Fundamental approach of obtaining the arc efficiency

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.

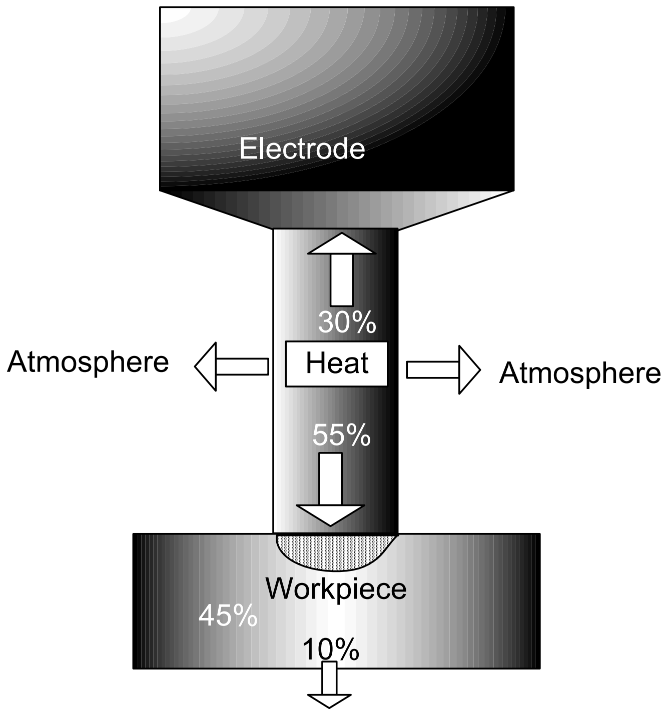


Fig. 8.1 Distribution of heat from the welding arc in DCEN polarity

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.

$q_a = [\phi + V_a]\, I$……………………………………………………………(equation 8.1)

where q_a = is the heat at anode

ϕ 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)

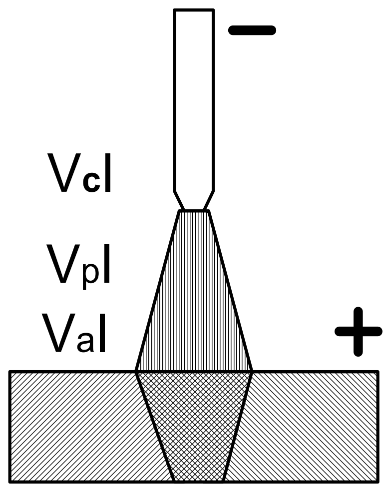
So arc efficiency = total heat used / total heat generated in arc= [q_a + m (V_p I)]/VI……………………………(equation 8.5)

Where V is arc voltage = $V_a + V_p + V_c$

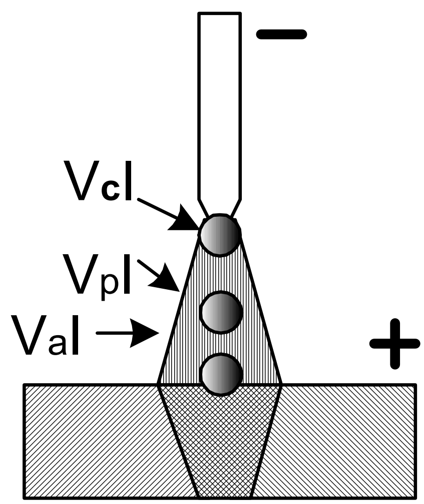
Another way is that [{total heat generated in arc- (heat with plasma region + heat of cathode drop zone)}/total heat generated in arc}]

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.



a)



b)

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).

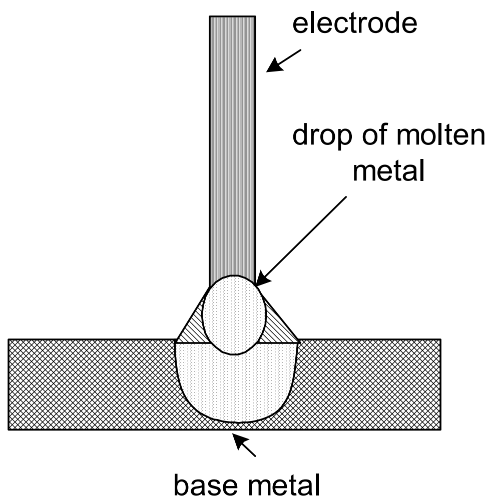


Fig. 8.3 (a) Schematic of short circuiting metal transfer

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.

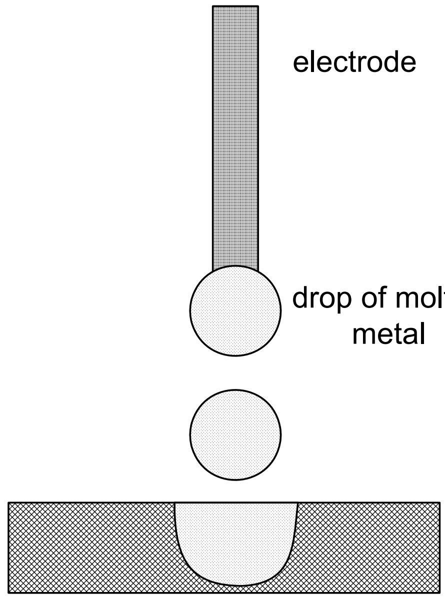


Fig. 8.3 (b) Schematic of globular metal transfer

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.

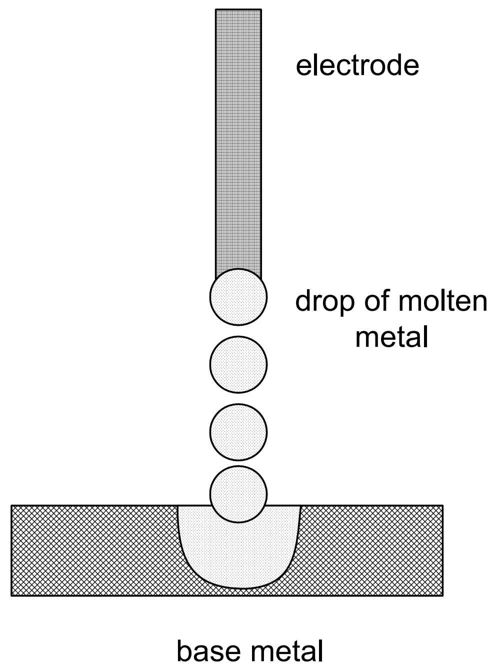


Fig. 8.3 (c) Schematic of spay metal transfer

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.

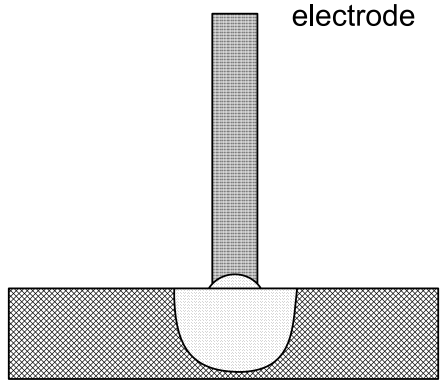


Fig. 8.3 (d) Schematic of dip transfer

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 = $a \times I + b \times L \times I^2$……………………………(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 ($a \times I$) accounts for electrode melting due to heat generated by anode/cathode reaction and second factor ($b \times L \times I^2$)

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%

References and books for further reading

- Richard Little, Welding and Welding Technology, McGraw Hill, 2001, 1st edition.
- H Cary, Welding Technology, Prentice Hall, 1988, 2nd edition.
- S V Nadkarni, Modern Arc Welding Technology, Ador Welding Limited, 2010, New Delhi.
- Welding handbook, American Welding Society, 1987, 8th edition, volume 1 & 2, USA.