Metal Transfer in Gas-Shielded Arc Welding

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The transfer characteristics of ten metals, at several currents and with electrode negative and positive, have been examined by high-speed photography and their behaviour compared with the theories of transfer. It is concluded that types of transfer can be classified, with the probable reasons for their particular characteristics, as follows.

1. 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.

2. 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 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.

3. 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.

4. 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 and thus achieving the configuration required for a plasma jet to form.

5. A coating of potassium and calcium carbonates produces spray transfer with mild steel in CO₂, electrode negative, because it results in thermionic emission and hence plasma jet formation.

INTRODUCTION

The advent of the gas-shielded consumable electrode processes and general availability of high-speed cameras has greatly increased progress in the understanding of metal transfer. Comparatively detailed data are available for the transfer of aluminium in argon with electrode positive, and some observations have been recorded for copper and mild steel. When the electrode is negative metal transfer characteristics are not so suitable for welding and this condition has not been so extensively investigated.

All theories of metal transfer postulate that the Lorentz force plays a predominant role but they differ in their conception of the manner in which its force is effective. The aim of the present work has been to extend the experimental observations of the transfer process to a number of other metal systems and to make a qualitative comparison with the features that are the basis of existing theories.

EXPERIMENTAL MATERIALS AND TECHNIQUES

High-speed photography with a Fastex WF3 camera and a xenon backing light was used to observe metal transfer with ten different metals using 1/16 in. dia. electrodes. In each case transfer was recorded with both polarities and several currents in argon and also for copper in nitrogen and mild steel in CO₂.

The effect of a very thin coating (molecular dimensions) of caesium and potassium carbonates on the transfer characteristics of mild steel was examined, using wire supplied by the Air Reduction Co., who discovered the improvement which such a coating can bring about.

For presentation of the observations the films were projected onto a glass plate and the outline of the drop and luminous region of the arc traced. The time interval between frames selected for illustration is recorded on each figure.

RESULTS

Numerous types of transfer were observed: the major variations were between transfer in argon and dissociable gases, and electrode positive and electrode negative; there was also a group of metals in which electrode vaporization was of paramount importance.

Transfer in Argon with the High Vapour Pressure Metals

Magnesium, zinc and cadmium had transfer characteristics which were related to the over-riding effect
of the vaporization of these metals in the arc. With electrode positive or negative there was intense vaporization of the metal and the molten drop was repelled from the base plate, often forming a long stringer, as shown in Fig. 1. The drops then descended onto the base plate some distance away from the point of arc impingement. Superimposed on this general repulsion was a lesser effect of polarity, since the arc was more erratic and the repulsion more marked with electrode negative.

Fig. 1. The very marked repulsion of the drop with volatile metals resulting in the formation of long "stringers." (Magnesium, 300 A. electrode negative.)

ever, with the tungsten arc process losses were found to be $10^2$ to $10^4$ times less than with the high vapor pressure metals.

Transfer in Argon with Electrode Positive
Aluminium, steel, copper, nickel, titanium, molybdenum, and tungsten all showed smooth transfer characteristics with electrode positive. In all cases there was evidence of a force aiding transfer and the drop diameter diminished with increasing current (Fig. 2). The number of measurements was inadequate to determine drop diameter-current relationships. It appears that the marked transition in drop size associated with aluminium is not a general phenomenon. With four of the metals (aluminium, titanium, molybdenum, and tungsten) transfer followed the pattern shown in Fig. 3, in which the drop decreased

Fig. 2. The variation in drop size with current with electrode positive. * After Needham and Smith.

Fig. 3. Left: Globular transfer. (Aluminium, 100 A. electrode positive.) Right: Spray transfer. (Aluminium, 240 A. electrode positive.)
a size with current with little change in the geometry of detachment. Copper differed slightly in that detachment of the drop was accompanied by a rapid sideways movement of the neck (Fig. 4). Steel and nickel departed from the general pattern at high currents, when the end of the electrode became tapered and the neck extended into a long filament terminating in a spray of fine droplets (Fig. 5). With molybdenum there was a second vapour stream from the plate which interacted with that from the electrode (Fig. 6), but it did not affect drop detachment.

**Fig. 6.** The formation of a second vapour stream from the plate with molybdenum. 175 A. electrode positive.

Transfer in Argon with Electrode Negative

The behaviour of the seven metals considered in this section fall into two groups. Group 1. Steel, aluminium, copper and nickel. Group 2. Titanium, molybdenum and tungsten.

With the Group 1 metals the drop size decreased with current (Fig. 7) but to a lesser extent than with electrode positive (Fig. 2). Superimposed on transfer towards the plate was a force repelling the drop from the plate. This repulsion was associated with the formation of a cathode spot. The effect was least with aluminium with which rapidly moving multiple spots were continuously in evidence, causing puckering of the drop surface but no appreciable change in its overall contour.

With steel at low currents the arc was mostly diffuse and drop formation undisturbed, but sporadically a cathode spot would form, which not only modified the drop surface but also resulted in the

**Fig. 7.** The variation in drop size with current with electrode negative. Two drop sizes at each current are shown for molybdenum and tungsten.
drop being lifted. With increasing current, the transfer tended towards the small drop tapered electrode type (Fig. 8) that had been observed with electrode positive (Fig. 5) but the frequency of spot occurrence also increased, making the transfer rough and uneven. With nickel, and particularly copper, the large drop when it had formed was still evident in the higher current range with titanium and, to a limited extent, with molybdenum but not with tungsten.

![Image](https://example.com/image1)

**Fig. 8.** Rough and uneven spray transfer with mild steel, 315 A, electrode negative.

cathode spot formation took place continuously, resulting effectively in permanent lifting of the drop, and the drop size did not decrease with current as much as it did with aluminum and steel.

The Group 2 metals (tungsten, titanium and molybdenum) were characterized by much more stable cathode spots and mixed small drop/large drop transfer. At low currents large drops formed and became detached, with little evidence of a force aiding transfer; in the case of titanium the cathode spot moved comparatively slowly over the drop surface and the drop was repelled slightly from the seat of the arc. (Fig. 9).

![Image](https://example.com/image2)

**Fig. 9.** Slow movement of the cathode spot resulting in rotation and slight repulsion of the drop. (Titanium, 250 A, electrode negative.)

As the current was increased mixed small drop/large drop transfer occurred. This is best described by starting from a time at which there was very little molten metal on the electrode tip. Then as the electrode melted a continuous spray of small drops was emitted (Fig. 10a). The liquid was not removed as fast as it formed, however, and so a larger drop began to develop and prevented the emission of the small drops, although the drop was elongated and the bottom modified to a tip (Fig. 10b). Eventually the drop built up to a size at which it became detached and the cycle was repeated.

With a further increase in current the initial removal of fine drops from the electrode tip was more intense, so that it took longer for the larger drop to build up and when it had done so small drops were still detached from its base (Fig. 10c). The phenomenon of slow arc movement accompanied by repulsion of

![Image](https://example.com/image3)

**Fig. 10.** (a) Spray transfer before the development of the large drop. (b) Large drop with base modified to a tip. (Molybdenum, 275 A, electrode negative.) (c) Detachment of a small drop from the large drop. (Molybdenum, 350 A, electrode negative.)

Transfer in Dissociable Gases

The transfer of mild steel in CO₂ and of copper in nitrogen was studied at several currents for both polarities. In all cases transfer was characterized by the development and detachment of large drops and drop lifting.

The root of the arc at the electrode was more pronounced and larger than with argon and increased in size with the development of the drop, being approximately equal to its projected area (Fig. 11). Drops were often detached as a result of a sideways movement of drop and arc, which was particularly pronounced with copper transfer in nitrogen, electrode positive (Fig. 12).

![Image](https://example.com/image4)

**Fig. 11.** Transfer in dissociable gases showing the increase in anode spot area with drop growth. (Mild steel in CO₂, 225 A, electrode positive.)

![Image](https://example.com/image5)

**Fig. 12.** Sideways movement of the arc prior to detachment. (Copper in N₂, 235 A, electrode positive.)
Effect of Caesium and Potassium Carbonate Coatings on Transfer Characteristics of Mild Steel

At electrode positive the transfer characteristics are little different from those observed using uncoated wire. However, with electrode negative the coating had a considerable effect. In argon the sporadic spray type transfer from a tapered electrode associated with an unstable arc, observed at high currents with non-coated wire (Fig. 8), was replaced by smooth, very fine droplet transfer from a more sharply tapered electrode, with a stable arc and narrower vapour stream (Fig. 13).

At low currents the coating appeared to burn off prematurely, so that none was available on the drop surface; the arc emanated from the top of the drop and was in continuous movement, presumably seeking a fresh supply of coating; as the arc moved it pushed the drop to one side (Fig. 14).

Transfer in CO₂ at high currents with electrode negative was also of the fine spray type as shown in Fig. 13; the effect of the coating was more marked in this case, since without it large drop transfer occurred (Fig. 12). At low currents transfer was still of the large drop type and at intermediate currents in the region of 120-130 A) mixed transfer of bursts of fine spray interspersed with large drops took place.

**Fig. 14.** The arc emanating from above the drop causing it to be pushed to one side. (Coated mild steel, 150 A, electrode negative.)

**COMPARISON OF EXPERIMENTAL RESULTS WITH THEORIES OF TRANSFER**

All theories postulate that transfer results from the action of the Lorentz force, but differ in their conception of the mode in which the force is effective. Ludwig² proposed that the force aiding transfer arose from a pressure gradient within the drop. Greene⁶ developed this model in detail to account for globular and spray transfer and the transition current along the lines illustrated in Fig. 15. Needham, Cooksey

**Fig. 15.** (a) If the current lines diverge in the drop the Lorentz force which acts at right angles to these current lines has a component aiding drop detachment. (b) If the current lines converge, a component of the Lorentz force opposes detachment.

**Fig. 16.** The high-velocity gas stream flowing past the electrode tip creates a force to detach the drop arising from skin friction on the surface of the drop and the pressure drop across the drop.
and Milner proposed that high velocity plasma jets act on the drop to detach and propel it across the arc (Fig. 16). Wells has pointed out that owing to the pressure in the arc column being converted into kinetic pressure in the gas stream there is a pressure drop across the electrode/plasma interface which aids transfer; this is designated the "magneto-kinetic force."

In a paper in the present series Amson and Salter concluded that the aerodynamic drag contributes about half the force aiding transfer and the magneto-kinetic force and Lorentz force the remainder, the magneto-kinetic force being the larger of the two.

In the present work some examples of transfer show the contribution of the Lorentz force within the drop to be negligible in aiding transfer. Thus with mild steel, electrode positive, in CO₂ (Fig. 11) and with copper in nitrogen a particularly large area of arc emission was observed; nevertheless large drops were transferred. Drop repulsion, however, appears to be associated with the formation of a constricted spot, but despite the obvious lifting of the drops, at no time were drops transferred to a size greater than free fall gravity drops.

The contribution by the plasma jet is difficult to assess because there are no means of determining its velocity and extent in a consumable electrode welding process. However, some information can be gained from the appearance of the arc. The appearance of an arc is determined by the energy balance, which governs the size and shape of the luminous region, and the gas composition, metal vapour in particular having a marked effect.

Schmitz calculated the shape of the luminous region for an arc between two rod electrodes, with heat lost by conduction only, obtaining the result shown in Fig. 17(i). The substitution of a plate electrode for one of the rods would be expected to change the shape to that shown in Fig. 17(ii). A plasma jet will increase the heat loss from the arc and constrict it (Fig. 17(iii)), the degree of constriction being an indication of the velocity of the jet. Vapour emitted from the electrode tip will modify the appearance of the arc and, if it is assumed that the properties of the arc are not appreciably altered, three extreme cases can be distinguished.

(i) When gas flow in the arc region is limited to velocities below about 100 cm/sec. Then the velocity of emission and diffusion of the vapour from the electrode causes it to flow in all directions, comparatively unaffected by the velocity of the gas, and the whole of the arc region is filled with vapour (Fig. 18(i)).

(ii) When there is a high velocity jet associated with the arc, e.g., with a velocity of 10⁴-10⁵ cm/sec and a low rate of vapour emission. Then the vapour flows along, and thus delineates the stream lines. If the stream lines in a welding arc were the same as those determined for the 2004 carbon arc in air the arc would appear as in Fig. 18(ii).

(iii) When the electrode has a high vapour pressure the velocity of emission of vapour is comparable to that of a plasma jet. Vapour will thus flow across jet stream lines and it is not possible to determine whether a jet exists from the appearance of the arc.

Zinc, magnesium and cadmium fall into the last category. Steel, nickel, titanium and aluminium come under category (ii), while with molybdenum, copper and tungsten the higher rate of vapour emission results in a somewhat broader vapour stream.

Judging by the appearance of the arc along these lines, spray or small drop transfer occurs in arcs with plasma jets, e.g., Figs. 3(6), 4, 5, 8, 10, 13, and large drop.

![Fig. 17. (i) The shape of the luminous region of an arc between two rod electrodes (after Schmitz). (ii) Substitution of a plate electrode for one of the rods. (iii) The introduction of a plasma jet constricts the arc.](image-url)
METAL TRANSFER IN GAS-SHIELDED ARCS  

Type 1. A drop transfer in arcs where there is no evidence for a plasma jet. E.g., Figs. 3(a), 11 and 12. This conforms with Amson and Salter’s assessment that the plasma jet and magneto-kinetic hypotheses make the major contribution towards transfer, since both of these are detached when it is considerably smaller than in Type 1, showing that there is an additional force aiding transfer. Characteristic examples are the high current transfer of aluminum and copper in argon, with electrode positive. The forces required to detach the drops are 300 and 450 dynes respectively, of which gravity contributes only a few per cent at detachment. This type of transfer is associated with a stable arc which envelops the drop and broadens out towards the plate, showing the existence of a plasma jet, and which conforms to the system analysed in Amson and Salter’s paper in the present series.

Type 2. The drop is distorted, lifted, or repelled from the plate as a result of arc action. This occurs with electrode negative with the low melting point metals and is associated with the formation of a cathode spot. The repulsive effect may be superimposed on a force aiding transfer, so that the overall transfer is towards the plate and can even be of the spray type; drops of a size greater than the free fall drop are never observed to detach. In many cases there is continuous multiple or rapid moving spot action. With nickel at 165 A there was an example of a large drop hanging in a quiescent arc on which a cathode spot formed for a short period. The characteristics of this isolated event could be observed to determine the magnitude of the associated repulsive force.

The force $F$, acting for the short time $t$, imparted kinetic energy to the drop $(1/2)mv^2$ and it subsequently lifted until its potential energy, $mgh$, had increased by this amount:

$$F = m(v/t)$$
$$\frac{1}{2}mv^2 = mgh.$$

From a determination of the drop diameter its weight was 0.46 g, the spot was in existence for $5 \times 10^{-2}$ sec, and as a result the drop was lifted 0.6 cm, so that the force exerted was about $3 \times 10^5$ dynes.

According to existing theories the only force available to repel the drop from the plate is the Lorentz force acting within the drop. This can be calculated from Greene’s formula:

$$F = J^2 \left[ \ln \frac{\sin \theta}{\sin \psi} - \left( \frac{1}{4} + \frac{1}{1 - \cos \theta} \right) \right]$$
$$+ \left( \frac{2}{1 - \cos \theta} \right)^2 \ln \left( \frac{2}{1 - \cos \theta} \right)$$

BASIC TRANSFER SYSTEMS

It is proposed that there are six basic modes of transfer, and that any observed transfer conforms to one or a combination of several of these modes. The six systems are illustrated in Fig. 19 and comprise the following.

Type 1. A large drop develops and detaches with little influence of arc forces. Characteristic examples are transfer of most metals in argon at low currents with electrode positive. Only two forces have to be considered; these are the force of gravity acting to detach the drop, and the restraining force of surface tension; the drop starts to detach when it has developed to a size at which these are equal.

Type 2. The molten electrode tip remains spherical under the action of surface tension, but the drop is

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Fig. 18. Flow lines and 4000°K isotherm for a 200 A carbon arc (after Maeker): (i) When the gas flow is below 10⁵ cm/sec, the luminous region of the arc is completely filled with vapour. (ii) When there is a high-velocity jet and a low rate of vapour emission the vapour flows along the stream lines.

Fig. 19. The six basic transfer systems.
where $i$ is the current in e.m.u., $\theta$ is the half angle subtended by the current-emitting area, and $\psi$ the half angle subtended by the electrode, both angles being measured from the centre of the drop base. In this type of cathode spot the current density is $10^4$ A/sq cm$^{19}$ and $\theta$ about 6° so that at 165 A the repulsive force is $5 \times 10^5$ dyes, i.e., a factor of 10 less than that observed. Another force must therefore be invoked to explain the behaviour of this type of system. This is the force that is associated with the mechanism of the cathode spot. Von Engel and Robinson$^{19}$ discussed this problem in detail and proposed that there is a localized unbalanced electron pressure at the cathode spot which in the mercury arc amounts to 5 atmospheres. Acting over the area of the cathode spot this pressure results in a force of the order of $10^5$ dynes and is sufficient to account for the drop repulsion observed.

Repulsion may occur with electrode positive in dissociable gases, e.g., steel in CO$_2$, but to what extent the observed effect is genuine repulsion, or merely turbulence within the drop resulting from anode spot movement is not clear. The liquid within the drop will flow as a result of the Lorentz force (in the same way as the plasma flows within the column), and where the electrode spot is moving about rapidly the flow becomes turbulent, resulting in the observed disturbed motion of the drop. The flow within the drop could also affect the evaluation of the magnetokinetic force. Again the overall force aids drop detachment as drop sizes are smaller than those of free fall droplets.

Smith$^{11}$ suggests the most probable cause of repulsion is jet action from the cathode, but no evidence for this suggestion could be found in the present work. In the one case where a strong jet was observed coming from the plate, i.e., the transfer of molybdenum, electrode positive at 175 A (Fig. 6), it had no significant effect on drop detachment. Defize and van der Willigen$^{12}$ claim that there is a constricted anode spot and that the repulsion thus arises from the Lorentz force within the drop. This is contrary to the present work in which a large anode spot was seen, and contrary to the current conclusion of Amson and Salter and the present workers, which is that spray transfer occurs when the arc is constricted at the anode because it results in the formation of a plasma jet.

Type 4. The end of the electrode is tapered and a fine spray of drops streams off. Typical examples are the high current transfer of steel and nickel in argon with electrode positive, and the spray periods with titanium, molybdenum and tungsten, electrode negative. This type of transfer is associated with well-developed plasma jets as evidenced by the vapour streams.

Type 5. The molten metal from the electrode streams off in an upward direction, associated with pronounced vaporization of the electrode material. This type of transfer occurs with the high vapour pressure metals, magnesium, zinc and cadmium. With zinc at 180 A 0.2 g/sec of metal is converted to vapour; if the mean vapour temperature is taken as 10,000° C the volume of vapour produced is $2 \times 10^5$ cu cm/sec and the velocity of the vapour stream of the order of $10^3$ cm/sec.
METAL TRANSFER IN GAS-SHIELDED ARCS  

Considering a drop of diameter twice that of the wire, gravity exerts a downward force of about 100 dynes, the restraining force of surface tension at the neck is about 400 dynes, and the vapour stream exerts an upward back reaction of the order of 10^5 dynes. Hence, it is thus able initially to propel the drop away from the plate.

With the other metals examined the vapour loss, as determined in experiments with the tungsten electrode system, was low by a factor of 10^2 to 10^3. Taking the upper limit (relevant to copper) the back reaction force with electrode positive is negligible, i.e., about 1 dyne. However, it may be appreciable with electrode negative, where the higher current density over a smaller area results in a higher velocity of the issuing vapour stream and possibly also a greater rate of vapour loss. It is difficult to assign figures to a calculation of the force, but quite feasible data leads to forces of 10^4 to 10^5 dynes (taking a rate of vaporization 0.01 g/sec and current density of 10^5 A/m^2 cm), and the influence of the vapour stream cannot be ruled out.

Type 6. The drop and arc move sideways and the neck thrust in the opposite direction (Figs. 4 and 19). Detachment does not occur when the drop is displaced sideways if the arc remains under the electrode. This process occurs to a lesser or greater extent with many metals, with small or large drop transfer, and independently of polarity. The curvature of the current path caused by the drop and arc movement introduces a sideways thrust of the Lorentz force and as the neck moves the curvature, and hence the magnitude of the force, increases until separation occurs.

Under this scheme of classification many types of transfer are a combination of two or more of the above systems. Thus, for example, the transfer of tungsten and molybdenum (Fig. 10) is a combination of Types 2 and 4, the transfer of steel in CO_2 and copper in nitrogen, electrode negative, a combination of Types 1 and 3, and 6.

DISCUSSION

The significance of the experimental observations has been discussed at length in the previous section and the only point it is proposed to consider here is the reason for globular transfer with dissolvable gases. Globular transfer occurs when there is no force tiding transfer, i.e., when there is no plasma jet. The jet action takes place down the pressure gradient along an increasing cross sectional area of the arc. These conditions are inherent in an arc operating from a rod electrode because of the shape of the high temperature conducting region as shown in Fig. 17, in which it is implicitly assumed that the arc emanates from around the tip of the electrode.

However, with dissolvable gases the arc emanates only from the base of the drop, the area of emission increasing with drop growth so that no jet forms (Fig. 11). Thus the basic reason for globular transfer in dissolvable gases is that the arc does not emanate in part from around the sides of the electrode. For the arc to "climb up" the electrode, the effective increase in the arc length and column energy dissipation must be compensated by a lower energy consumption in the potential drop at the electrode. Since the energy dissipation in the column of the nitrogen and CO_2 arcs is 4-5 times that in argon (the column gradient in argon is about 8-10 V/cm) these arcs are less likely to "climb up" the electrode.

The reason for the effectiveness of the coating with electrode negative is that it reduces the cathode voltage drop by bringing about thermionic emission. This compensates for the increase in arc length necessary when the arc "climbs up" the electrode, which it has to do so as to emanate from the relatively large area required for the comparatively low current density associated with thermionic emission.

It is interesting to note that according to this explanation, large drop transfer will tend to predominate whenever the energy dissipation in the arc column is high. Since the voltage drop in the helium column is 2-5 to 3 times that in argon, transfer characteristics in helium might be expected to be less satisfactory than in argon. There is not much published data on this point but what there is supports this contention.

CONCLUSIONS

The many types of transfer that are observed can be classified, with probable reasons for their particular characteristics, as follows.

1. If the metal has a high vapour pressure, e.g., magnesium and cadmium, the arcs are repelled from the plate, regardless of the electrode polarity, because of the back reaction thrust of the issuing vapour stream.

2. With low vapour pressure metals in argon with electrode positive, globular transfer gives way to spray transfer with increasing current as a result of the formation of a plasma jet. Two types of system are observed: if the metal has a high thermal conductivity, e.g., aluminum and copper, the drop size decreases with current without any change in the geometry of transfer; if the thermal conductivity is low the electrode tip becomes tapered and a spray of fine drops is emitted as a result of the Lorentz force causing the liquid to flow down the tapered tip.

3. In argon with electrode negative the low melting point metals exhibit a repulsion from the plate. This is primarily because of the mechanism of electron emission, although the Lorentz force within the drop and the back thrust of the vapour stream may also contribute to the repulsion.

With metals which have a high melting point, e.g., tungsten, this repulsion is absent because the current is emitted thermionically over a much larger area. Molybdenum and titanium approximate to the behaviour of tungsten but also show some evidence for slight repulsion.

4. In dissolvable 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 with dissolvable gases.
deters the arc from "climbing up" the electrode and thus achieving the configuration required for a plasma jet.

(5) The successful action of a coating of potassium and caesium carbonates in producing spray transfer with mild steel in \( \text{CO}_2 \), electrode negative, arises because it brings about thermionic emission, and thereby decreases the cathode drop. For this to happen the arc has to climb up the electrode to attain the required low current density of emission, and thus the arc geometry for plasma jet formation is achieved.

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References

The de- electrode, in Part 1, "Part 1" that de- the arc's...