Metal Transfer in Metal-Arc Welding

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(Continued from the previous issue)

Cooksey and Milner[9] (1962) examined the metal transfer characteristics of ten metals, at several currents and with different polarities by high speed photography (using a Fastax WF3 camera and a xenon backing light) and compared their behaviour with the theories of metal transfer. They concluded that types of transfer could be classified, with the probable reasons for their particular characteristics, as :

(i) If the metal has a high vapour pressure the drops are repelled from the plate, regardless of the electrode polarity, because of the back reaction thrust of the issuing vapour stream.

(ii) With low vapour pressure metals in argon, electrode positive, globular transfer gives way to spray transfer with increasing current as a result of the formation of a plasma jet. If the metal has a high termal conductivity, the drop size decreases with current without any change in the geometry of transfer ; if the conductivity is low, the electrode tip becomes tapered and a spray of fine drops is emitted because the Lorentz force causes the liquid to flow down the tapered tip.

(iii) In argon, with electrode negative, the low melting point metals exhibit a repulsion away from the plate primarily because of the mechanism of electron emission. High melting point metals do not show this repulsion because the current is emitted thermionically over a much larger area.

(iv) In dissociable gases, transfer is of the globular type, as the plasma jet necessary for spray transfer is absent. This is because the high rate of energy consumption in the arc column deters the arc from "climbing up" the electrode thus achieving the configuration required for a plasma jet to form.

(v) A coating of potassium and caesium carbonates produces spray transfer with mild steel in CO_2, electrode negative, because it results in thermionic emission and hence plasma jet formation.

King and Howes[32] (1962) attributed the metal transfer (with argon-aluminium welding) to the high velocity gas jets produced in the arc (i.e. magnetic plasma jets).

Smith[59] (1962) examined the characteristics of short circuiting with bare wire in CO_2 shielding by oscillography and Cine photography (4000 frames per second). The frequency of short circuits was obtained as a function of open circuit dc voltage (obtained from a bank of lead-acid cells). The "f-v characteristics" curves had been obtained for different welding parameters. The results showed that there existed an optimum open circuit voltage at which the frequency of short circuits was maximum and this optimum open circuit voltage increased with either higher feed rates or higher electrode diameters.

Stular[56] (1962) observed that the metal transfer with cored electrodes in various shielding atmospheres (using color slow motion film) took place in short circuits the frequency of which was dependent mainly on the arc length, chemical composition of the core and the electrode and the quantity of gases in the electrodes. The carbon content of an electrode primarily affected the arc voltage and subsequently the number of short circuits due to the change of forces affecting the globules during the period of transfer. The weight of metal per ampere per minute was found to be independent of the number of short circuit. Pores and gases appearing in the globules played an important role in the proportion of forces affecting metal transfer while the gravity and the pinch effects played an insignificant role.

Paton and Zaruba[16] (1962) described the mechanism of metal transfer in CO_2 shielding. It was reported that with electrode wires of 1 mm or less diameter, the metal transfer was in short-circuits and with larger wire diameters, there existed a definite range of welding conditions (determined by the arc voltage and the arc current) where the short circuits were obtained. They had analyzed arc voltage and arc current and concluded that the rate of increase of current at short-circuit was an important factor determining the stability of the arc. If the rate of increase of short-circuit current was too high, the resulting pinch effect might prevent the droplets to transfer by breaking the bridge by explosion. Thus there existed an optimum value of the rate of increase of short-circuit current to ensure stability of the process. With the increase of wire diameter, this optimum value decreased.

Defize[11] (1962) obtained the mean drop diameter together with the area of the 'active surface' with cine film studies on metal transfer under various shielding atmospheres :

A, $A+20\%O_2$, $N_2+20\%O_2$, $N_2+20\%H_2$, He, CO_2, and H_2.

He observed that excepting A and $A+20\%$ O_2 shielding gases, generally coarse droplets were obtained with reverse polarity and concluded that high thermal conductivity of the plasma gases (He, H_2, CO_2 and more true with dissociable gases) led to coarse drop transfer at reverse polarity (because of arc contraction). In CO_2 welding, the transition to spray transfer could not be obtained merely by raising the current as predicted by Greene (1960).

Inshizaki et al.[32] (1962) proposed a new method for evaluating the "workability" of electrodes in terms of average globules size. The method consisted of striking an arc between a carbon electrode and a welding electrode and collecting the globules quenched in water. The globules were found to be covered with slag and before they were analysed, they were gently ground in a mortar to remove the slag. For particle size representation, the globules were sieved through standard sieves, the weight in each was averaged, and then the particle diameter for a 50% value of the integrated weight of globules assumed as solid spheres (this assumption was found to be partly true for small particles, and particles larger than 3 mm diameter had an irregular shape) was designated as d-50 and taken as the criterion for evaluation of particle size. The results showed that, the particle size (i.e. d-50 values) decreased with the increase in current and the diameter of the electrode. The particle size and the thickness of the coating material as well as the carbon content of the electrode were found to have an important effect on the particle size. With increasing carbon content the particle size decreased. This was due presumably to the reaction $2C+O_2 \rightarrow 2CO$ in the globule. The method is simple and interesting.

An analysis by Lancaster[33] (1962) of heat flow in the electrode for the inert gas shielded aluminium (reverse polarity) welding arcs led to the conclusion that in the current range where transfer was by gravity (the sub-threashold range) the molten drop at the tip of the electrode had a steady temperature which was below the boiling point, whilst in the range where the transfer was projected (the post-threshold range) the temperature of the drop varied from about the melting point immediately after transfer to boiling point immediately before the next transfer. He suggested that transfer in the post-threshold region was due to a redistribution of magnetic forces caused by ebullition. Boiling resulted in the injection of metal vapour into the arc stream which increased the conductivity of the current-carrying region. This in turn resulted in a concentration of magnetic pressure along the axis of the molten drop, which caused it to elongate and thereby acquire sufficient forward momentum to overcome the restraining action of surface tension and be projected in a forward direction. Below the threshold, transfer was by gravity assisted by static magnetic forces. He also obtained the frequency of drop transfer in the post threshold range as :

$$N = \frac{4\alpha\, E_A^2\, I^2}{\pi^3\, r^4\, K^2\, (T_B^2 - T_F^2)},$$

where N = frequency of droplet transfer, sec^{-1},

E_A = anode heat of the arc, cal/sec/amp,

I = current, amp,

α = thermal diffusivity,

r_e = electrode radius, cm,

K = thermal conductivity, cal/cm²/cm/sec,

T_B = boiling temperature of Aluminium, °C,

T_P = melting point of aluminium, °C

Using, $\alpha = 0.33$, E_A=5.5 A/A, K=0.7 Cal/cm²/cm/sec,

T_B=2500 °C, and T_F=660 °C, he obtained the theoretical frequency and found it to be very nearly equal to the experimental values.

Conn[8] (1962) conducted cine film (exposure time 10^{-6} second) studies with glass or plastic slides placed close to the electrode to collect the deposits of broken-up metal using upto 2.5 mm diameter electrodes. He proposed a new mechanism of metal transfer based on his observations. He found that the molten cylinder developed at the end of the electrode became unstable if the ratio of length of the cylinder over its diameter reached certain values depending on the material of the electrode, its diameter and gas pressure under which welding proceeded. Alternate increases and decreases of diameter appeared in the liquid cylinder due to surface and capillary forces. As a result, the cylinder took on a shape similar to a chain of beads or pearls. The beads were of greater diameter than the electrode cylinder. They were connected by constrictions smaller in diameter than the electrode. The length of chain between the centers of two beads was designated as an 'unduloid'. The beads then quickly increased in diameter and the constriction decreased. Finally spheres were formed under the influence of surface tension. The spheres were stable and larger in diameter than the original electrode. They were now ready to be transferred from the electrode to the work. Sometimes in addition to the primary unduloids, second— (or third-) order unduloids formed from the constrictions between two adjacent primary (or secondary) beads. He also maintained that till the molten liquid remained in the cylindrical shape, 'pinch effect' could not become effective but once the unduloids were formed the magneto hydrodynamic forces played important roles in detaching the drops.

Inshchenko and Dyurgenov[30] (1963) made a mathematical study of the mechnism of periodic short-circuiting and the characteristics of the self adjustment and stability of welding with a short arc. They derived the following equations for changes of an arc length taking into account the growth of the drop and for frequency of short-circuit :

$$\frac{dLa}{dt} = K_f F_v^1 - F_v,$$

$$t_c = t_a + t_{sc}, \text{ and}$$

$$t_a = \frac{L_i}{(1-K_f) F_v} + \frac{K_f t_{sc}}{1-K_f},$$

where L_a = arc length,

K_f = form factor of the drop, dependent on the electrode fusion rate (F_v^1) which had been assumed to vary exponentially with time (t),

F_v = electrode feed rate,

t_c = total cycle time,

t_a = arcing time,

t_{sc} =short circuit time

L_i = length of arc immediately after the drop transfer.

The studies, however, are limited to a short arc. and small diameter wires used in gas-shielded welding

Abella and Sullivan[1] (1964) discussed a successful method of welding stainless steel with short-circuit arc shielded with 90%He—7.5% argon—2.5% CO_2.

High speed motion picture observations of the CO_2 shielded arc with uncoated steel were made by Salter[51] (1964). These showed that, for welding currents below 400 amperes, the metal droplets formed on the end of the melting electrode was not transferred smoothly across the arc but appeared to be repelled by a force within the arc. It was also shown that in the case of 77.8% CO_2—20% argon—2% O_2—0.2% N_2 shielding gas on uncoated steel, this force of repulsion was absent.

Gregory and Herrschaft[52] (1969) showed from high speed motion picture studies of CO_2 shielded short-circuiting arcs that there existed a repulsive force much greater in magnitude when welding galvanized steel than when welding uncoated steel. They attributed the spatter formation in CO_2 short-circuiting arc welding of galvanized steel to both the short-circuiting and an upward repulsive force acting on the molten tip of the filler electrode.

Ruchl and Collins[49] (1970) described a modified power supply source to get controlled droplet transfer in inert gas-shielded metal-arc welding. This method used a rectified current wave form with a series of surges. They showed that a uniform, round droplet began to form on the end of the electrode as the peak current value was reached. This drop got detached from the electrode at a point about 120° after the start of current surge and began to move under influence of the arc force toward the workpiece. The current value then dropped to an instantaneous nominal value. The peak current was higher than the transition current.

Van Adrichem[19] (1970) discussed the various types of metal transfer in a paper presented at the colloquium on Physics of the Welding Arc.

Essers et al. (1971) studied the mechanism of metal transfer from coated (basic, rutile and double coated basic type) electrodes, straight polarity, using an automatic mechine and keeping a fixed arc voltage. The 'weldability' of the electrodes was estimated by melting rates and 'recovery of welding electrode' (defined as a ratio of the weight of the bead to the weight of consumed core wire including the weight of the iron powder in the consumed coating). By cleaning the droplets collected on a fast moving copper strip, the size distribution was also determined. They concluded, 'The nature of drop detachment from coated electrodes appears to be associated with the shape of the coating at the end of the electrode during welding. A deep cup favours the detachment of small droplets and increases the melting rate. The occurrence of a cup depends on on the composition of the coating. Normal basic electrodes tend to have none or only a shallow cup of irregular form. This is due to the presence of $Ca\ F_2$. If $Ca\ F_2$ is present only in the outer layer of the coating, its effect is cut off and a deep cup is formed, which eads to good welding properties.'

Recently Salter and Dye[51] (1971) has discussed the selection of gas mixtures for MIG welding for ferrous and non ferrous metals based on the transfer characteristics of different shielding gases.

3. Conclusions :

Since more than half a century, research in the field of metal transfer in arc welding has been in progress. Because of the peculiar nature of the problem, the results obtained by many of the early investigators cannot be gainfully compared. In this historical review of the literature, the aspects covered are : coated electrodes, MIG, and CO_2 processes. The following conclusions where a general agreement have been found can be deduced :

(1) In any metal-arc welding with consumable electrodes almost 90% of the metal is transferred in liquid form.

(2) There is a marked difference between the transfer of metal from bare and coated electrodes. The frequency of molten droplets is far more for bare wires than for coated electrodes.

(3) There is a gradual fall of the arc voltage indicating the growth of the droplets. If the droplet is transferred by short-circuit, the arc voltage usually falls sharply to almost zero. The droplets are also found to oscillate to some extent.

(4) In the case of metal transfer with coated electrodes :

   (i) The molten globules are covered with slag.

   (ii) They usually contain gas or metal vapor which expands causing explosion to occur resulting in metal spatter. This is more true for vaporisable metals and steels having high carbon contents.

   (iii) The frequency of droplet transfer is mainly dependent on the arc-length, and the nature and thickness of the coating. A higher arc-length produces lesser frequency of droplet transfer.

   (iv) The metal transfer can take place either by bridging the arc gap or by free flight depending on the arc length. Free flight transfer occurs with a long arc. When an arc is bridged by molten globule, usually a short-circuit is formed which is indicated by a sudden fall of arc voltage to almost zero. Sometimes the arc may be bridged by molten slag followed by metal transfer, but the conductivity of the 'bridge' may not be large enough to cause a short-circuit. Again, there could be an instantaneous short-circuit but without any metal transfer. This is possibly due to breaking off the 'bridge' formed by bad contact between the molten droplet and the molten pool in the work.

(v) The dominant forces causing metal transfer are : Surface tension, plasma jet, vapor jet and gaseous eruptions. The other forces like gravity, electromagnetic (i.e. pinch force) and entrainment drag are mostly absent.

(vi) The nature of the coating affects the mode of metal transfer. The general modes of metal transfer being short-circuiting, repelled and non-axial types. The sizes of the droplets with acid, rutile and basic coatings are small, medium and large respectively.

(vii) Polarity does not seem to affect the mode of metal transfer.

(viii) Depending on their durations, the short-circuits can be classified as 'major' and 'short', the durations being of the order of 10^{-2} second and 10^{-3} second or less respectively.

(5) The geometrical shape of the globules is a function of its size and the mode of transfer. Small globules are approximately spherical but large globules are elongated. The globule size is determined by electrode diameter, current density and arc-length.

(6) In the case of metal transfer with MIG, the major factors affecting mode of transfer are : type of shielding gas, polarity, current density, arc-length and electrode material.

(i) If the area of 'active surface' is comparatively large, the electomagnetic pinch force aids in metal transfer.

(ii) High thermal conductivity helium gas produces coarse droplet transfer without transition to projected transfer as compared to low thermal conductivity argon gas. N_2, H_2 and CO_2 also have high thermal conductivity.

(iii) Addition of some percent of oxygen to pure argon significantly improves transfer for steel wires, probably due to lowering of the liquid metal surface tension.

(iv) If the metal has a high vapour pressure the droplets are repelled from the plate, regardless of the electrode polarity, because of the back reaction thrust of the issuing vapour stream.

(v) With low vapour pressure metals in argon, electrode positive, globular transfer gives way to spray transfer with increasing current as a result of the formation of a plasma jet. If the metal has a high thermal conductivity, the droplet size decreases with current ; if the conductivity is low the electrode tip becomes tapered and a spray of fine droplets is emitted because of the electromagnetic force causing the liquid of flow down the tapered lip.

(vi) In argon, with electrode negative, the low melting point metals exhibit a repulsion away from the plate primarily because of the mechanism of electron emission. High melting point metals do not show this repulsion because the current is emitted thermionically over a much larger area. In these cases, the area of the cathode spot being very small, coarse droplets are transferred.

(vii) In dissociable gases the transfer is usually of the coarse globular type, so the plasma jet necessary for projected transfer is absent.

(viii) The burn-off of the wire is a function of polarity, current density, nature of shielding gas, arc-length, wire extension etc.

(ix) The emissivity of the coating of thinly coated electrodes produces a large difference in metal transfer under different polarities and CO_2 shielding. A coating of potassium and caesium carbonates produces spray transfer with mild steel in CO_2, straight polarity, because it results in thermionic emission and hence plasma jet formation.

(7) Because of the peculiar mechanism of metal transfer, any theoretical investigation is limited by its applicability.

References

1. Abella, F.J., and Sullivan, R.P., 'Gas Metal-Arc Welding of Stainless Steel Using Short-Circuiting Transfer', Welding J., 43(10) p.839-842, 1964.
2. van Adrichem, Th. J., 'Physics of the Welding Arc', paper presented at the Annual Assembly of the International Institute of Welding (DOC. 212-171-69) p.1-29, 1970.
3. Alexander, P.P., 'The Calorimetric Study of the Arc', Trans. A.I.E.E., 49, p. 519-523, 1930.
4. Amson, J.C., 'Discussion on Characteristics of the Short-Circuiting CO_2-shielded Arc by A.A. Smith', Proc. of symposium on Physics of the Welding Arc., The Institute of Welding, London, p. 109, Oct. 29 Nov. 2, 1962.
5. Amson, J.C., and Salter, G.R., 'An Analysis of the Gas-Shielded Consumable-Metal Arc Welding System', Ibid., p. 133-147.
6. Begeman, M.L. ; Amstead, B.H., and Mashruwala, U.I., 'Effects of Reduced Atmospheric Pressure on Arc-Welding Characteristics', Welding J., 29(10), Res. Suppl., P. 433-s to 440-s, 1950.
7. Bung, K., 'Werkstoffubergang im elektrischen Schweisslichtbogen,' Z. VDI, 72, p. 750. 1928.
8. Conn, M.W., 'An Instability of the Molten Electrode in Arc Welding', Welding J., 41(4), Res. Suppl., p. 171-s to 174-s, 1962.
9. Cooksey, C.J., and Milner, D.R., 'Metal Transfer in Gas-Shielded Arc Welding', Proc. of a Symposium on Physics of Welding Arc, The Institute of Welding London, p. 123-132, Oct. 29-Nov. 2, 1962.
10. Credy, F. ; Lerch, R.O. ; Seal, P.W., and Sordon, E.P., 'Forces of Electric Origin in the Iron Arc', Trans. A.I.E.E., 51, p. 556-563, 1952.
11. Defize, L.F., 'Metal Transfer in Gas-Shielded Welding Arc, Proc. of a symposium on Physics of the Welding Arc, The Institute of Welding, London, p. 112-122, Oct. 29-Nov. 2, 1962.
12. Defize, L.F., and van der Willigen, P.C., 'Droplet Transfer During Arc Welding in Various Shielding Gases, 'Brit. Weld. J., 7, p. 297-305, 1960.
13. Doan, G.E., 'Cathode Energy of the Iron Arc', Trans. A.I.E.E., 49, p. 723-731, 1930.
14. Doan, G.E., 'Metal Deposition in Arc Welding', Welding J., 17(1), Res. Suppl., p. 15s to 19-s, 1938.
15. Doan, G.E., and Lorentz, R.E., 'Crater Formation and the Force, of the Electric Welding Arc in Various Atmospheres', ibid., 20(2), Res. Suppl., p. 103-s to 108-s, 1141.
16. Dean, G.E., and Weed, J.M., 'Metal Deposition in Electric Arc Welding', ibid., II(9), p. 31-33, 1932.
17. Engel, A. von, 'Natur der Werkstoffanderung in elektrischen Schweissbogen, 'Wiss. Veroff. Siemens 16(3), p. 70-88, 1937.
17. Eschholz, O.H., 'Metal Deposition in Arc Welding', Electrical Welding, 75, p. 1473—1475, 1920.
19. Essers, W.G. ; Jelmorini, G., and Thichelaar, G.W., 'Metal Transfer from coated Electrodes', Metal Construction and Brit, Weld. J., 3(4), p. 151-154, 1971.
20. Flamm, P., 'Graphische Zerlegung der Metalltransportvorgange in elektrischen Lichtbogen', Elektroschwg., 1, p. 27-30, 1930.
21. Gillette, R.H., and Breymeier, R.T., 'Some Research Techniques for Studying Arcs in Inert Gases', Welding J., 30(3), Res. Suppl., p. 146-s to 152-s, 1951.
22. Gordon, G.M. ; Cotter, O.A., and Parker, E.R., 'Effect of Current and Atomospheres on Arc Temperatures', ibid., 35(2), p. 109-s to 112-s, 1956.
23. Green, J.B., 'The Flow of Welding Metal,' Welding Engineer, 12, p. 25-29, 1927.
24. Greene, W.J., 'An Analysis of Transfer in Gas-Shielded Welding Arcs,' Trans. A.I.E.E. (Applications and Industry), 47, p. 114-202, 1960.
25. Gregory, E.N., and Herrschaft, D.C., 'CO_2 shielded Short-Circuiting Arc Welding of Galvanized Steel, 'Welding J., 48(6), p. 463-470, 1969.
26. Hazlett, T.B., and Gordon, G.M., 'Studies of Welding Arcs using Various Atmospheres and Power Supplies,' ibid., 36(8), Res. Suppl., p. 382-s to 386-s, 1957.
27. Hilpert, A., 'Material Transference in the Welding Arcs,' ibid., 8(12), p. 21-23, 1929.
28. Hilpert, A., 'Investigations on Phenomena of Arc Welding and Gas Cutting by Slow Motion Pictures', ibid., 12(7), p. 4-10, 1933.
29. Hudson, R.G., 'A Theory of Metallic Arc Welding', Ibid., 1(10), p. 6-10, 1919.
30. Ishchenko, Yu.L., and Dyurgerov, N.G., 'The Mechanism of Periodical Short-Circuits of the Arc Gap and the Stability of Welding with a Short Arc', Svar. Proiz., N9, p. 10-13, 1963.
31. Ishizaki, K., Oishi, A., and Kumagai, R., 'A Method of Evaluating Metal Transfer Characteristics of Welding Electrodes', Proc. of a

Symposium on Physics of the Welding Arc, The Institute of Welding, London, p. 148-155, Oct. 29-Nov. 2, 1962.

32. King, L.A., and Howes, J.A., 'Material Transfer in the Welding Arc', ibid., p. 180-186.

33. Lancaster, J.F., 'Influence of Heat Flow on Metal Transfer in the Metal/Inert Gas Welding of Aluminium', Ibid., p. 170-174.

34. Larson, L.J., 'An Exploration of the Modern Welding Arc', Welding J., 15(10), p. 14-20, 1936.

35. Larson, L.J., 'Metal Transfer in the Metallic Arc', ibid., 21(2), Res. Suppl., p. 107-s, 1942.

36. Lincoln, J.C., 'Discussion on Cathode Energy of the Iron Arc by G.E. Doan', Trans. A.I.E.E., 49, p. 731, 1930.

37. Ludwing, H.C., 'Metal Transfer Characteristics in Gas Shielded Arc Welding', Welding J., 36(1), Res. Suppl., p. 23-s to 25-s, 1957.

38. Ludwig, L.R., and Silverman, D., 'Arc Stability with DC Welding Generators', Trans. A.I.E.E., 52, p. 987-999, 1933.

39. Maecker, H., 'Plasmastromungen in Lichtbogen infolge eigenmagnetischer Kompression', Zeitschrift fur Physik, 141, p. 198-216, 1955.

40. Milner, D.R. ; Salter, G.R. and Wilkinson, J.B., 'Arc Characteristics and their significance in Welding', Brit. Weld. J., 7, p. 73-88, 1960.

41. Muller, A. ; Greene, W.J., and Rothschild, G.R. 'Characteristics of Inert-Gas-Shielded Metal-Arcs', Welding J., 30(8), p. 717-726, 1951.

42. Needham, J.C. ; Cooksey, C.J., and Milner, D.R. 'Metal Transfer in Inert-Gas Shielded-Arc Welding, Brit. Weld. J., 7, p. 101-114, 1960.

43. Nieburg, F., 'Krafte in Schweisslichtbogen', Elektroschwg., 9, p. 101-106 and 127-129, 1938.

44. Orton, L. H., and Needham, J.C., 'Short Time Phenomena in the Iron Welding Arc, Metal Bridging and Short Circuiting of the Arc', Welding Research, 3(1), p. 17r—24r, 1949 Based on E.R.A. report Ref. 7/T73).

45. Ozawa, M., and Morita, T., 'Research of Welding Arc', Welding J., 33(6), Res. Suppl., p. 280-s 284-s to 284-s, 1954.

46. Paton, B.E., and Zaruba, 1.1., Peculiarities of Arc Discharge When Welding with a Short-Circuiting Arc Gap', Proc. of a symposium on Physics of the Welding Arc, The Institute of Welding, London, p. 102-107 Oct. 29-Nov. 2, 1962.

47. Pintard, J., 'Some Experimental Data on Short-Circuit Transfer', ibid., p. 92-97.

48. Ronay, B., 'Evolution of the Areronograph', J. Am. Soc. Nav. Engrs., 46, p. 285-298, 1934.

49. Ruchl, W.F., and Collins, C.L., 'Controlled Droplet Transfer in Gas Metal-Arc Welding', Welding J., 49(2), p. 95-99, 1970.

50. Salter, G.R., 'Argon-CO_2 Mixtures for Welding Mild Steel,' Brit. Weld. J., 11, p. 1964.

51. Salter, G.R., and Dye, S.A. 'Selecting Gas Mixtures for MIG Welding', Metal Construction and Brit. Weld. J., 3(4), p. 151-154, 1971.

52. Shajenko. P., 'Effect of Magnetic Field on Transfer Characteristics of Particles in an Electric Arc'. Welding J., 39(2), Res. Suppl., p. 83-s to 88-s., 1960.

53. Smith, A.A., 'Characteristics of the short-Circulting CO—Shielded Arc', Proc. of a Symposium on Physics of the Welding Arc, The Institute of Welding, London, p. 75-91, Oct. 29-Nov. 2, 1962.

54. Spraragen W., and Lengyel, B.A., 'Physics of the Arc and Transfer of Metal in the Arc Welding', Welding J., 22(1), Res. Suppl., p. 1-s to 41-s, 1943.

55. Strelow, W., 'Die Vorgange in Schweisslichtbogen', Elektroschwg., 3, p. 81-87, 1932.

56. Stular, P., 'Metal Transfer with cored Electrodes in various Shielding Atmospheres', Proc. of a Symposium on Physics of the Welding Arc, The Institute of Welding, London, p. 98-102, Oct. 29-Nov. 2, 1962.

57. Sunnen, J.F., 'Electrical Parameters During Metal Transfer', Ibid., p. 67-74.

58. van der Willigen, C.P., and Defize, L.F., 'High Speed Cinematography Determines Droplet Size in Arc Welding', Canadian Welder (Canadian Machinery and Manufacturing News), p. 187-196 March, 1954.

59. Winsor, L.P. ; Schetky, L.M., and Wyant, R.A., 'Instrumentation for the Evaluation of the Stability of the Welding Arc', Trans. A.I.E.E., 68, p. 525-533, 1949.