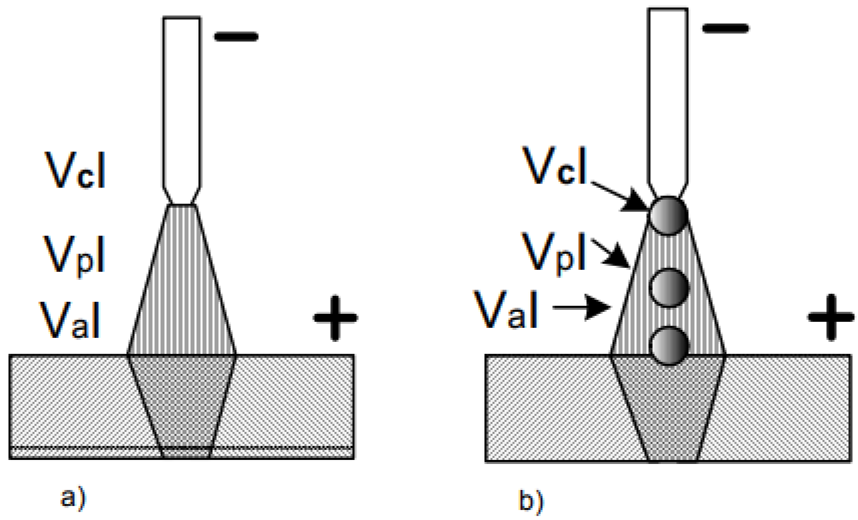


Fig.4.8 Schematic of heat generation in different zones of the arc of a) nonconsumable arc and b) consumable arc welding processes.

❖ Arc welding processes (SMAW)

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. 4.9). 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) welding etc.

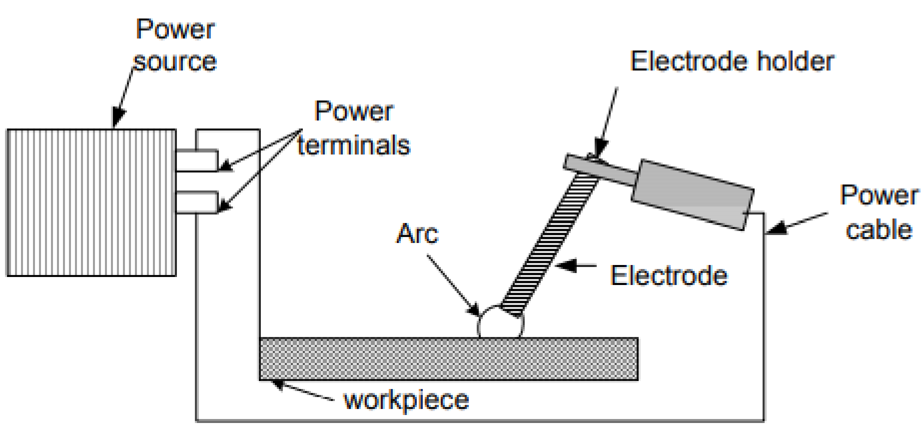


Fig. 4.9 Schematic diagram showing various elements of SMA welding system

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)

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

❖ 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. 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. 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.

❖ 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.

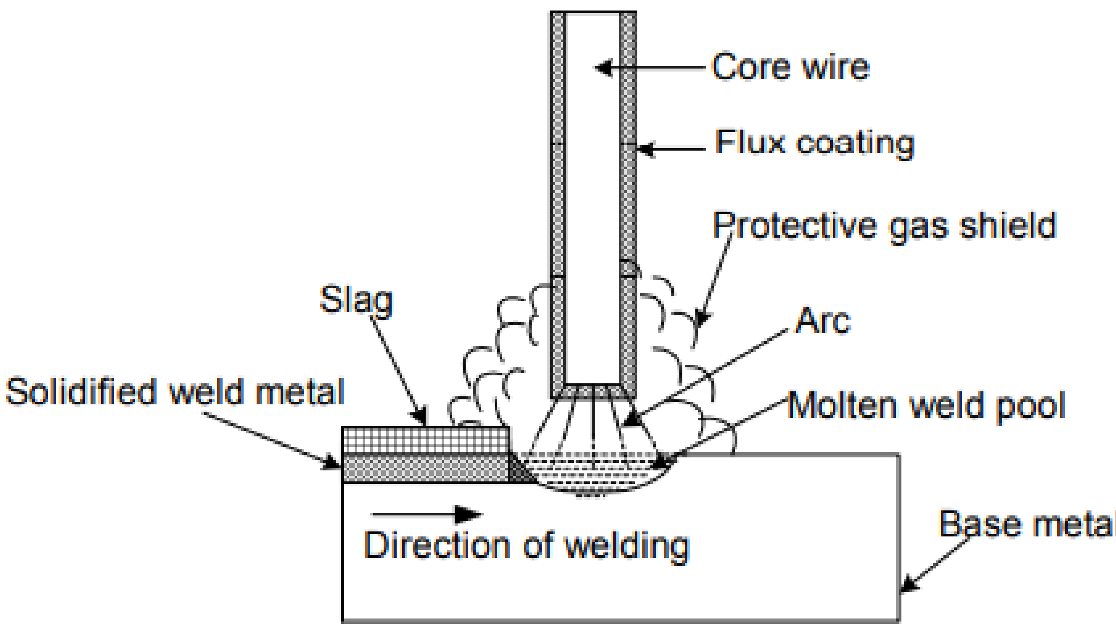


Fig. 4.10 Schematic diagram showing constituents of SMAW

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