Some Characteristics of the MIG Arc and Their Influence on Metal Transfer

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Introduction

Metal Inert Gas (MIG) welding is a process in which a continuously fed wire electrode is passed through a nozzle in the welding torch where it picks up current from a contact tube and gets melted in an arc. The wire, as it comes out and the arc are shielded by an inert gas issuing out of the nozzle. The process has become very popular comparatively recently. It may, therefore, be of some interest to study the characteristics of the MIG arc and the influence such characteristics exert on the transfer of molten metal drops. Metal transfer with argon shielding only is proposed to be discussed. However, many of the observations made will be applicable to other shielding gases also.

The Arc

A welding arc consists of a sustained electrical discharge through a high temperature conducting plasma, producing sufficient thermal energy so as to be useful for the joining of metals by fusion. Electrical conduction in the arc takes place through a gaseous column which has high electrical conductivity. The gas column called the plasma, contains a radiating mixture of free electrons, positive ions and highly excited electrically neutral atoms.[1]

Electron Emission

It would be of interest to understand how electrons are emitted from a cathode in an electric arc. There are two mechanisms. One of them is known as Thermionic emission which has been explained by the physicists. The other, known as cold cathode emission, is not yet fully understood and all explanations are rather speculative.

Thermionic Emission—Thermionic emission from a material depends on its 'work function' which is a measure of the energy required to extract an electron from the metal surface. A metal of low 'work function' will have good emissive property. A metal having high 'work function' has poor emissivity and can act as a good source of electrons only at very high temperatures. Metals like aluminium and iron have high work functions and they can work as good electron emitters only at temperatures much in excess of not only their melting temperatures but also their boiling points. As they are able to supply almost no thermionic electrons, they are called *'Cold Cathode' materials.* Tungsten, though it has a slightly higher work function than aluminium or iron, is still considered a good *thermionic material* because it has a high boiling point which permits it to be heated to a high temperature without being dissipated into vapour. Therefore, with tungsten electrode in TIG welding, the arc is maintained by thermionic emission of electrons.

The electrode metal in consumable electrode welding is selected on the consideration of base metal to be welded and no consideration can be given to its electron emissivity. In a covered electrode, however, many ingredients are added to increase the electron emissivity. Thus, instead of the 'cold cathode', a thermionic cathode is obtained and the arc becomes stable. The emissive ingredients allow a transfer of metal droplets with fewer short circuits and permit the use of A.C. machines with lower open circuit voltages. The proportion of each ingredient required is critical and requires careful choosing.

With easy availability of electrons from a thermionic cathode at a lower cathode voltage, fewer positive ions are required to sustain the arc. Consequently the arc is maintained with less positive ion bombardment of the cathode and thus less cathode heating.

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Cold Cathode Emission—The position is entirely reversed in MIG welding using a bare wire cathode of metals like aluminium or iron. The arc cannot be supported with thermionic emission, since the area of emission is confined and the work function is high. The positive ions must therefore perform most of the function of maintaining the flow of current through such arcs. The kinetic energy of flow of the large number of positive ions towards the negative electrode supports the drops of molten electrode metal in such an arc. This explains the formation of large globules with Direct Current Straight Polarity (henceforth referred to as DCSP) which appear to be supported by some force from the bottom[2].

With a bare wire cathode of metals like aluminium or iron where practically no thermionic emission is possible, the cathode is a 'cold cathode'. Obviously such metals with low emissivity must have some mechanism other than thermionic emission functioning in their welding arcs ; otherwise such arcs would not exist. As mentioned earlier, electron emission with a cold cathode is not yet fully explained. For such electrodes, the theory of field emission has been postulated. In the phenomenon of field emission, well defined cathode spots are said to develop on the electrode. At any moment, there may be many of these cathode spots present and they are constantly vanishing and re-appearing elsewhere. The spots move around with a velocity of the order of 10^4 cm/sec. Vaporisation of the electrodes occurs and the current density is many many times higher than with thermionic emission. Very high local energy dissipiation produces a state of matter which has been found difficult to explain theoretically and the accepted concepts of work-function and vaporisation are inapplicable.[2] For this reason, it has not been possible to put forward a satisfactory theory of cathode mechanism for this type of arc.

The phenomenon of 'field emission' releases a tremendous amount of heat energy in the cathode region. Consequently with electrode negative, the melting rate is high. This is quite contrary to the observation in TIG welding where the electrode heating is less when it is negative and is much more when it is positive.

MIG Arc—DCSP

MIG welding with electrode negative i.e. DCSP is, therefore, characterized by a high melting rate. Burn off rates with straight polarity are almost double of those with reverse polarity. Molten metal, however, clings to the wire end as large globules until they become sufficiently large in size to be drawn to the work piece by gravity. These large drops are transferred at the rate of only a few per second. The transfer is erratic and the arc unstable. The weld is broad and the penetration is shallow. (See Fig. 1)

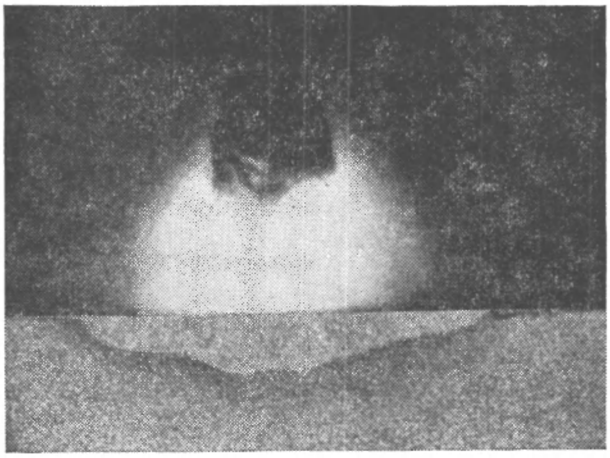

Fig. 1—Typical straight polarity arc and cross section of weld—argon, 1/16 in. dia mild-steel electrode.

MIG Arc—Direct Current Reverse Polarity (henceforth referred to as DCRP)

Compared to the high melting rate and irregular globular transfer with DCSP, the melting rate is low with DCRP but at high current density, the arc is characterised by a well directed stiff axial spray transfer with papillary penetration. At low current, the transfer is globular (See Fig. 2). A gradual increase in current increases the melting rate and at the same time

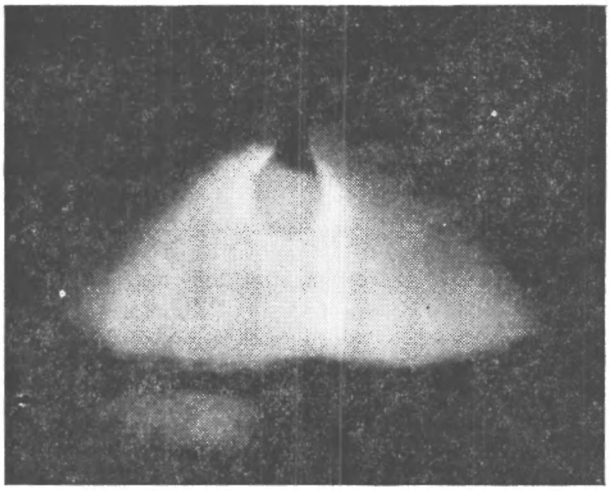

Fig. 2—Typical arc with globular transfer.

produces an increase in the metal transfer frequency and a decrease in drop size. This gradual change in transfer frequency and drop size continues till a critical current value (called transition current) is reached when there is a sudden change to very fine droplet transfer at high frequency. At the same time, the electrode tip becomes sharp and pointed. Around the electrode tip and the metal droplets is a region of incandescent vapour. As a result of the rapid rate with which the drops form and traverse the arc, there is a needle like continuum from the electrode to the work which is known as a vapour jet. This jet is enveloped by an umbrella of excited plasma which is composed almost entirely of shielding gas. The unique well directed axial spray transfer is found eminently suitable for many welding applications. (See Fig. 3)

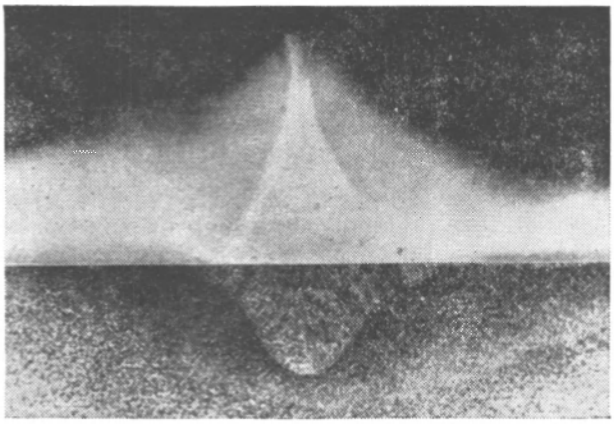

Fig. 3—Argon-Shielded, inert-gas (Consumable) arc showing fine spray-type metal transfer.

Another characteristic of DCRP is a phenomenon called 'sputtering' or cleaning action in the plate which is the cathode. In aluminium welding this is beneficial, as the tenacious aluminium oxide layer is cleared. Under certain conditions, sputtering may not be desirable as in the case of steel where the action is not uniform being more intense in certain areas than others. The arc plasma wanders, arc becomes less stable and the melting is irregular. Localised heat generated by cathode sputtering may ultimately develop a gouge in the vicinity of the arc and there may be undercut in the weld deposit. Oxygen addition is made in argon to minimize this effect, stabilize the arc and develop a more uniform shaped bead. Better electron emissivity of the iron oxide is considered to be the cause of this improvement.

With reverse polarity MIG arc where the job is the cathode, penetration is deep, narrow and papillary ; the bead appearance, though not ideal, is considered acceptable.

MIG Arc—AC

A. C. if used for MIG welding, will not only produce the undesirable irregular globular transfer during every negative half cycle but will also create the additional problem of arc re-ignition that is associated with the use of bare electrode in A.C.

MIG Arc—Use of Emissive Coating

A recent development describes application of an atomic-film of material like rubidium, cesium, calcium, potassium, barium, strontium etc. on the wire electrode which increases its electron emissivity to an appreciable extent.[2] Thus the electrode is changed from 'cold cathode' to thermionic cathode and the use of DCSP and A.C. becomes practicable.

The availability of specially treated electrodes is as yet very much restricted and normally, a user of MIG process is left with no choice but to employ DCRP.

Metal Transfer Across the Arc

It is well known that there are forces existing in an arc and these make transfer of molten droplets possible even against gravity as in the case of overhead welding. This transfer had so far been explained by pinch effect due to the constriction of the current in the wire electrode—particularly in the neck of the globule under formation at the electrode tip, and the expansion of gases at the electrode tip.

Experimental observation in inert gas shielded arc welding, however, shows that these two effects cannot fully explain the behaviour of metal droplets under transfer. It has been observed that the droplets get considerably accelerated after detachment indicating that there is a force acting on it even after it gets detached from the electrode tip. In fact, in a 270 amp. MIG using 1/16" aluminium electrode, the initial velocity (i.e. just after the detachment) and the final velocity were found to be 180 cm/sec. and 300 cm/sec. for a 7 mm. flight and the average acceleration was 40,000 cm/sec. per sec.[4,5] It has also been observed using high speed cine-photography that the vapour stream emanating from the aluminium droplets under transfer is directed forward in advance of the droplets and is *not trailing* behind. This clearly indicates presence of a force pushing the droplets forward. Dropping of quartz particles into a horizontal TIG arc also shows the existence of a force pushing the particles forward at high velocity.

This force is considered to be the plasma jet, having a velocity of the order of 10^4—10^5 cm/sec under the action of which the molten droplets attain a velocity of the order of 10^2—10^3 cm/sec. This explains the regular type of well-directed transfer observed in MIG welding.[4,5].

It is thought that the plasma jet exerts a force on the molten globule formed at the tip of the electrode. As this force exceeds the restraining force of surface tension, the globule is pulled away from the tip, the acceleration increasing as the diameter of the restraining neck decreases, till the globule is detached and accelerated freely under the action of plasma jet. At lower current values, the jet force is not sufficient and the metal transfer is irregular and globular under the action of gravity. Above the transition current, the well-directed spray transfer comes into action.

Plasma Jet Action--Plasma jet action which is considered responsible for the metal transfer across the arc requires a little more elaborate discussion. The origin of plasma jet is due to the action of the self-induced magnetic field generated by the flow of charge carriers along the arc column. Under the influence of this force, the electrons will move towards the arc axis and during the travel will collide with the neutral atoms at a very high frequency and thus carry these atoms with them. A local region of high pressure is thus created in the axis in opposition to the electromagnetic force. The increase in pressure is related to the current density and as the cross-sectional area of the arc increases, the pressure decreases giving rise to a pressure-gradient along the length of the arc column. In particular, where the arc is severely constricted either naturally as in the case of DCRP-MIG or artificially as in the case of plasma-arc torches, a marked region of high pressure can occur and the arc plasma flows from the high pressure region towards the low pressure region. To maintain continuity of the flow, the surrounding gas is sucked into the constriction which thus acts as a pump. The velocity attained by the gas under this jet action is of the order of 10^4 cm/sec.

Constriction required is provided by the Tungsten electrode in TIG welding and by the consumable electrode in MIG since in each case the current is constrained by the diameter of the electrode. A small electrode diameter with high current density will, however, provide a much more intense jet so that this is found to be quite pronounced in MIG welding.

The plasma jet is very intense in DCRP MIG arc, as the electrode end melts and presents a sharp and pointed cone. With DCSP, the jet action is very much reduced. Cathode sputtering developed in the wire electrode does not present a well-defined cathode. Moreover, the molten metal at the electrode tip appears to be supported by the kinetic energy of the positive ions. As a result, a broad arc plasma with indistinct boundaries forms between the electrode tip and the plate. The metal transfer is by gravity. Large drops of metals are transferred at the rate of only a few per second. Their erratic motion causes the arc plasma to shift and as a result the weld becomes broad with low penetration. Due to cathode sputtering many large drops are scattered as spatter.

The intense plasma jet in DCSP is not only responsible for the unique stiff axial and well-directed metal transfer across the arc, but also at least partly responsible for the deep crater in the arc and the papillary penetration pattern. The jet develops a more intense core in case of dissociable gas and this explains extremely deep penetration characteristics in CO_2 shielded MIG welding. High velocity plasma jet is also considered to transfer an appreciable part of arc column energy to the work piece. The main source of heat at the work piece in the DCRP arc is however the energy due to cathode reactions and this, together with plasma jet action, is responsible for the deep penetration.

Plasma jet is also considered to be of importance in determining the effectiveness of inert gas shielding. The inert gas flow through the shielding nozzle has a velocity of the order of 10^2 cm/sec. but in the centre of the shroud the arc is sucking the gas to form plasma jet having a velocity of the order of 10^4 cm/sec. The difficulty experienced in maintaining adequate shielding while using high current may be explained by this.

Effects of Current on Metal Transfer

As the force of the plasma jet is dependent on the current used, the metal transfer behaviour also changes with current. A more detailed discussion on the effects of current is, therefore, called for. Only DCRP will be considered as this is practically the only useful polarity in MIG welding.

Transition Current : Axial Spray

It has already been mentioned earlier that as the current is gradually increased from a low value, a critical current value called the transition current is reached at which the transfer is suddenly changed from irregular globular to well-directed stiff spray transfer. Frequency of transfer is appreciably and markedly increased and the drop sizes decreased. To give an example, using 1/16″ mild steel wire in a shielding of argon with 1% oxygen, an increase of current from 255 to 265 amps. changed the drop frequency from 15 drops/sec. to 240 drops/sec.[3] (See fig. 4)

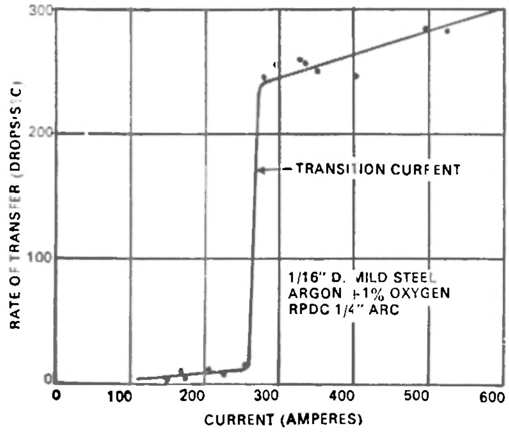

Fig. 4—Effect of current on the frequency of drops transferred in an Argon-Shielded arc.

It should, however, be mentioned that there is no sudden change in melting rate at the transition current.

Factors affecting Transition Current to Axial Transfer—When using a particular shielding gas, the transition current depends on electrode composition as well as electrode diameter and extension.

Electrode Composition—The influence of electrode composition can best be explained with an example. In an argon shielded arc, aluminium develops spray transfer at a current that is approximately 1/3rd that required for mild steel. Even minor changes in the composition which are normally encountered in mild steel electrodes can produce large changes in transition current. As an example, some 1/16″ electrodes with a fixed extension showed a transition current of 220 amps. while under the same conditions, some other electrodes in the same family did not develop spray transfer until the current was raised to 310 amps.[3] Even the changes in chemistry along a wire due to normal heterogenity of an ingot have been found to cause changes in metal transfer characteristics.

A good explanation cannot be offered for the effect of chemistry on transition current. Probably a critical concentration of metal vapour in the arc stream is necessary to initiate the unique spray transfer. Therefore, the presence of alloying elements having low boiling points might influence in lowering the transition current.

Electrode Diameter & Extension—The transition current increases with the electrode diameter and decreases with the extension. The following empirical relationship shows the effects of these variables[3] :

$I_s = a + bD - cL$
where I_s = Transition current
D = electrode diameter
L = electrode extension
a, b, c are empirical constants depending on electrode composition.

Changes in transition current due to changes in electrode diameter and extension and their effects on melting rate as found out in an experiment are shown in the table below.[3]

TABLE
(for Mild Steel)

Electrode dia. inch	*Transition Current amp.*		*Melting Rate in lb. per hour at transition current*	
	Extension (¼″)	*Extension* (2″)	*Extension* (¼″)	*Extension* (2″)
0.030	160	120	4.8	11.2
0.062	275	230	6.3	10.3
0.094	370	315	8.3	9.7

It will be apparent from the above that increasing the extension has brought down the transition currents and with sufficient extension, it is possible to get much higher melting rates than with lower extensions.

Transition Current : Axial Spray to Rotating Spray

After attaining axial-spray at the transition current if the magnitude of current and electrode feed rate are continuously increased while holding electrode extension fixed, a second critical level of current will be reached beyond which arc characteristics again change. Above this second transition current, the tip of the electrode bends and rotates about the major axis of the body of the electrode. (See Fig. 5) Continued increase in current will increase the angle of bend until the electrode tip is almost at right angles to the axis of the electrode. As the metal is no longer transferred axially to the weld pool but is transferred in all directions as spatter, the arc is no longer useful in the conventional manner as a tool for welding.

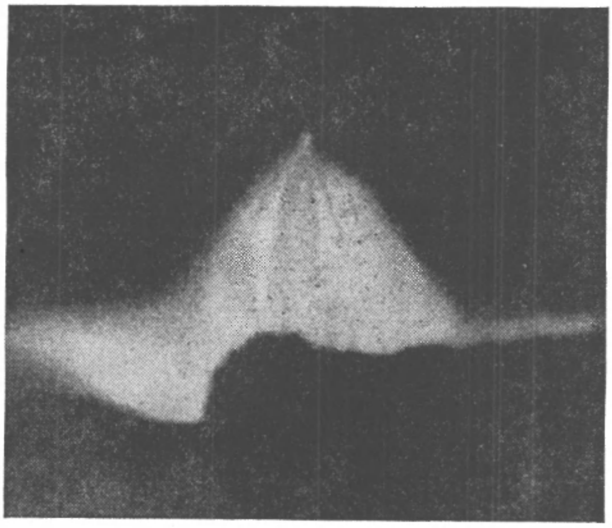

Fig. 5—Typical arc with rotating-jet transfer.

Factors Affecting Transition Current to Rotating Spray—The transition to rotating spray for a particular composition of the electrode is again dependent on electrode extension and diameter. An increase in welding current causes the electrode tip extension to become progressively more plastic due to its own resistance heating. Simultaneously, the increase in current causes the reaction forces at the electrode to become stronger. A current level is ultimately reached at which the forces become great enough to bend the plastic electrode tip and cause it to rotate in the same manner as the free end of a suspended garden hose supplying water.

It is, therefore, apparent that the transition current to rotating spray will decrease with increasing extension and decreasing electrode diameter. The effect of elevation of the transition current by increasing the electrode diameter is due not only to the lower electrical resistance but also to the higher mechanical stiffness the larger diameter offers. The relationship of this second transition current with extension and electrode diameter can be expressed by an emperical formula[3] :—

$$I_r = x + yD + \frac{zD^2}{L}$$

where :

I_r = transition current to rotating spray.
D = electrode diameter.
L = electrode extension.
x, y, z are constants depending on electrode composition.

Composition plays an important part in determining the current at which transition to rotating spray will occur. Rotating spray is not usually developed within the current range that is normally used in high conductivity materials like aluminium. Using an 1/16″ aluminium electrode with a 2″ extension, a rotating spray was not observed at 800 amps. although a steel electrode of the same diameter and extension developed rotating spray at 350 amps.[3] Rotation also develops with stainless steel, other ferrous alloys and bronzes.

Control of Spray Transfer Characteristics and Melting Rates

From the current value at which axial spray develops to the value at which rotating spray starts should be considered the most useful range for welding. In order to widen the range, the lower limit can be brought down by decreasing the electrode diameter and increasing the extension. To extend the upper limit further up, it is however necessary to use the shortest possible extension and largest possible diameter so that the highest possible current can be used still maintaining axial spray characteristics. When high deposition rates must be obtained with low welding currents, it can be achieved by the use of an electrode of smaller diameter or longer extension or a combination of both, However, where highest deposition rates are required and there is no objection to the use of high currents, the only answer is to use the highest possible current to suit the electrode of largest possible diameter and shortest possible extension.

It should be mentioned here that though rotating spray is not useful as a conventional welding tool, under certain conditions this technique can be utilized for obtaining a wider weld deposit, reducing weld penetration and for welding in a deep groove or in surfacing applications. Such applications are, however, limited to the use of current just above the limit where rotation develops. At higher current levels such arcs will be useless because of excessive spatter.

Summary

(1) An examination of the objectionable characteristics of MIG arc reveals that they are the result of the cold cathode phenomenon. Poor transfer occurs when electrode is negative. When the weldment is negative, sputtering which can be objectionable under

certain circumstances develops. Cathode action also adversely affects the bead contour to an extent.

(2) Electrode negative i.e. Direct Current Straight Polarity (DCSP) with bare wire electrode (without emissive coating) cannot, therefore, be used in MIG welding. With DCSP, transfer is erratic and globular and the arc unstable. Melting rates with DCSP are, however, high—almost double of those with reverse polarity.

(3) Undesirable characteristics observed with negative polarity disappear with the use of positive i.e. Direct Current Reverse Polarity (DCSP) and desirable metal transfer characteristics giving well-directed stiff axial spray are obtained provided a current above a critical value called the transition current is used.

(4) A. C. gives irregular globular transfer during the negative half cycle. In addition, it creates the problem of arc re-ignition.

(5) With emissive coatings on electrode, DCSP and AC can also be used but the use of such specially treated electrode is as yet very much restricted. The user of MIG welding has, therefore, practically no choice but to employ DCRP.

(6) The use of DCRP no doubt means that the harmful effects of cathode phenomena will now be transferred to the weldment but the effect, now distributed over a wider base, are no that harmful. In fact, sputtering, in case of aluminium welding, turns out to be not only desirable but a necessary phenomenon because of its cleaning action. In mild steel welding, where sputtering is considered objectionable, its effects can be counteracted by the addition of a small percentage of oxygen in argon. Because of the high temperature developed due to cathode action, the penetration is deep and the bead contour, though not ideal, is considered acceptable. Well-directed spray action of the arc, more than compensates for the difficulties resulting from cold cathode action on the weldment.

(7) The unique well-directed transfer observed in DCRP MIG welding is considered to be due to a force pushing the molten particles forward at high velocity. This force is known as plasma jet.

(8) The origin of the plasma jet is due to the action of the self-induced magnetic field generated by the flow of charge carriers along the arc, creating a local region of high pressure along the axis but with a pressure gradient along the length of arc column. The pressure is highest at the point where the arc is constricted i.e. at the tip of the electrode.

(9) Normally three types of transfer are possible with DCRP. Globular transfer at low currents, axial spray transfer beyond a transition current and rotating spray beyond a second transition current.

(10) The current range between the axial spray and rotating spray transition points should be considered the most useful range for welding.

(11) Though rotating spray is not useful as a conventional welding tool, it can be used at current levels just above the limit where rotation develops, to achieve wider weld deposits and to ensure wetting of the side walls in deep-groove welding.

(12) With a particular shielding gas used and the electrode composition remaining unchanged, the transition currents at which axial spray and rotating spray develop will depend on electrode diameter and extension.

(13) In order to widen the useful range of current (from transition to axial spray to transition to rotating spray), the lower limit can be brought down by decreasing the electrode diameter and increasing the electrode extension. To extend the upper limit, shortest possible extension and largest possible diameter should be used.

(14) For high deposition rate with low welding currents, a smaller diameter electrode or longer extension or a combination of both should be employed. However, where use of high current is not objectionable, for highest deposition rates, use should be made of largest possible diameter with shortest possible extension.

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