Metal Transfer in Metal Arc Welding

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1. Introduction

The theory of metal transfer in arc-welding has long attracted the attention of investigators since the beginning of this century. The mode of metal transfer determines, to a large extent, the techno-economical characteristics of the welding process. The metallurgical changes in the weld metal, the formation of the weld bead, the spatter losses and the positional weldability are all governed by the mode of metal transfer.

Metal arc welding can be described as a flow system in which the heat flow is developed for melting of the work piece and the electrode and in which mass flow governs the transport of metal and slag from the electrode to work, and the transport of gases from the coating or gas-shield. This mass flow is promoted by a momentum flow, resulting from a non-equilibrium of forces which govern metal transfer and control of the weld pool. Both mass and momentum flow contribute to and in turn are influenced by the heat flow. Transfer of energy from the power source to the arc system and conversion of electrical energy are related to charge flow and coupling the power source and the arc system to each other. These flow phenomena are thus inter-related and influence to a certain extent the metal transfer mechanism.

In metal arc welding, material is transferred from the welding electrode to the work in the form of molten globules or droplets. To a certain extent, the size of these droplets determines the welding characteristics of the electrode. It is known that small droplets result in a smooth bead, and that the smaller the droplet, the more stable the arc. This stability relationship is especially noticeable in arc welding. Electrodes producing small droplets, moreover, melt more quickly than those which give the larger drops, because a large drop usually clings to the electrode for a relatively longer time, thus impeding the melting of fresh weld metal. On the other hand, the welder will generally prefer to employ an electrode giving a larger drop when it is required to span the gap between two plates.

Till 1950, most of the work reported on metal transfer refer to coated electrodes while the research with inert atmospheres was probably started in 1951. With the introduction of CO_2 gas as a cheap substitute for argon and helium in the mid fifties of this century, many investigations have been reported on this aspect. Research with mixtures of any two or more of the various gases like argon, oxygen, nitrogen, CO_2 etc., has also been reported. In the present paper, these above mentioned aspects have been dealt with.

In their quest for exploring the unknown, researchers have been studying the mechanism of metal transfer both experimentally and theoretically. A historical review shows that there has been a general

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agreement in the conclusions drawn by them on various aspects of metal transfer, yet many more remain obscure.

2. Historical Review

Hudson[29] (1919) seems to have initiated the studies on metal transfer in arc welding. He took cine pictures (32 exposures per second) and observed that the metal drops usually contained cavities—the drops seemed to expand and small particles were thrown out at high velocity. These particles formed 'metal spray'. Hudson concluded that 'the metal deposited during arc welding was transmitted, in part at least, in the form of minute particles which were projected from the globule by the internal expansion of some vapor, possibly carbon monoxide—the expelled particles passed through the arc too rapidly to become vaporised and reached the plate in a fluid state.'

Eschlolz[18] (1920) concluded from energy considerations of the welding arc that at least 85% of the deposited metal was transmitted in the liquid form.

The photographing of the metal transfer has been difficult because of the intense heat of the arc. In order to avoid the effect of the arc glare, Green[23] (1927) and Bung[7] (1928) used ultra-red rays emanating from the molten metal and took 60 exposures/second to study the influence of the composition of electrode on the flow of metal. Details of the results, however, were not published.

Hilpert[27, 28] (1929, 1933) took moving pictures of the arc by means of the 'outshining' method. A powerful carbon arc was placed behind the welding arc. Electrode and molten drop appeared as silhouettes with the arc as a bright spot on a bright background. The moving pictures (2400 exposures/second) showed that the molten drop frequently short circuited the arc. An oscillograph was synchronized with the moving pictures to record the short circuits. The moving pictures as well as the oscillograms showed a marked difference between the transfer of material from bare and coated electrodes. The number of short circuits with coated electrodes was found to be much less than with bare electrodes. He observed that in overhead welding, the time of short circuits with bare electrodes was 25.77% of the total arcing time and with coated electrodes it was only 2.96%. Hilpert assumed that all of the metal was transferred during short-circuit period and concluded that the molten drops were larger for coated electrodes than for bare wires. Hilpert[28] also observed that when welding with covered electrode every drop was coated with a thin layer of slag.

Alexander[3] (1930) and Doan[13] (1930) stated that the metal transfer occurred in the form of molten globules with occasional short circuits.

Lincoln[36] (1930) on the other hand, observed that heavily coated electrodes produced no short circuits and the metal transferred in the form of small particles.

A method for the determination of the size and duration of the drops was developed by Flamm[20] (1930) based on the assumption that all transfer took place during the short-circuit period. The total welding time T, was divided into two periods : the arc period B, during which the arc burns, and the short-circuit period K. Thus $T=B+K$. From the oscillograms, B and K were measured and the ratio B/T giving the duration of drop was computed.

Strelow[55] (1932) investigated the dependence of the frequency of drops on the coating of the electrode. The frequency of short circuits was observed by means of an oscillogram. The number of transfers per second was 26 for bare, and 6 for covered electrodes, the ratio B/T was 0.70 and 0.92 respectively.

Doan and Weed[16] (1932) constructed a device for recording individual deposits. A polished strip of mild steel was set in a welding machine and was advanced at the rate of 4 cm/sec. The deposits from the electrode appeared separated. Oscillographic records of current and voltage of the arc were also taken. It was stated that the deposits were accompanied by current peaks and the size of the current disturbance corresponded quite well with the size of the globule. They also concluded that at least 90% of the metal was transferred in the liquid form.

It was long felt that metal transfer was caused by the presence of force or forces in the arc. Creedy et al.[10] (1932), for the first time, measured the forces acting on the iron electrode of a welding arc. They used an apparatus based on the principle of Ballistic Galvanometer and observed that the force increased rapidly with decreasing arc length and attributed this to the recoil force of particles projected from the electrodes, particularly the cathode. For a fixed arc length the force was found to be proportional to the square of the current. This was referred to as 'pinch effect'. The force measured ranged from 50 to 1000 dynes. Creedy et al. also noticed that molten drops were transferred across the arc without any short-circuit taking place (as indicated in the oscillograms).

Ludwig and Silverman[28] (1933) found that 'the bridging of the arc gap by molten metal is a necessary part of the process of welding'. Moreover, in oscillograms of arc voltage, pulsations of high frequency and small magnitude were obtained in welding with iron electrodes but absent with tungsten electrodes. These pulsations were believed to have an 'origin at the Cathode', caused by losses from the positive column thereby increasing its potential drop or an increased cathode fall of potential.

Ronay[48] (1934) constructed a practical instrument (arcronograph) for the measurement of B/T (i.e. ratio of the arcing period to the total duration of the globule) and applied it to investigate the flow of metal from bare and covered electrodes. The records of the arcronograph, it was claimed, also supplied information as to the quality of the weld deposits.

Larson[34] (1936) caught the particles travelling through the welding arc by passing a specially prepared thin strip of metal through the arc. The particles were classified as to size to the nearest 0.0254 mm diameter and counted. It was observed that for one particle with 0.254 mm diameter, there were six particles with 0.102 mm and one hundred twenty particles with 0.025 mm. The velocity distribution of particles was determined for overhead welding over a slot. The trajectories of the particles coming up through the slot were measured and their initial velocities computed. The velocities ranged from 60 to 975 cm/sec, but there was no apparent relation between the size of particles and their initial velocities. The drops from a steel electrode with heavy cellulose covering were found to be 'bright spheres with no coating of slag'. This seems to disprove Hilpert's[28] (1933) hypothesis that when welding with covered electrodes every drop was coated with a thin layer of slag. Larson also obtained evidence against Hilpert's assumption that all metal was transferred during the short-circuit periods. According to Larson, '...... with an arc only slightly larger than the normal it is possible to eliminate short-circuits without appreciably reducing the rate of melting of the electrode.' Later, Larson[35] (1942) improved the method of determining size and velocity of a particle. This method was based on the fact that trajectories of small particles projected through the air depended both on initial velocity and the size of the particle. Measurements on the trajectory enabled him to compute both size and initial velocity.

It appears that Larson (1936) appreciated the importance of arc length, for the first time, in the short-circuit formation. Thus, based on Larson's observations it can very well be concluded that the apparent contradictions obtained with the results of the earlier investigators arose on account of the effect of arc-length.

Engel[17] (1937) gave a mathematical analysis of the heat flow in the electrode and thus the melting rate. He assumed that there was no heat loss through the sides and that the end of the electrode remained at a fixed temperature. These assumptions, however, seem to be an over simplification of the system.

Doan[14] (1938) considered theoretically an idealised process of flat-position welding in which drops formed slowly at the tip of the electrode and fell into the work solely under the force of gravity. Such a process was analogous to drop formation at the end of capillary tubes and led to the result that the maximum weight of a drop was proportional to the second or third power of the surface tension. Naturally, in the case of arc welding, the molten globules are detached long before they reach this maximal size. Doan also reported an increase of melting rate of bare wires by 25 to 50% with the addition of 0.1 to 1.0% of antimony.

Nieburg[43] (1938) measured the 'force' acting on welding arcs by suspending a weld rod elastically and measuring deflections by means of a mirror and an oscillograph. Mild steel (bare, dipped, white-asbestos-coated and blue-asbestos coated), copper and aluminium (bare and dipped) electrodes having 4 and 6 mm diameters were used. The results showed that the 'force' increased with the increase in current reaching an optimum value at which there was no further increase in force with further increases of current. This optimum current was dependent on the type of coating as well as the polarity and was believed to be necessary for smooth transfer of metal. Straight polarity gave much higher 'force' than reverse polarity. The 'force' was of the order of 1960 dynes at 200 amperes and reverse polarity with white-asbestos-coated steel electrode (4 mm diameter).

Doan and Lorentz[15] (1941) determined the 'force' acting on electrodes by means of a torsion balance using 3.8 mm electrode at currents ranging from 70 to 220 ampere. The 'force measured in air was in good agreement with Nieburg's results. The 'force' in helium and nitrogen was considerably below than in air at the same currents.

Spraragen and Lengyel[54] (1943) contributed much to the understanding of the mechanism of metal transfer by critically discussing some of the works reported till 1942.

Winsor et al.[59] (1949) discussed instrumentation for the study of metal transfer. They introduced the concept of fast speed electronic counter for counting the short-circuits with metal transfer.

Orton and Needham[44] (1949) analysed the short-circuiting mechanism for dc down hand welding with the help of a cathode ray oscilloscope (time scale resolution 0.1 sec/metre and sensitivity 0.7 mm/volt) using 8 SWG bare or 'sul' coated steel electrode and maintaining 3 mm arc-length. They divided the different short-circuits into four different classes based on their durations : (i) 'major' short-circuit with duration of about 10^{-2} second and level of voltage of the order of 1 volt, (ii) 'minor' short-circuit—about 10^{-3} second and 2-3 volts. (iii) 'short' short-circuit—about 10^{-4} sec and 3-6 volts, and (iv) 'ultra' short-circuit——10^{-5} second and 10 volt. They concluded that 'major' short-circuits were associated with metal transfer whilst the 'minor' and 'short' duration short-circuits sometimes occurred as independent phenomena, frequently one or other of them just preceded and occurred in association with a 'major' type short-circuit. This was believed to occur either due to momentary bridging the gap followed by an explosive rupture of the bridge without metal transfer, or due to a rapid make-break mechanism for a molten metal globule about to be detached from the weld pool, so that the extremely short time intervals of short-circuiting recorded were in effect indicative of major material transfer. They further observed that there was no change in arc voltage level with the growth of the molten globule and thus concluded that the arc was 'rooted not on the base of the molten globule, but at some position further up the electrode rod'.

Begeman et al.[6] (1950) computed the rate of burn-off with coated electrodes as affected by the polarity, the energy input as well as the atmospheric pressure. Straight polarity gave higher burn-off with E 6010, 5/32" diameter electrodes than with reverse polarity. With the increase in pressure upto about 18" Hg absolute, the burn-off rate decreased but beyond 18" Hg. absolute pressure, it remained almost constant. Approximately 85 to 90% of the electrode metal was found to transfer in the liquid form.

Gillette and Breymeir[21] (1951) studied the type of metal transfer under inert atmospheres by using a Fastax camera (14,000 frames/second). The set up was so arranged as to give a sharp image on the moving film. From the films, they calculated the size and velocity of particles transferring across the arc as well as acceleration, kinetic energy and the forces involved, They concluded, '...... whenever metal transfer takes place it is almost completely in the form of discrete particles of diameters approaching that of the consumable electrode. The particles accelerate very rapidly as they are pinched off of the electrode end and then traverse the arc at substantially constant velocity'. Normally there was no indications of shorting and at any one instant there was only one particle across the arc with aluminium but generally two or more with steel. They stated that a 'force' many times greater than gravity but suppressed with straight polarity played the prominent role in metal transfer. About 543 particles (0.035" in diameter) were obtained per second in manual welding with 1/8 in. steel electrodes keeping an arc length of 0.78 in. The melting rate of stainless steel per kilo watt hour was found to be slightly higher with straight polarity.

Muller et al.[41] (1951) investigated with argon shielded aluminium and 2% Mn Steel (reverse polarity) the effect of arc length and the electrode extension on the burn-off rate. The burn-off rate was found to be decreasing with increasing arc-length but was in part determined by the length of wire extension. From the studies of drops with motion pictures, they observed that there existed a 'transition zone' depending on the current and wire feed giving 'relatively long and erratic intervals' between drops at below the transition zone, whereas at beyond this zone, 'short regular intervals' between drops were obtained. The number of peaks obtained from the oscillographs in a given interval of time was used to compute the average droplet size. With the increase in current, the droplet size decreased. They also concluded that at below the 'transition zone' the transfer occurred by gravity while at above this zone, electromagnetic pinching force became prominent.

van der Willigen and Defize[58] (1954) studied the characteristics of metal transfer using various types of electrodes—contact, basic coated and gas shielded—with cine photography (3000 frames per second). An external powerful light source was placed behind the arc and thus the welding arc was made almost invisible against the background. The droplets of molten metal were filmed in silhouette. The desired arc-length was maintained manually. They determined the diameters of droplets from the films and defined a term 'characteristic droplet volume' as an indication of the average volume of the droplets transferred under a particular condition. The 'characteristic droplet volume' (Vc) was expressed as :

$$Vc = \frac{\Sigma\, n_i\, v_i^2}{\Sigma\, n_i\, v_i},$$

where n_i is the number of the droplets with volume v_i. Each droplet was found encased in a protective slag. (e.g., about 38% of the total volume of the droplet of molten material with contact electrode, C 18, contained slag). The results showed that the gas-shielded electrodes (Phillips 48) gave large droplets which were transferred by short-circuiting the gap. Contact electrode (C 18) gave small and free droplets. In addition to black and white silhouette films, color photographs were also taken.

Ozawa and Morita[45] (1954) studied 'the ripples' obtained in oscillograms of arc voltage in metal arc welding. They said that the 'ripples of small magnitude were due to 'self regulation characteristics of the arc'. Assuming a constant electrode feed rate and a variable melting rate, they deduced mathematically the frequency and amplitude of the 'ripples'. The frequency was found to be directly proportional to the current and dependent on the electrode material.

Maecker[39] (1955) made a very important contribution to the understanding of transfer phenomena. He discussed the role of plasma jet and thus introduced magneto hydrodynamics into the transfer physics. Plasma jet was described as a flow of arc plasma due to longitudinal component of self-induced electromagnetic force. Whenever there is a constriction in the arc, either by cathode or anode spot, or by point to place geometry or else, self-induced magnetic force gives rise to a pressure gradient, which in turn is converted into a plasma flow from the region of high current density to those of lower current density, the so-called plasma jet. This plasma jet was believed to aid in metal transfer.

Gordon et al.[22] (1956) estimated the temperature of the arc under various atmospheres by an infrared energy distribution method (spectroscopy) and observed that arc temperature was higher with dissociable gases (CO_2, N_2 and air) than monotomic gases (Argon and Helium).

Hazlett and Gordon[26] (1957) conducted experiments to determine the metal transfer characteristics under various shielding gases (CO_2, He, Argon and 0_2) and different power sources (dc and rectified ac). Movie films (5000 frames/second) were taken when welding steel. They observed that large droplets were attached to the wire and supported by the pressure of the arc column when CO_2 gas was used. When these droplets touched the work, short-circuits were formed causing the droplets to detach almost 'explosively'. With argon plus 5% 0_2 shielding, small discrete droplets were transferred across the arc. Metal transfer in atmospheres of helium and pure argon was described as a mixture of the above two types. With shielding gases other than pure argon, the mechanism of metal transfer was found unaffected by the polarity except that the size of the molten droplets was 'far less for reverse polarity than for straight polarity'. For pure argon, however, they obtained different' arc action' with different power sources. Gillette and Breymeir (1951) also reported a similar phenomenon.

Ludwig[37] (1957) concluded from his studies of drop formation and transfer in argon that the 'pinch effect' was a major factor in metal transfer across the arc.

Studies on droplet transfer under CO_2, CO and argon atmospheres were conducted by Defize and Van der Willigen[12] (1960) using movie film (3000 frames/second). They observed that CO_2 and CO shielding produced coarse droplets under both straight and reverse polarities. They used a current density of upto 10,000 amps/cm^2 (with 1.2 to 2.5 mm diameter steel electrodes) and the droplets remained coarse. With reverse polarity using argon and argon plus 3 to 5% Oxygen atmospheres they got a 'transition current' below which the droplets remained coarse and beyond which fine droplets were produced. The value of the transition current was less with argon than with argon plus 3 to 5% O_2. But with straight polarity, droplets remained coarse with argon shielding. It was also observed that there was heavy contraction of arc plasma with CO_2 shielding. Very small cathode spots were also found in CO_2 and in argon atmospheres when the wire was connected to the negative pole (i.e. straight polarity). It was concluded that the diameter of the cathode spot and the arc plasma were responsible in determining the droplet size.

Shajenko[52] (1960) conducted experiments to find out the effect of magnetic field on metal transfer characteristics using a d-c variable voltage power supply with 1/4" covered ferrite electrodes and 240 amperes. He observed that with the 'deflection of the arc', the spatter increased and welds of poor quality were produced. He concluded that filler metal was transferred across the arc in the form of small particles by explosive forces due to the tremendous release of heat energy on small areas on the tip of the welding rod and by subsurface explosions of minute gas enclosures.

It was postulated by Needham et al.[42] (1960) that high velocity plasma jets in the (argon-gas shielded) arc were responsible for metal transfer in high current density welding arcs. Experimental evidence of this hypothesis had been obtained from a high speed cine-photography examination (9000 frames per second) of aluminium transfer, which showed that there was a force acting on the globule after it had become detached from the electrode and that the vapour emanating from the globule streamed in the direction of travel. According to this hypothesis a gas stream exerts a force on a sphere placed in its path by pressure drag and skin friction. For photographing the transfer phenomenon, the electrode tip, the crater and transferring metal, were silhouetted by a high intensity carbon arc (focussed on to the welding arc from behind). The frequency of droplet transfer, the velocity and acceleration of droplets and the threshold or transition current for various materials have been found out. For various materials (1/16" diameter in argon atmospheres) the transition currents obtained experimentally are shown in Table-1.

TABLE—1

Experimentally determined transition currents for various metals (1/16" diameter) in Argon

Metal	*Transition current*	
	Reverse polarity	*Straight polarity*
Al—5% Si	125	235
Titanium	215	295
Copper	220	275
Mild steel	220	240
Nickel	250	250

Compound transfer (i.e. more than one droplet at the same instant in flight) was also noticed.

Greene[24] (1960) presented a theoretical analysis of metal transfer (Gas-shielded) based on a mathematical model in which gravity, surface tension and self induced magnetic forces were taken into account by the introduction of a dimensionless quantity N_t, called 'transfer number' which governed the size of the drop as a function of the welding current. It was assumed that the current density at the surface of contact between the arc and the drop was homogeneous and remained constant during variations of the current. The 'transfer number' was given by :

$$N_t = \frac{R^3 I^2}{Y A^2}$$

where R = radius of the electrode in cm,
I = current in electromagnetic units,
A = area of the arc on the drop ('active surface') in sq.cm.,
Y = surface tension of the liquid drop in dynes/cm.

The 'transfer number' remained constant during the variations of the current if it was assumed that the surface tension would vary only slightly with fluctuations in the temperature produced by variations in the current strength, and if A increased proportional to I. Greene showed that at a certain value of the current a sudden change in the diameter of the drop occurred; he called this value the 'transition current'. The greater the transfer number, the greater was the transition current.

Sunnen[57] (1962) studied metal transfer with low-hydrogen electrode using ac source and an automatic welder. A photoelectric cell was used to control a desired apparent arc length (which otherwise changed with the heating of the electrode). Results obtained from the high speed camera synchronized with the camera of the oscilloscope showed large difference in transfer between short and long arc welding. With a long arc, metal transfer took place without short-circuit, whereas with a short arc, most of the metal was transferred during short circuit. It was also concluded that a short circuit did not necessarily mean metal transfer. On the otherhand, metal transfer could take place without short circuit—this was true not only for long arc but also for short arc where sometimes liquid slag transfer took place by bridging the arc, but apparently the electrical conductivity of the bridge was not large enough to short circuit the arc. The oscillograms also showed gradual and slight decrease of the mean arc voltage between short circuits (short circuits were 5 to 10 per second). This contradicts Orton and Needham's observation that there was no change in arc voltage with the growth of the droplets. It was observed with alternating current that the droplets moved down at every passage of current through zero and was raised again when it was at the maximum of the sine wave. However, the droplet transfer took place in most of the cases at the maximum of the sine wave where the pinch effect was maximum. With slow transfer, it was noticed that gas formation either by vaporisation or chemical reactions within the droplets, tended to detach it. He had also discussed various measurement techniques for metal transfer : (1) Arc voltage cumulative record, (ii) Voltage envelope curve, (iii) Reignition peaks by electronic counter, and (iv) Phase-shift technique. He also concluded that the study of the electrical parameters by the above mentioned techniques offered promising and powerful investigational methods.

Amson[4] (1962) stated that the ease or difficulty with which a metal behaved in short-circuiting mode of metal transfer could be described by the relative value of a dimensionless number, called "thermal responsivity", A_t and expresses as :

$$A_t = \frac{rpc}{K} = \frac{r}{\alpha},$$

where r = electrical resistivity,
p = mass density,
c = specific heat,
K = thermal conductivity,
$\alpha = \frac{K}{pc}$ = thermal diffusivity

For Al and mild steel the "thermal responsivity" values are 7.2×10^6 and 610.0×10^6 respectively showing that it would be easy to have short-circuiting mode of metal transfer with mild steel than with Al. However, the A_t—value of a metal did not by itself decide completely whether the metal could be used generally in the short-circuiting mode, but it could be used in a way to indicate the behaviour of a wide range of metals in a particular system.

Pintard[47] (1962) conducted experiments on short-circuit transfer phenomenon with steel (0.06 to 0.09 C and 3.11 mm diameter) electrodes in air with direct current (drooping characteristic source) at constant welding speed on an automatic welder maintaining 4 mm nominal arc length. The results obtained from cine photography showed that the emissivity property of the coating and the polarity affected the frequency of short circuits. Bare electrodes or electrodes thinly coated with either silica or titanium dioxide produced higher short circuits with straight polarity whereas electrodes thinly coated with calcium gave lesser frequency of short circuits with straight polarity.

Amson and Salter[5] (1962) presented a mathematical analysis of the inert gas shielded welding arc system. The basic assumption made on current density distribution was that it was uniform, but depended on the current strength. With certain assumptions and approximations deduced from experimental observations, the relative contributions of the various forces acting on the droplet had been distinguished.

(To be continued)