METAL TRANSFER IN GAS METAL ARC WELDING

by

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ABSTRACT

The Metal transfer in gas metal arc welding using an E70S-3 electrode and argon/ 25 percent carbon dioxide shielding gas was studied. The relationship of each metal transfer mode with arc voltage variation was defined and used to characterize the stability of the welding process. The distribution of droplet transfer rate and the relative percentage of each mode as a function of voltage were analyzed . Additionally isopleth diagrams of droplet transfer rate as a function of voltage and current were also prepared. These diagrams show the regions of high droplet rates which reflect an acceptable operation area of stable welding condition. High droplet transfer rate in gas metal arc welding is a desirable welding condition and can be quantified using a high speed oscilloscope and high speed video camera. A criterion that characterizes metal transfer mode based on voltage variation is developed. This relationship of voltage variation and metal transfer mode can be applied in welding process control. The conception can be incorporated into advanced welding systems, with computerized real-time current and voltage variation sensing, to produce consistent and quality welds, with desirable and stable metal transfer. construct a computerized welding machine to produce a desirable stable metal transfer mode.

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1.0 INTRODUCTION

From the definition of welding, by the American Welding Society (AWS), as " A materials joining process used in making welds, "(1) it is easy to comprehend that a dependable, efficient and economical welding process for joining metals is critical in manufacturing.

Since the end of World War I, arc welding has been a necessary and important process in manufacturing industries. Various welding processes, of different characteristics and applications, have been developed.

The most popular processes have been oxyfuel welding (OFW), shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), and gas metal arc welding (GMAW).

When oxyfuel gas is used for welding, it provides a most versatile welding process (1). However, it requires a great deal of skill and is relatively slow. Economic consideration have caused the other processes to be favored.

Shielded metal arc welding (SMAW) is the most popular method of joining metal. High quality welds can be made rapidly and with excellent uniformity. The method can be applied to various material thickness.

Gas tungsten arc welding (GTAW) is easily performed on a variety of materials. The clean and high-quality welds often required little or no post-weld finishing.

Gas metal arc welding (GMAW) is extremely fast and economical. This process is easily used for welding on thin gauge materials as well as on heavy plates. The high welding rate and reduced post-weld cleanup are making gas metal arc welding one of the fastest growing welding process.

However, a good quality weldment and easy operation are the main goals sought by welding metallurgists. In order to improve the weldability and welding quality, welding metallurgists need to understand the reactions at the two electrodes, anode and cathode. Specific variables that affect the arc include voltage, current, arc length, gravity, electrode polarity, and shielding gas.

Weisman (2) proposed that the forces that affect welding are :

(1) Pressure generated by the evolution of gases at the electrode tip.

(2) The electrostatic attraction between the electrodes.

(3) Gravity.

(4) The "pinch effect" caused by a momentary necking of the liquid drop that is conducting current.

(5) Explosive evaporation of the necked bridge

between the drop and electrode due to the very high density of the conducting current.

1.1 SCOPE OF THE WORK

Because of the high transfer rate, suitability for various materials and weldings positions, and the excellent bead morphorlogy, gas metal arc welding is extensively applied. In order to obtain sound welds with good bead morphlogy, the metal transfer in GMAW need to be clearly understood. Therefore the experiments in this study were conducted, Through the aid of a high speed oscilloscope, laser back-lighting, high speed video camera and recorder, the instantaneous arc voltage and welding current, and the continuous metal transfer from the solid electrode through the arc into the weld pool were investigated and the mode of metal transfer was related to the arc voltage and welding current.

1.2 Welding Arc

The potential drop across an arc (V)can be expressed by equation (1) as suggested by Nottinghem (3)

$$V = A + B / i^n \qquad (1)$$

A and B are constants dependent on the arc length and electrode material; n depends on electrode material only and i is the welding current. However, Suits(24) observed the dependence of the exponent, n, on the composition and pressure of the arc atmosphere. The value of n decreases with increasing gas pressure.

Spraragen and Lengyel (4) indicated that the potential drop in a welding arc is not uniform. There is a sharp drop of potential immediately in front of the electrodes and a gradual and approximately linear fall in the central arc. This is found to be the case regardless of the material of the electrode used or the gas surrounding the electrodes. Sparagen and Lengyel (4) have also shown that the cathode drop and anode drop vary only slightly with the current, on the other hand, total arc voltage and anode drop increase with increasing atmospheric pressure. The cathode drop of the arc was found to be independent of the current, arc length or the composition of the electrode.

The potential drops at the arc boundaries are identified as the cathode and anode drop. They are caused by the space charges which accumulate in front of the electrodes. An excess of positive ions moving toward the cathode produces a net positive charge immediately in front of the cathode. This is called the cathode sheath.

Conrady (5) concluded that the potential fall is linear through the plasma and the transition from the cathode drop to the plasma is abrupt.

Jackson (6) however proposed a nonlinear potential or voltage distribution along the arc axis, schematically illustrated in Figure 1. As for the high current-electrode arc welding the relationship for arc potential and arc length in gas metal arc welding is shown in Figure 2.

The investigations of Gunthersgchulze(7) and Child(8) and many other investigators revealed that cathode drop varies within narrow limits with the current and trends to a definite limit with increasing current, this limit being almost always nearly equal to the ionization potential of the arc atmosphere. The anode drop, on the other hand, rises with the current and shows a marked variation for different electrodes. The anode drop is at the same order as the heat conductivity of the metal. Anode drop and cathode drop are shown to be independent of the arc

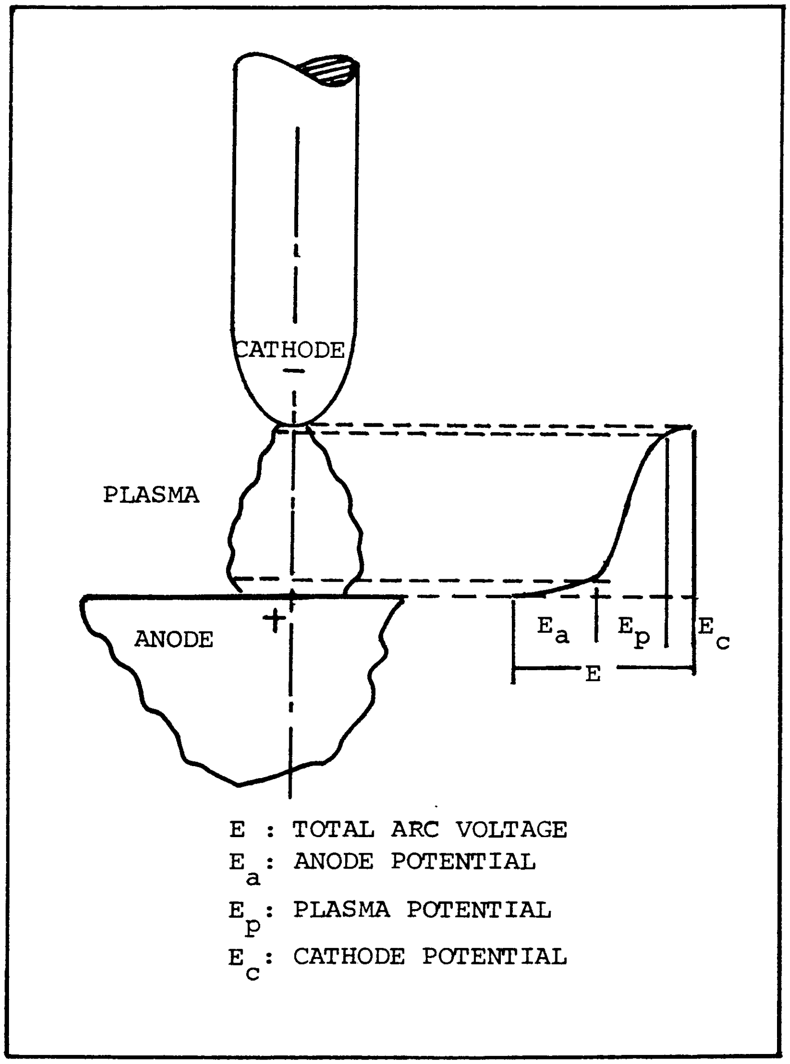


Figure 1

Potential Distribution in a Welding Arc (Ref.6)

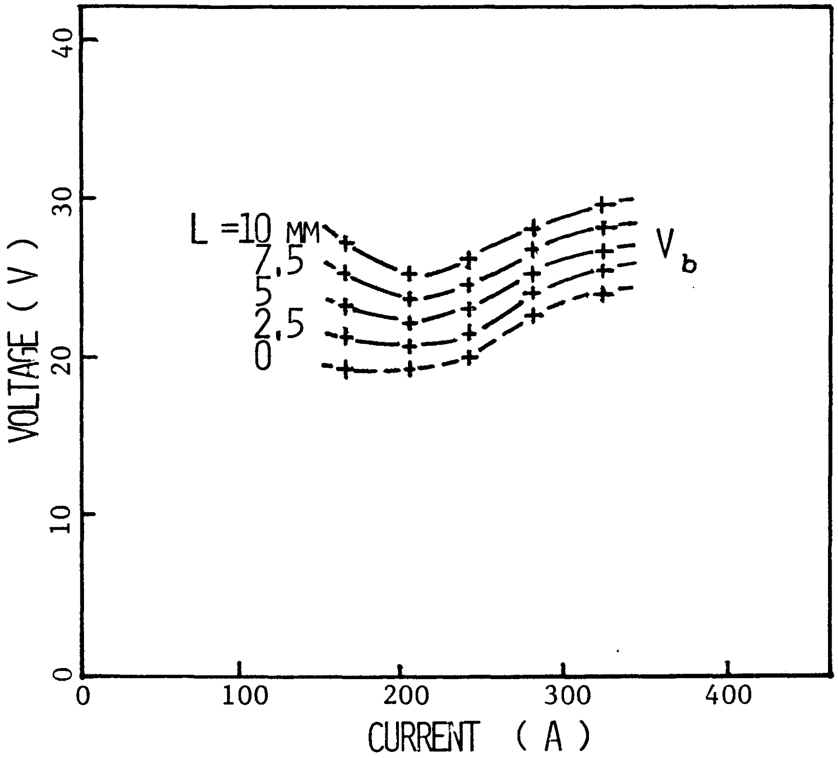


FIGURE 2

Variation of voltage on a function of arc length for GMAW with 1.2 mm diameter steel electrode (ref. 15) length. The total potential drop is a linear function of the arc length.

In all arcs, except those which the cathode has a small area, the current at the cathode is sharply concentrated in a small area, know as the cathode spot which wanders rapidly on the tip of the cathode for metals. Within the limitation of electrode size, the area of a cathode spot of a metallic arc is proportional to the total current, which results in almost constant current density, providing the anode is not too near. The cathode spot is the hottest part of a cathode and appears as a bright spot with a sharply defined boundary.

Spraragen and Lengyel(4) proposed that the essential feature of an arc is the emission of electrons from the cathode, which produces sufficient ionization of surrounding gas to give a positive space charge just outside the cathode. This space charge creates the cathode drop and thus permits a large electron emission at relatively low voltage. Likewise the potential drop in front of the anode is due to a space charge similar to the cathode sheath. However if the current is not too low there is no particular current-carrying spot on the anode, the anodic spot.

According to Slepian (13), in the immediate vicinity of the cathode the current is carried largely by positive ions and not by electrons. These ions originate in the plasma and are generated by thermal ionization. In the arc this explains the passage of the current to the cathode, Therefore, it is no longer necessary for the cathode to have a larger electron emission. A high temperature appears to be essential, but it may be in the gas immediately adjacent to the cathode and not at the cathode itself.

Compton (9) concluded that in the case of a tungsten arc in the air, the thermionic emission at the temperature of the cathode spot is adequate to account for the arc current- thermionic emission of electrons.

Langmuir (14) suggested that the high field in front of the cathode is instrumental in increasing the electron supply by pulling electrons out of the cathode.

Generally the hot cathode is an essential characteristic of the arc discharge and the thermionic current can be estimated by Richardson's (4) equation

$$I = A \quad T^{1/2} * \exp(-b/T) \qquad (2)$$

Where I is current , T is absolute temperature A and b are constants of the material.

Weized, Rompe and Schon(11) successfully applied the Slepian's theory to divid a cathode into three regions. The first region is a heat conduction region, adjacent to the plasma of uniform temperature and temperature gradient, significant heat conduction taking place in the axial direction. The thickness in this region is several hundred atomic mean free path lengths and the current is carried by electrons. The temperature decreases from plasma temperature to nearly that of the electrode and the potential gradient increases toward the electrode. The potential drop in this region is about one-half of the ionization potential. The second region next to the heat conduction region is the ionization region . The potential drop in this second region is about equal to the ionization potential of the gas. The third region, between the region of ionization and the cathode, consists of a space charge layer of mostly positive ions. The positive ions generated in the ionization region move toward the cathode and the electrons move toward the plasma.

Seeloger(12) considered the current at the cathode to include not only the ions generated in the cathode fall space by impact of electrons, but also those generated from the plasma by thermal ionization, by photoelectric effect and by high field emission.

Spraragen and Lengyal(4) suggested that if the current of an arc is not too low, there is no particular current-carring spot on the anode. The current is distributed over the entire tip of the electrode. Since there is nothing resembling the cathode spot on the anode, the role of this electrode in the arc is somewhat subordinate. The potential drop in front of the anode is due to a space charge similar to the cathode sheath. The electrons emitted from the anode provide a negative space charge in the neighborhood of the anode. The anode drop is, however, not as characteristic of the electrode and the surrounding atmosphere as is the cathode drop.

It is well known that a high anode temperature is not necessary for the maintenance of the arc. Nevertheless, the temperature of the anode is high in all arcs. Lummer (4) concluded that the anode is at the boiling temperature of the anode material. The temperature of the anode was determined from the surface brightness, and the values at varying pressure were found to satisfy the thermodynamic relation for the boiling temperature. The replacement of air by carbon dioxide, nitrogen or argon causes no change on the temperature.

The region between the anode drop and the cathode drop of an arc is highly conducting and exhibits a relative low-voltage gradient. This region is called the positive column or the plasma. The electric gradient in the plasma is approximately constant which indicates the absence of a net space charge. Electrons enters the positive column from the cathode sheath and are accelerated toward the anode. While passing through the positive column the electrons suffer numerous collisions. Their motion is a random motion with a superimposed drift.

The space charge of these electrons is compensated by positive ions which originate largely in the plasma. When a neutral atom or molecule is ionized the net charge naturally does not change. However, the velocity of the positive ions generated will be considerably less than the velocity of the electron and therefore a positive ion will remain longer in an element of volume than an electron does.

Compton (9) determined that the positive ion density cannot be explained by positive ions liberation from the anode by electron impact, ionization in the positive column by electron impact and photoelectric ionization. He proposed that thermal ionization is responsible for the production of positive ions. In the thermal ionization process the energy necessary for ionization is derived largely from the electrons falling through a field, as in the case of ionization by direct impact. Electron generally suffer many collisions even while traveling a relatively small potential drop and lose their energy during these collisions, thereby increasing the kinetic energy of the neutral atoms and ions. Some of the energy produces so called excited atoms building up the necessary energy for ionization gradually in the gas and distributed among the neutral atoms and ions through collisions. In order that the plsma be stable the number of new positive and negative charge carriers produced in the discharge and on the electrodes must be equal to the number of such carriers neutralized by either discharge or arrival at the opposite electrode. Besides, the arc must not only be in electrical equilibrium but also in thermal equilibrium. The heat generated must be equal to the heat dissipated. Furthermore electrical and thermal equilibrium of the arc are related to each other. For example, a disturbance in thermal equilibrium, such a cooling of the cathode causes a change in the emission of electrons and a change in the electrical balance. On the other hand a change in the current or voltage causes a change in the amount of heat produced and thus shifts the thermal balance.

1.2.1 Types of Arcs

Weisman (2) proposed that , at low welding currents in argon, liquid material from the electrode is transferred in the form of drops having a diameter greater than that of electrode. With electrode positive, the drop size is roughly inversely proportional to the current, and the drops are released at the rate of a few per second. With an arc sufficiently long to minimize short circuits, drop transfer is reasonably stable and associated with a relative absence of spatter. Above the critical current level, however, the characterics of this transfer change to the axial spray mode. In axial spray transfer, the tip of the electrode becomes pointed and from it, minute drops are transferred at the rate of hundreds per second. The current at which this occurs is called the transition current.

There are two fundamentally different types of arcs, the thermionic (glow discharge) and the non-thermionic arcs (high field arc discharge) .

B. Spraragen et. al (4) proposed that materials such as carbon, tungsten and perhaps also calcium and magnesium, the thermionic current density is of the order of 10 to 10^2 Ampere/mm^2. In the second group, which include mercury, copper, silver and gold, non-thermionic current density is only of the order of 10^{-4} to 10^{-3} ampere/mm^2.The two groups are distinguished by the behavior of the cathode spot. In the first group the cathode spot appears fixed, and attempts at moving it rapidly invariably results in the extinction of the arc. Electrodes of the second group permit rapid motion of the cathode spot. These non-thermionic arcs were called high-field arcs by many authors. Discharges between iron, aluminum and other electrode are combinations of thermionic and high-field arcs.

Seeliger et al. (10) observed the transition of a glow discharge into an arc discharge while controlling the temperature of the cathode. The current at which the discharge changed from a glow discharge into an arc discharge was observed for various pressures range from 100 to 700 mm Hg, and arc lengths varying from 1 to 4 mm. By a suitable cooling arrangement it was possible to prevent the tungsten cathode from reaching a temperature necessary for thermionic emission and still obtain an arc discharge. A detailed computation shows that the cathode temperature can be kept at 100 C. The current density at the cathode of this new non-thermionic discharge between tungsten electrodes is of the order of 1^2 Ampere/cm^2, and a high-field arc obtained.

1.2.2. Arc Stability

The electrical behavior of the whole discharge is determined by the current-voltage relation

$$V = f(i) \qquad (1)$$

called the characteristic. V is the voltage drop across the electrodes, i the current. In the case of gas discharge, as in Figure 3 the circuit consists of an emf, E and a resistance R in series. The external circuit characteristic can be expressed as

$$E = V + Ri \qquad (3)$$

Where E is emf, R is resistance.

The non-linear curve in Figure 3 represent curve is internal characteristics and the straight lines 1, 2 and 3 are the external characteristics of electrical circuit for fixed E and varying R. The slopes of these lines are given by dV/di = -R. The possible values of current and voltage are the intersection points Z_0, Z_1, Z_2, Z_3. As R is decreased, the slope of the external characteristic turns counter clock-wise and the system traces the curves from Z_0 to Z_1. Reaching the point Z_1 the voltages suddenly drops and the system changes over to point Z_2. Starting at Z_2, however, it is possible to reach the point Z_3 by decreasing R. Between Z_1 and Z_3, however, the discharge

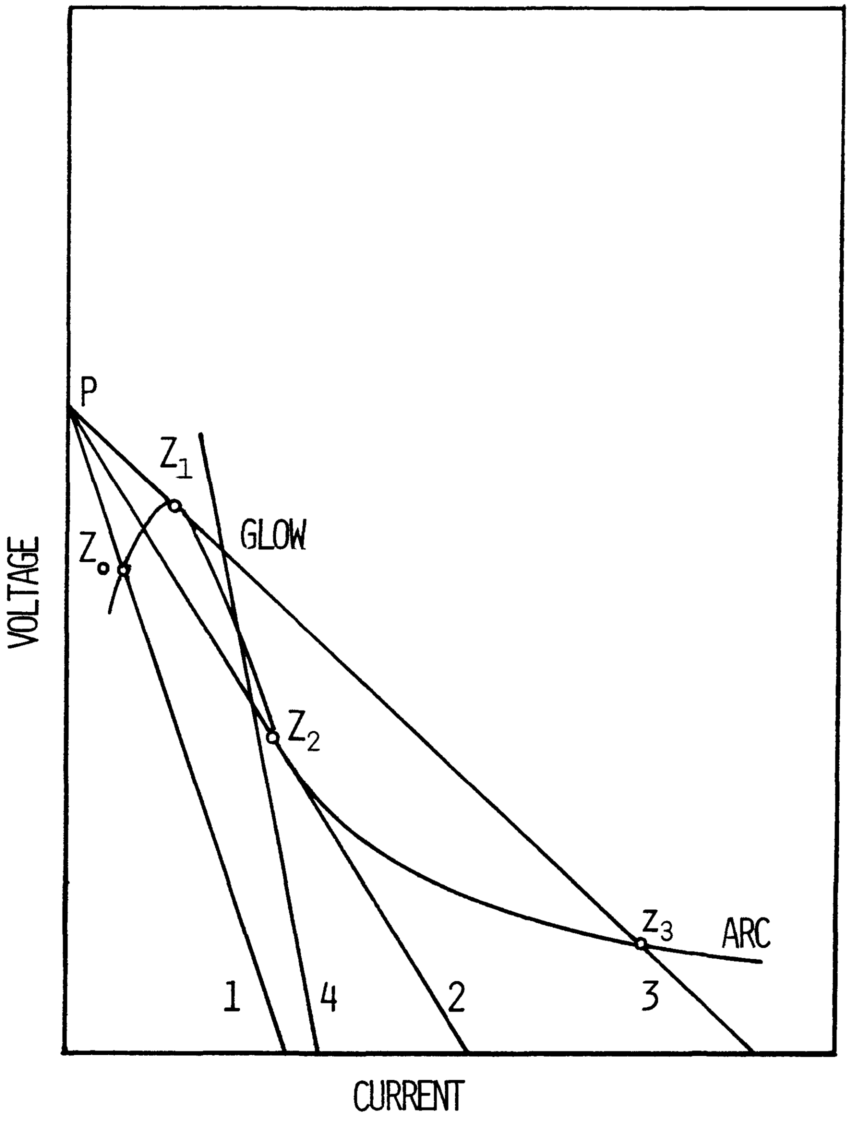


Figure 3

Transition between Glow Discharge and Arc Discharge (ref.4) Line 1, 2, 3, 4 are the external characteristics for fixed E and varying R. Z_0, Z_1, Z_2, Z_3 are intersection point of internal and external characteristics.

is unstable and the complete transition can not be obtained unless a large resistance is used such as shown by line 4. The condition for stability is that the external characteristic should be steeper than the internal characteristic, i.e.

$$- \frac{dV}{di} < R \tag{4}$$

Weisman (2) suggested that for helium and argon, the stability is achieved through the transition from the unstable excited stages to the stable ionized stage.

1.3 Arc Welding Process

Arc welding makes use of the high temperature, produced by the arc, to join the work pieces. The arc is due to the electric potential difference between the two electrodes for GMAW the filler metal and work piece, either one of which may be a cathode, the other one the anode. The voltage difference between the two electrodes drives the electrons from cathode to anode across the arc gap which is of a high resistance. The electric resistance of the arc gap produces a high temperature because of high kinetic energy of electrons, The high temperature melts the electrode and the work piece and joins them. So the electrodes serves not only as a conductor but also a metal filler in every kind of arc welding except the tungsten arc welding. In order to prevent oxygen and /or nitrogen pickup in the filled metal in the weld pool, the transmitted metal also needs a shielding gas, produced by decomposition of the coating of the electrodes or supplied externally to cover the molten puddle.

The main factors that affect the weld arc and metal transfer mode in inert-gas-shielded welding are arc voltage, arc length, current across the arc, as well as electro-magnetic, surface tension, and gravitional forces.

According to Muller, Greene and Rothschild (23), the longer the arc length the higher the arc current. However, arc length can be related to the loss of heat energy from radiation, resulting in a decrease of metal transfer rate with increasing arc length.

Further Muller et al. (23) consider the metal transfer below the transition current. In this case the liquid metal drop size is determined by the surface tension of material independent of the current density or electrode diameter. The liquid-solid interface moves back up the electrode as heat is applied. When sufficient metal is melted, the weight of the liquid and magnetic pinch effect causes a section adjacent to the liquid-solid interface to neck. Below the transition point, the magnetic force is insufficient to cause droplet detachment across the arc gap, and transfer occurs by gravity or other means.

Above the transition current the electro-magnetic pinching force become very large. Also, the surface of the wire tip probably reaches the boiling point before enough wire is melted to form a drop large enough to transfer by gravity ,etc. However, the more intense magnetic force present at high current is great enough to pinch off a small drop and then project it across the arc. This force is sufficient to project the drop vertically against gravity for a considerable distance when welding in the overhead position.

1.3.1. Welding Current: Electrode positive

Weisman (2) suggested that the area over which the current flows into the arc terminals (anode and cathode spots) has a strong effect on the arc configuration and on the flow of heat energy into these terminals .

Nishiguchi, and Matsunawa (15,16) shows the tip of electrode under the influence of high current with Figure 3. At high current levels, the tip of the electrode becomes tapered while at low current the electrode tip shows rounded end.

Furthermore, Pintard (26) also showthat the size of the droplet transferred in the arc is influenced by welding current as shown in Figure 5.

The axial spray transfer is unique not only because of its stability but because of the absence of spatter. Furthermore, the drops are transferred along the electrode axis rather than along the shortest path between the electrode and work pieces. The metal therefore can be directed where needed for making fillet, vertical or overhead welds.

The transition current is not fixed but is dependent on a number of parameters, including the electrode composition, diameter and extension. A great difference in transition current is found with various metal systems. For example, using equivalent conditions and a 1.6 mm (1/16 in). diameter electrode, the transition current for aluminum is approximately 170 A and for steel is approximately 275 A .

The key to spray transfer is so-called " pinch effect" which automatically squezes the drops off the electrode. This occurs as a result of electromagnetic effects.

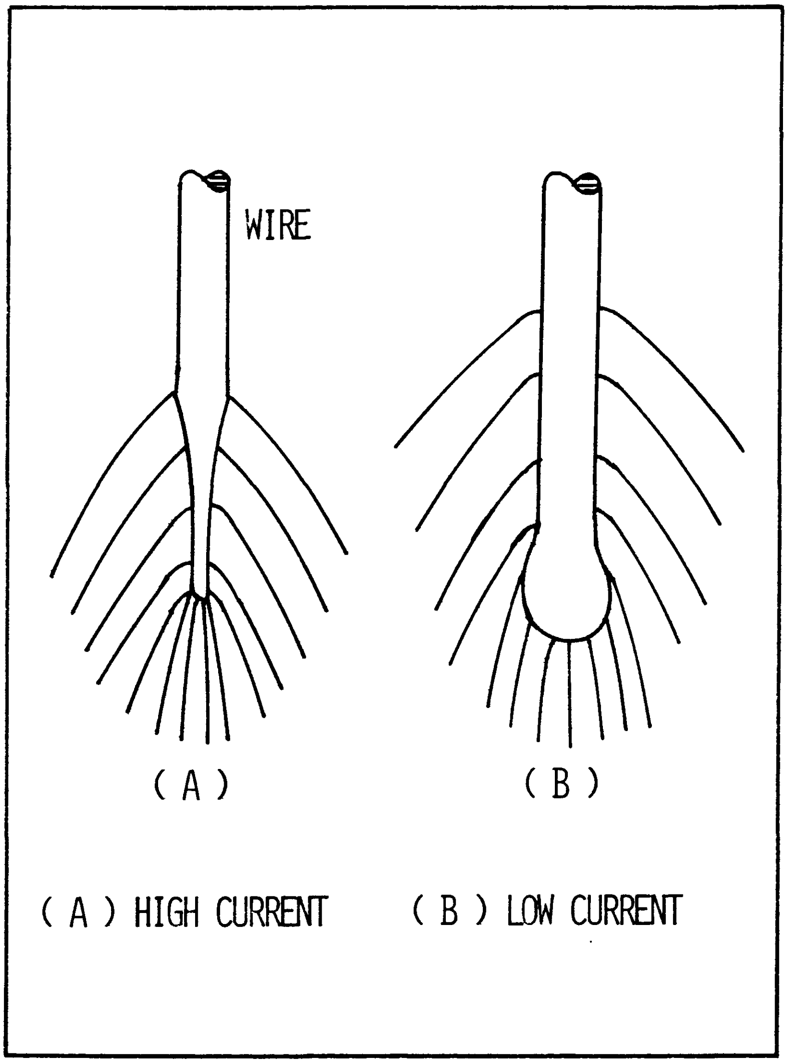
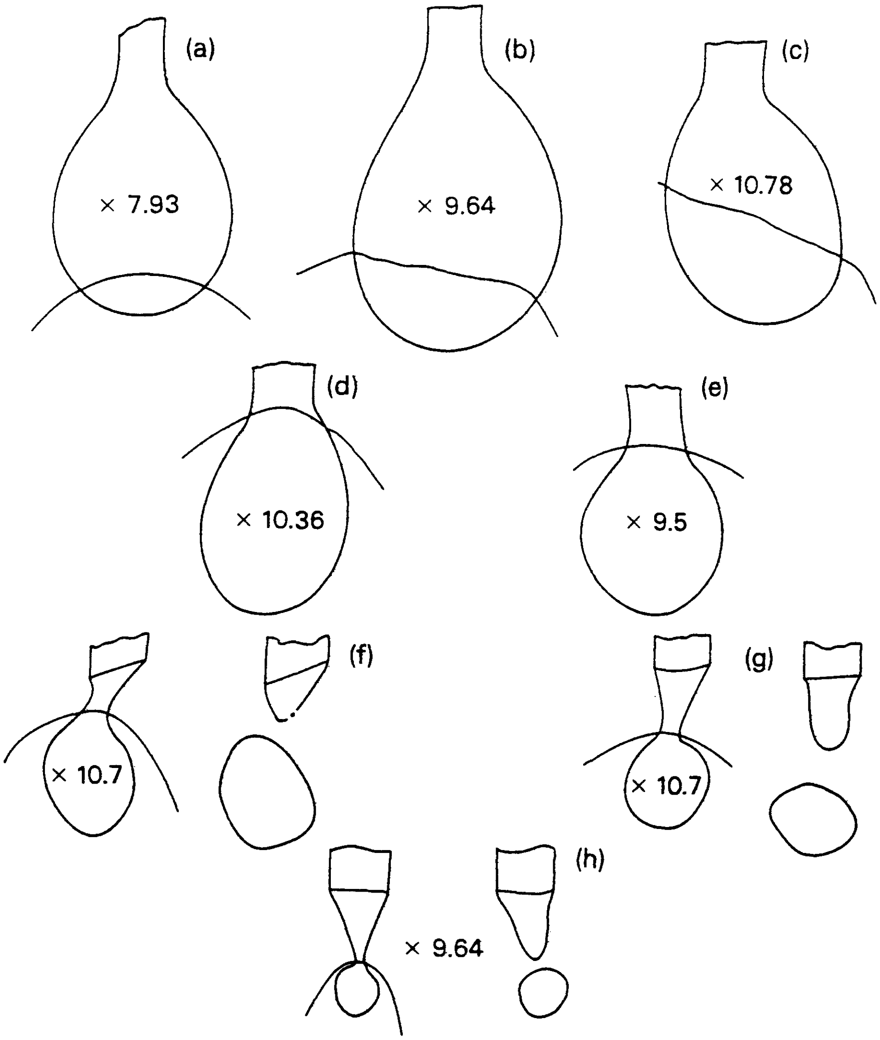


Figure 4

Effect of Current level on electrode tip and arc configuration (ref. 16)



(a) 60A, (b) 100A, (c) 120A, (d) 140A, (e) 160A,
(f) 190A, (g) 200A, (h) 220A. (Pintard 1966a)

Figure 5.

The molten droplet at the tip of 1.2 mm steel wire in GMAW immediately prior to transfer. 1.2 mm diameter steel wire in argon (Ref. 20)

The transfer current is almost directly proportional to the diameter of the electrode, rather than to its cross sectional area. Hence it is not dependent on some critical current density.

The transition current defines the lower limit of the useful current, and low current spray arcs can obtained with small diameter electrodes. The useful upper limit of welding current is defined by the initiation of a spatter-forming rotation of the arc and globules from the electrode tip; this has been termed "jet rotation". Table 1 shows the effect of electrode diameter on drop-to-spray metal transfer.

1.3.2. Extension

Figure 6 illustrates the influence of another less significant variables, the electrode extension. An increase in the extension allows a slight decrease in current at which spray transfer develops. However it affects the melting rate due to its electrical resistance heating effect. (see 1.3.5)

1.3.3. Welding Voltage

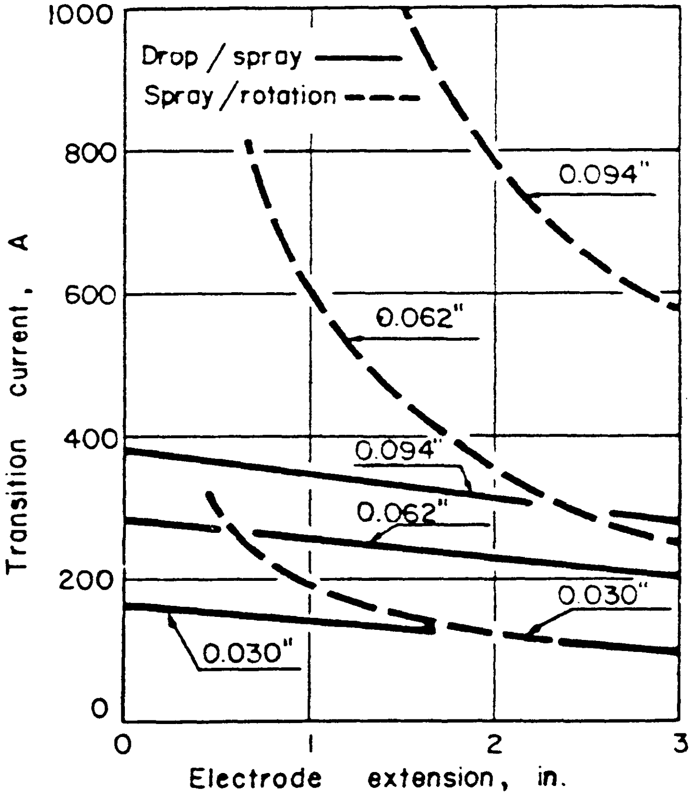
The welding voltage is composed of anode voltage E_a, cathode voltage E_c and plasma voltage. Weisman

Table 1

Approximate drop-to-spray metal transfer transition current (ref. 2)

Electrode diam	Steel Ar +2% 0_2	Aluminum Argon
0.030 in.	155±5	90±5
0.035 in.	170±10	95±5
0.045 in.	220±10	120±10
0.0625 (1/16) in.	275±20	170±15
0.094 (3/32) in.	370±25	----
0.8 mm	160±5	90±5
1.0 mm	185±10	100±5
1.2 mm	220±10	120±10
1.4 mm	235±15	130±10
1.6 mm	275±20	170±15
2.0 mm	310±20	----
2.4 mm	370±25	----

*The current varies with electrode extension, alloy content, shielding gas, etc.



mm	0.76	1.57	2.38	25	50	75
in.	0.030	0.062	0.094	1	2	3

Figure 6

Effect of Electrode extension and diameter on transition current (ref.2) conclude that the total potential of an arc falls with increasing current, then rises again with a further increase in current. Typical curves are shown in Figure 7. The decrease in total arc potential with increasing current can be attributed to an increase in thermal ionization and thermal induced electron emission at the arc cathode. The total potential of arcs generally increase as the spacing between the arc terminals increase. Because the column is continually losing charge carriers by radial migration to the cool boundary of the arc, lengthening the arc exposes more of the arc column to the cool boundary, imposing a great requirement on the charge carrier maintenance causing the arc potential to rise.

Furthermore, the voltage has been influenced by the electrical conductivity of the arc plasma. Jackson, (16,17) presents two diagrams that demonstrate the effect of different inert shielding gases on the characteristics of tungsten arcs with a molten titatium anode shown in Figures 9, 10.

1.3.4. Polarity

The GMAW process was developed largely as a technique to be used with electrode positive since the

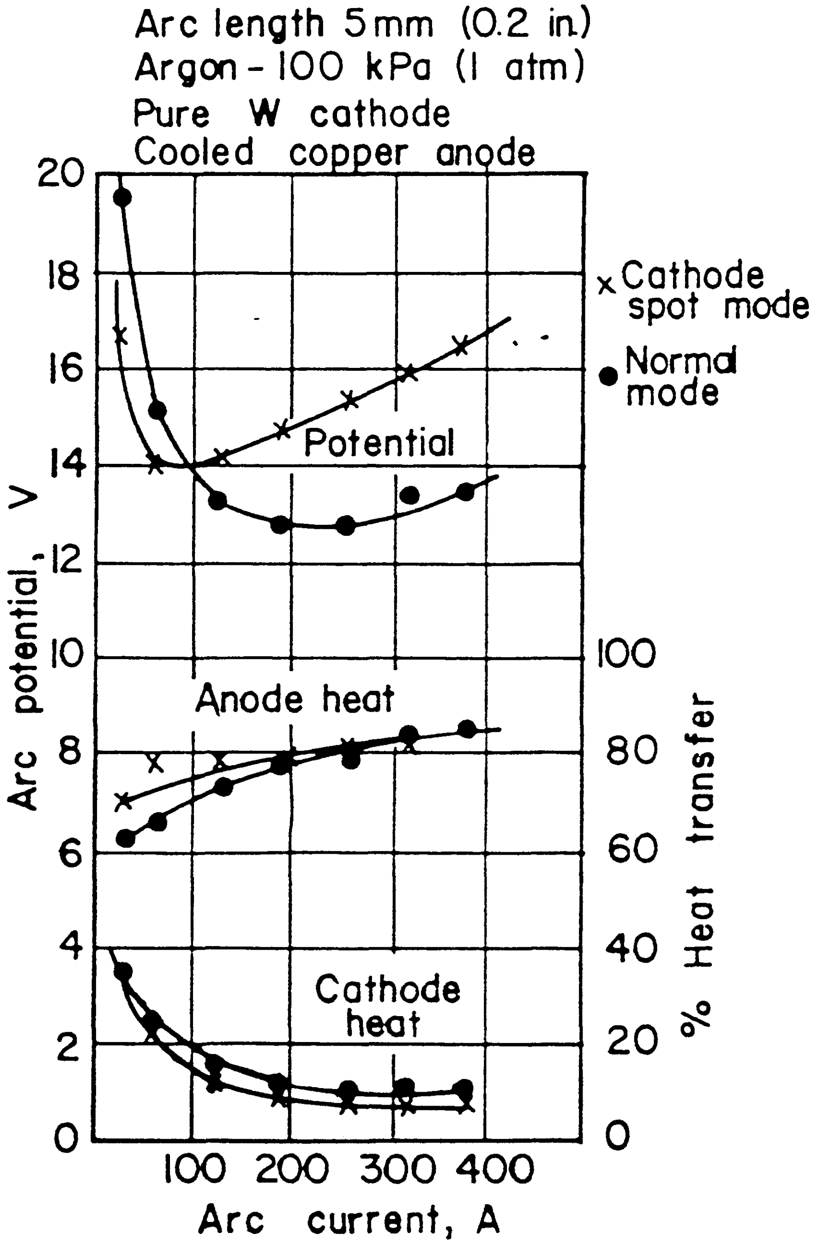


Figure 7

Typical volt-amper and percent heat transfer characteristic of an argon shielded tungsten arc (2)

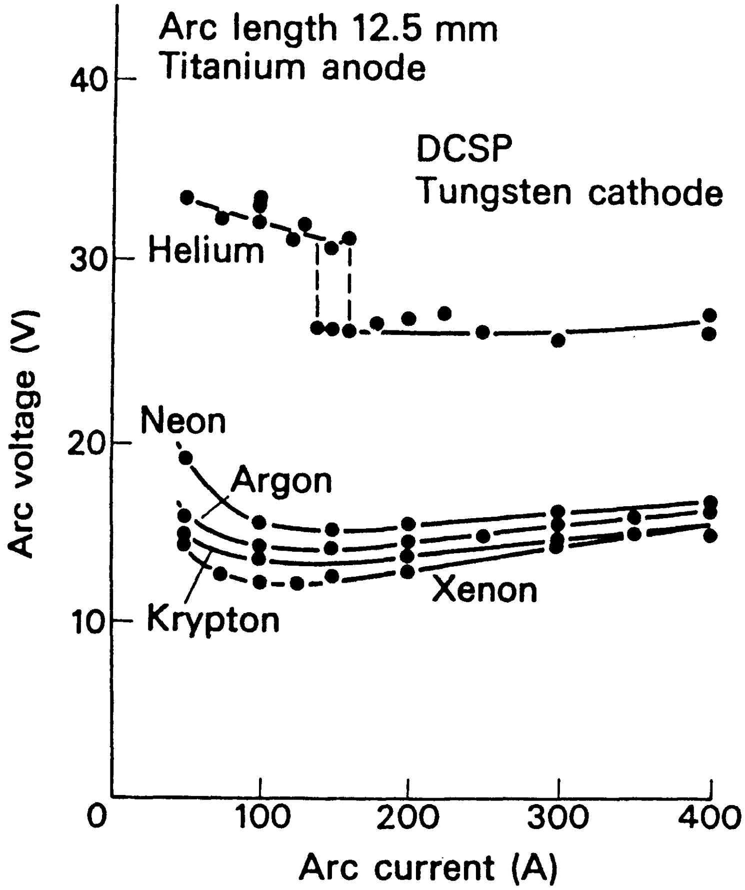


Figure 8

Effect of shielding gas on transfer arc voltage and current (Ref. 15)

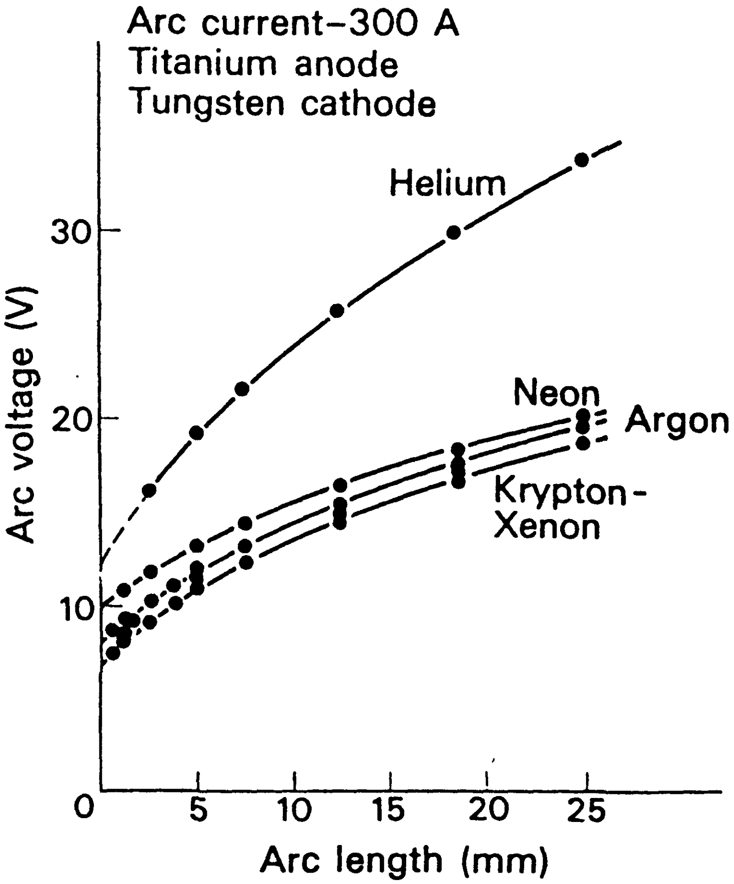


Figure 9

Voltage-Arc length characteristic for arcs in various gases (Ref. 16) arc becomes very unstable and spattery when electrode negative is used. The drop size with electrode negative is generally very large , and due to arc forces, the drops are often repelled away from the work pieces as spatter. This appears to be caused by the concentration of current on the cold cathode spot. A sufficiently thermionic cathode, however, will develop a spot diameter which reduces the drop size, and the arc becomes equivalent to that typical of reverse polarity.

A number of methods have been developed to increase the thermionic properties of electrodes. The earliest method used oxygen additions to argon to form thermionic iron oxides on the surfaces of steel wires. Although this solution was helpful for ferrous metals, it was ineffective for other alloys. With wash coating containing calcium and titanium oxide mixtures, the metal transfer and stability for steel electrodes becomes equivalent to those that had been associated only with reverse polarity. Monatomic films of alkali metals have been proven universally effective for improving the transfer of cold cathode metals. By depositing small quantities of cesium and rubidium compounds on the wire surface, metal transfer is also improved. These compound may also stabilize the alternating current arc.

1.3.5. Shielding Gas

According to the statement by Weisman (1), in the case of arc welding , arc starting and arc stability are greatly influenced by the ionization potentials of the metal and flux vapors as well as various electronic transitions that occur in the shielding gases under the extreme temperature conditions that exist in the arc. Easy arc initiation and subsequent stability of the arc are criticaly related to the minimum ionization potential of the elements in the arc atmosphere. The arc atmosphere consists of flux materials and metals in the vapor phase as well as gases introduced externally for shielding purposes. In the cases of helium and argon, the stability is achieved through the transition from the metastable excited stage to ionized state.

Although helium is inert, its melting effect are unlike argon because it does not usually produce an axial spray arc. Instead, the transfer is globular at all current levels and with both polarities. Helium shielded arcs are useful, nevertheless, because they provide deep penetration. Spray transfer is produced in helium by mixing relatively small quantity of argon with it. Using dilute mixtures, the deep penetration is not adversely changed. Although twenty percent argon in helium is sufficient to achieve these results, the normal commercial mixtures contain twenty five percent argon to include a factor. Active gases such as carbon dioxide and nitrogen are much like helium in their effects on the arc. Spray transfer can not be achieved without treatment of the electrode surface; besides, greater instabilities in the arc and chemical reactions between the gas and superheated metal drops cause considerable spatter.

These arcs are more difficult to control than those in argon, The modification of the cathode is possible to improve the transfer, the anode is not amenable to such changes. Arcs shielded with carbon dioxide have been improved greatly with the addition of alkali metal compounds (such as cesium and sodium) to the steel surface and spray transfer has been achieved. However, spray transfer is possible only with direct current electrode.

The relative degree of shielding required in welding various material or alloys will depend on relative oxidation rate of the metals oxides and the relative stability of the oxides.

The specific heats of the common gases are regarded as a measure of the ability of a gas to absorb or store heat. Table 2.10 shows that more energy is need to raise

Table 2

Physical Properities of some common Shielding Gases (ref.2)

Name of Gas	N_2	A	He	H_2	CO_2
Molecular weight	28.0134	39.948	4.0026	2.01594	44.011
Normal boiling point					
K	77.347	87.280	4.224	20.268	194.65
°C	−195.81	−185.88	−268.94	−252.89	−78.51
°F	−320.44	−302.57	−452.07	−423.19	−109.3
Density at 21.1 °C (70 °F), 1 atm:					
kg/m³	1.161	1.656	0.1667	0.0841	1.833
lb/ft³	0.07249	0.1034	0.01041	0.00525	0.1144
Specific volume at 21.1 °C (70 °F), 1 atm:					
m³/kg	0.8613	0.6039	5.999	11.89	0.5455
ft³/lb	13.79	9.671	96.06	190.5	8.741
Specific gravity at 21.1 °C (70 °F), 1 atm: (air = 1)	0.9676	1.380	0.1389	0.0700	1.527
Specific heat-const. pressure at 21.1 °C (70 °F), 1 atm:					
J/kg • K	1041	521.3	5192	1490	846.9
Btu/lb • °F	0.2487	0.1246	1.241	3.561	0.2024
Specific heat-const. volume at 21.1 °C (70 °F), 1 atm:					
J/kg • K	742.2	312.1	3861	1077	653.4
Btu/lb • °F	0.1774	0.0746	0.7448	2.575	0.1562

Note: Table 2.10 was prepared by the Cryogenic Data Center, National Bureau of Standards, Institute for Basic Standards, Boulder, Colorado 80302.

helium than argon to a given temperature. That means helium shielding gas will absorb more energy in the arc and release more energy in the workpiece than for argon.

When argon is used as a shielding gas the arc is stable and the heat produced is fairly uniform despite changes in the arc length. Although argon is inert, because of its large atomic diameter, it is easier than helium to ionize. The ease with which argon is ionized is an aid to arc starting, however, the temperature and heat produced are lower with argon than with other gases. The low thermal conductivity of the gas results in a high concentration of heat and deep pentration.

Argon is a denser gas and is heavier than air. Therefore, as argon flows out , it easily replaces the air around the weld. The density of argon also helps it to better withstand drafts, although gas coverage may be inadequate if the air velocity exceeds one mile per hour.

Argon or argon-rich gas mixture are necessary to shield the arc in spray transfer.

The helium atom is small and it has high electrical resistance. The voltage require to produce an arc in helium is higher than other gases, resulting in a hotter arc with higher temperature. The resistance is greatly affected by changes in arc length affecting the heat and temperature. The high heat and temperature make helium an excellent gas for thick, high conductive metals because high travel speeds can be reduced. The major drawback of helium as a shielding gas is its highly changeable heat.

Argon or argon- helium mixtures are used when joining reactive metals such as aluminum, titanium and magnesium. However, when welding ferrous metals small addition of oxygen or carbon dioxide are needed to to prevent undercut irregular welds.

An oxidizing gas, such as oxygen or carbon dioxide, will form oxides on the wire surface that affect the electrode thermionic properties. This means the electric conductivity of arc atomsphere will increase, that also increases the arc current.

The use of carbon dioxide is limited to steels which can be properly alloyed to tolerate an oxidizing atmosphere and to steel which do not have to be essentially free of carbon as, for example, low carbon stainless steels.

Jackson (16,17) also indicates the shielding gas affects the voltage-current characteristics for comsumable-electrode inert-gas arc welding with various gases as shown in Figure 10.

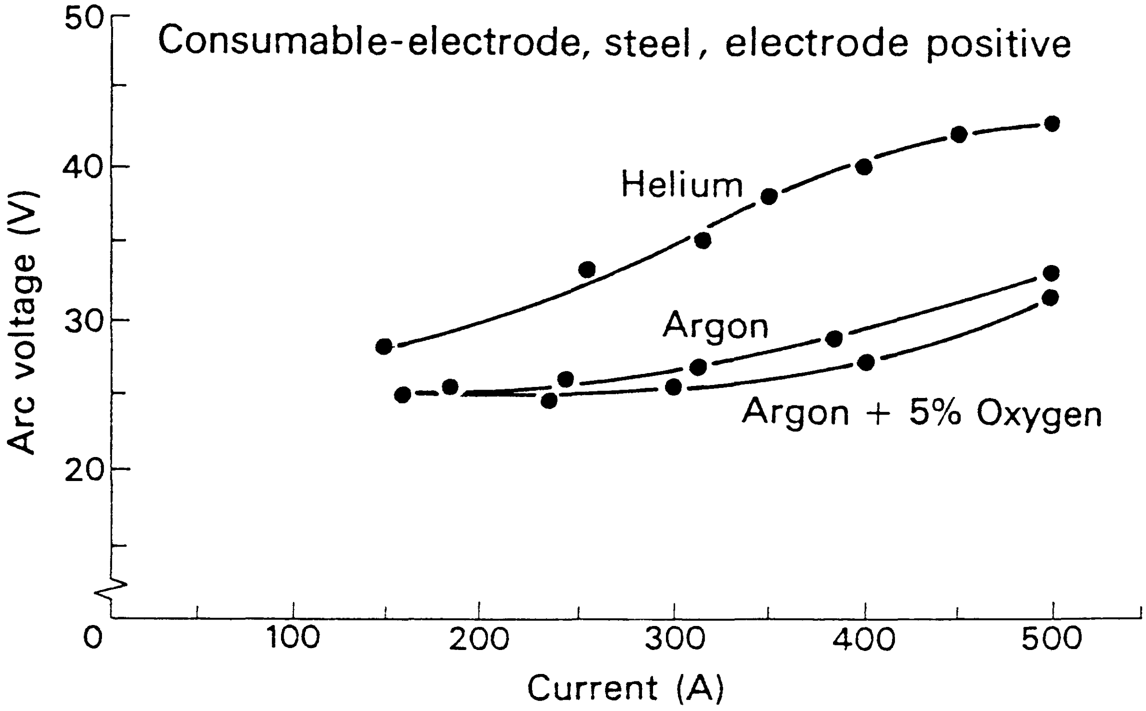


Figure 10

Voltage-Current characteristics for Gas metal arc welding with different shielding gases (ref.17)

An arc in 100 percent nitrogen is much higher in temperature than an arc in 100 percent argon. Arc instability has limited the use of pure nitrogen as a shielding gas, but it is used as a mixture with argon. Adding nitrogen to argon increases the arc temperature and heat in much the same way as in the argon helium mixture.

Although several parameters are involved in promoting spray transfer, the arc plasma developed through the choice of arc shielding gas is of primary importance. Weisman (2) indicated that a transfer observed in the argon shielded consumable electrode arc may not be obtained with some other gases. Not all gas consumable electrode welding arcs exhibit axial metal spray transfer. It appears that only a gas shield composed predominantly of argon provides the unique plasma properties with the self magnetic force to develop axial spray transfer through the arc . Only in argon does current conduction occur over the whole metal droplet surface, through the bell-shaped plasma. If special current is conducted out of the underside of the molten metal drop, through the plasma, magnetic force are developed that may oppose metal transfer through the arc, thus preventing axial spray transfer. This suggests that the plasma properties of argon develop gases conduction which promotes a magnetic force field conducive to axial spray transfer.

1.3.6. Welding Power Source Characteristics

Actually, CP power sources used in GMAW constant potential, do not generate perfectly constant voltage. The graph presented by Jeffus and Johnson (1) is shown in Figure 11. The graph shows that there is a slight decrease in voltage as the amperage increase. The rate of voltage decrease per 100 Ampere increase is known as slope. So the slope given in Figure 11 is said to be twenty. The machine slope is affected by circuit resistance including the resistance of leads, and connectors. A higher resistance means a steeper slope. As the slope increases, both the short circuit current and pinch effect are reduced. A flat slope has both an increased short circuit current and a greater pinch effect.

The machine slope affects the short-circuiting metal transfer mode more than it does the other modes. Too much current and pinch effect form a flat slope causing a violent short and arc restart cycle, which results in increased spatter. Too low current and pinch effect from a steep slope will result in an erratic short circuit pattern as insufficent energy is available for arc reignition.

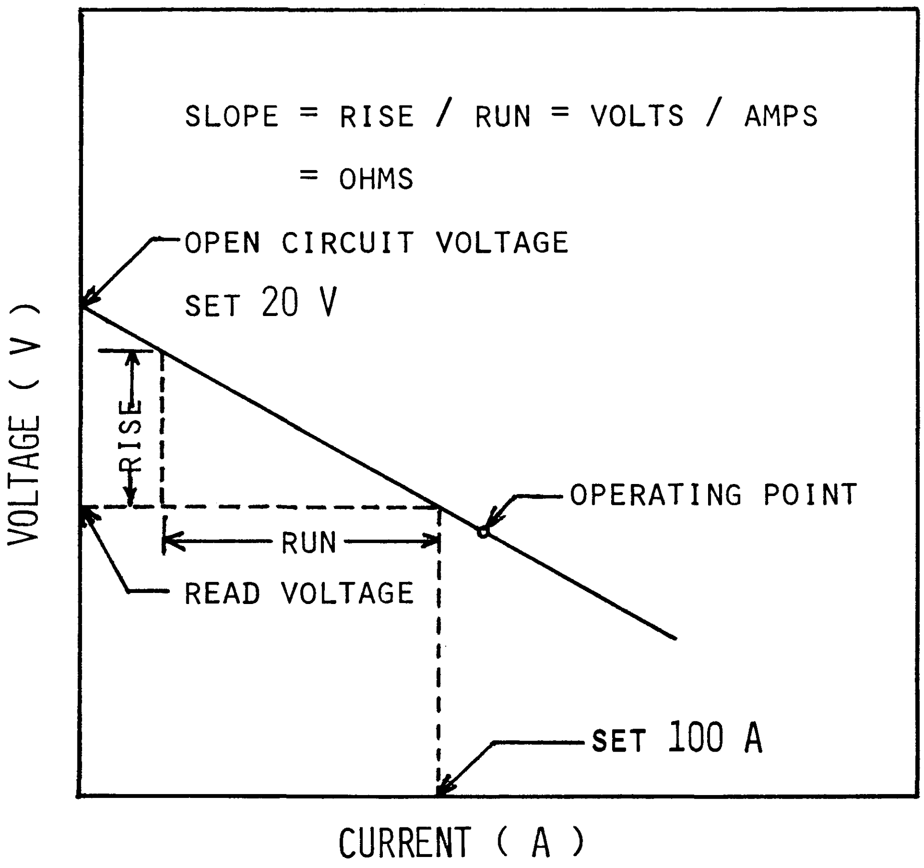


Figure 11

Welding power supply characteristic curve, illustrating the slope calculation (Ref.1 and 21)

The slope can be adjusted for some machines to obtain a proper spatter- free metal transfer. However, for other machines without this adjustable function, the same goal may be achieved by adjusting the distance between the contact tube and work piece to give the circuit resistance or the slope that will cause a smoother short circuiting with less spatter.

Change in inductance (time or rate of current change on the time lag between an increase in load and the rise of current to that of new load level) affects the pinch effect in short circuiting transfer and starting of axial spray transfer. Manz (21) indicated that the Volt-Ampere curve, as in Figure 11 is normally used to represent the static output characteristic of a power supply for gas-metal-arc welding The slant of the curve is referred to as a gas-metal-arc unit. The slant of the curve is referred to as the " slope " of the power supply and has the dimensions of resistance as defined as eq.(5)

$$\text{Slope} = (\text{ rise / run }) = (\text{ Volt/Ampere }) = \text{Ohms} \qquad (5)$$

Eq. (5) states that slope is equivalent to an impedaence. In a welding system slope would be best measured at the arc. That means anything which adds impedence to the welding system adds slopes. Power cables connections, loose terminals, dirty contacts, etc. add to the slope. The rectifier forward voltage drop of transform impedence also contribute to the slope. Furthermore, the conductance of plasma, due to the ionization of shielding gas, must affect the slope although to a lesser degree.

Not all Volt-Ampere curves are straight lines. Many of them have inflections as shown in Figure 12. The slope of the Voltage-Ampere curve of Figure 12 is referred to as the slant of the curve measured about the probable operating point. The slope is different at all three point A,B and C. The line descriped by eq. (6) is used by NEMA,

$$E = 20 + 0.04\ I \tag{6}$$

Where E is potential (V), I is Current (A).For convenience, the slope of a Volt-Ampere curve is designated by its slant at point B is usually used to define the slope of the power supply because it represents the most probable operating condition.

For short-circuiting transfer, an increase in inductance means a reduced current surge. Figure 14 shows that the effect inductance of a welding machine causing a slower rate on the pinch effect. This action has a "calming" effect that reduces spattering due to a violent arc restart. Unlike slope, however, induction does not

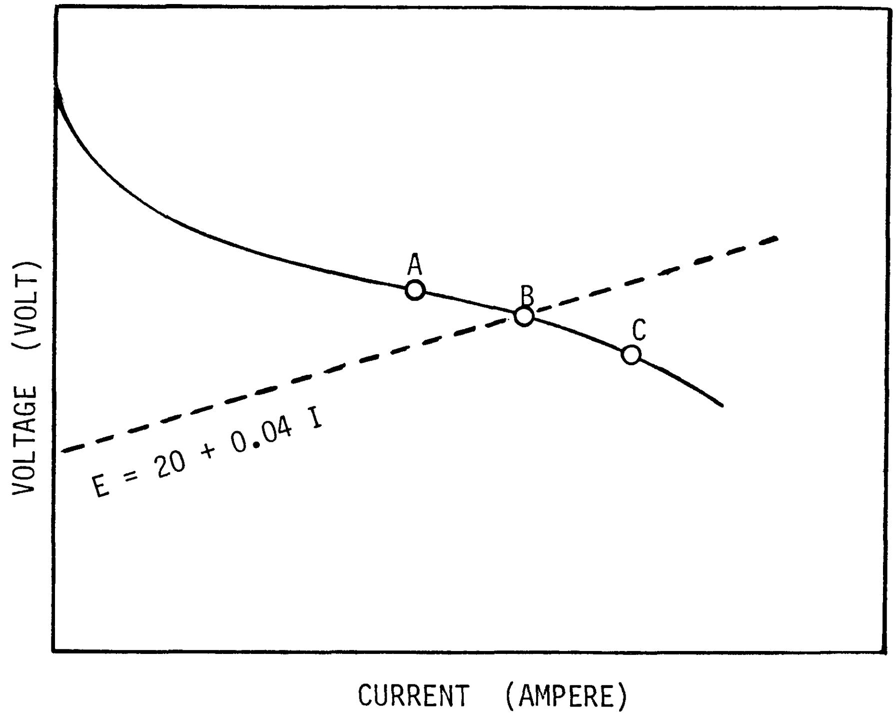


Figure 12

Definition of the operating point is defined as the intersection of operating curve and the equation $E = 20 + 0.04\ I$. The slope of machine is defined as the slope of the operating curve at the operating point (Ref. 21) reduce the arc length. As a result, the arc is stronger and lasts longer, producing deeper penetration and a more fluid puddle. Increased inductance reduces spatter and makes the start of axial spray smoother. Too high an inductance may cause the electrode to short or stub during starting.

1.3.7. Melting Rate

The heat in an arc is generated at the anode cathode regions and within the plasma. Portions of this energy will melt the electrodes which support the arc unless they are adequately cooled. Comparatively, substantially more heating is released from the cathode. Furthermore, Weisman (2) suggested that when the electrode is the cathode terminal, considerable control of the energy release is possible. while, Little can be done about the release of energy at the anode, which is related mostly to the current magnititude and less to composition and other factors.

Thermionic metals, such as tungsten and molybdenum, having very high melting points, and can easily supply electrons to sustain the arc On. the other hand, the cold cathode accompanied by a lower heating energy due to some coating of oxide or alkali metal surface film, will have

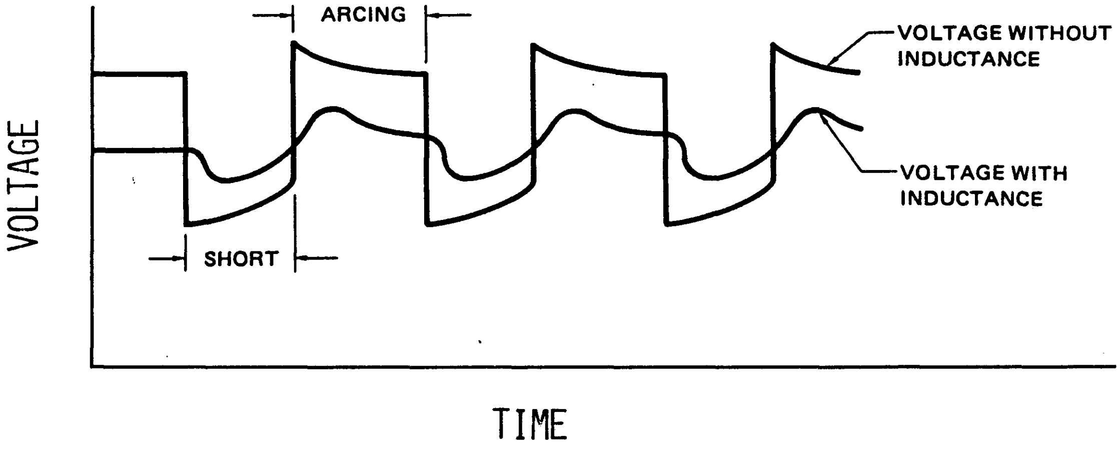


Figure 13

Effect of inductance on arc voltage in welding (Ref. 16) a lower thermionic temperature, thence , have a lower melting rate. Therefore the melting rate can only be modified directly by current or cathode heating, but not by the shielding gas or flux or the arc length.

In addition, the electrical resistance heating of the extension of the small diameter electrode affects the melting rate of electrodes also. So the melting rate can be written simply as

$$MR = a\ I + b\ L\ I^2 \tag{7}$$

Where MR is the melting rate, "a" is the proportionality constant for anode or cathode heating. Its magnititude is dependent upon polarity, composition, and, with direct current electrode negative, the emissivity of the cathode. "b" is the constant of porportionality for electrical resistance heating and includes the electrodes resistivity. "L" is the electrode extention or stick-out. "I" is the welding current.

Arc power is not a term in this equation, nor is it essential since the plasma drop at the work are not part of the relationship affecting melting rate.

1.3.8 Drop Rate and Size

According to Jackson (16) , the important factors that control drop rate and size are current, electrode diameter and extention, and shielding gas. The larger drop transfer mode changes to small drops in argon and argon with 5 percent oxygen was as Table 3.

The current ranges suggest that drop size is influenced by surface tension and pinch forces which oppose each other. When the pinch force exceeds the surface tension, small drops are formed. And the result of calculation (table 4) shows that when the order of magnititude of pinch force become the same as that of tension force the drop rate increases rapidly. The drop size in gas metal arc welding is in the range of 1.27 mm to 3.81 mm (0.05 inch to 0.15 inch).

1.3.9. Metal Transfer Mode in GMAW

The three basic modes(1) of metal transfer in GMA welding are short-circuiting arc metal transfer, globular transfer, and axial spray transfer. The three basic modes have their own range of welding voltage, current densities, metal transfer rates, welding transfer rates, welding conditions, weld positions, and welding

Table 3

The condition of electrode diameter and current for drop size reduction (Ref. 2)

Electrode Diameter, inches	mm	Current Range, Amperes
1/16	1.56	200-250
3/32	2.06	300-350
1/8	3.13	350-500

Table 4

THe composition of surface tension force and pinch force (Ref.2)

Electrode diameter	Surface tension force, dynes	Pinch force, dynes
1/16	420	250
3/32	630	530
1/8	840	1000

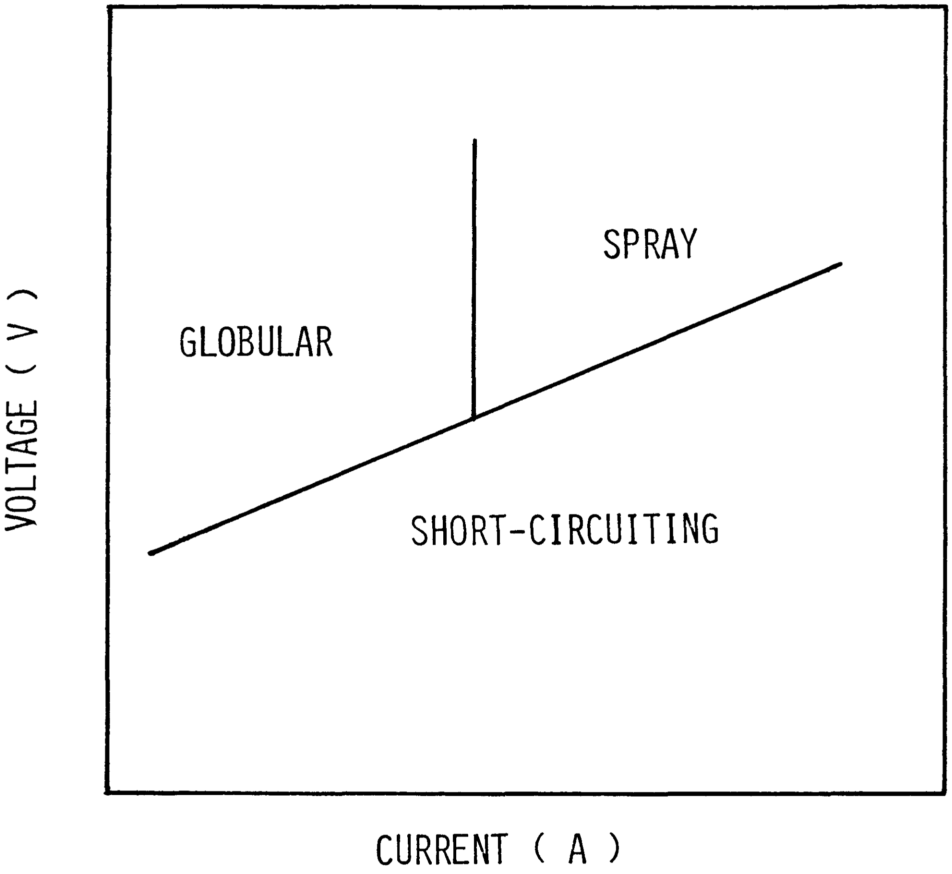


Figure 14

Metal transfer modes as function of arc voltage and current manipulation techniques. Figure 18 illustrates the distribution area in the current-voltage diagram.

1.3.9.1. Short-Circuiting Arc

The short-circuiting transfer mode has the lowest power or current density of the three basic modes of transfer. Whenever the voltage is low, only the short circuiting metal transfer mode can occur. Small weld puddle sizes and easily controlled weld beads make this an all-position process. When the current is low the metal transfer occurs during intervals of controlled short circuits at rates in generally excess of 50 per second. In this condition the short circuiting arc can be used to weld thin sections This process has the advantage of being very easy to use. Unfortunately when the energy input is low, incomplete fusion and reduced peneration can be a problem in sections thicker than 6 mm. The lower power density (small ratio of power to metal deposited) results in lower deposition rate.

GMAW short-circuting transfer is the result of an intermittent cycle of establishing and extinguishing an arc. With molten drops of metal transferred across the arc column. This direct metal transfer reduces both the time that the molten metal is exposed to contaminants reducing. the possibility of atmospheric contamination. The metal transfer itself starts with an arc between the wire and base metal. Figure 16 (a) that shows the arc melts a small spot on both the surface of the loss metal and the filler electrode. As the wire is being fed the arc length is shortened until the molten spot on the wire is forced into the small molten spot on the base metal. Figure 16 (b) shows the instant at which the arc is extinguished. This results in a surge of current that melts further the electrode. In Figures 16 (c) and (d), according to electromagnetic theories, the magnetic force around the wire pinches the melted wire. The combination of the brief high current flow and slightly higher rebound voltage melts the end of the wire quickly and depositing the droplet Figures 16 (e) shows the cycle starts over again. Depending upon these factors, the frequency can range from as few as twenty cycles a second to more than 200 cycles a second. It is important when using short circuity welding to direct as much heat as possible on to the base metal. The mainpulation pattern and the position of the electrode with relation to the puddle are important. The metal transfer become is erratic and spatter is increased if the arc is directed toward the plate ahead of the puddle. The spatter is due to the

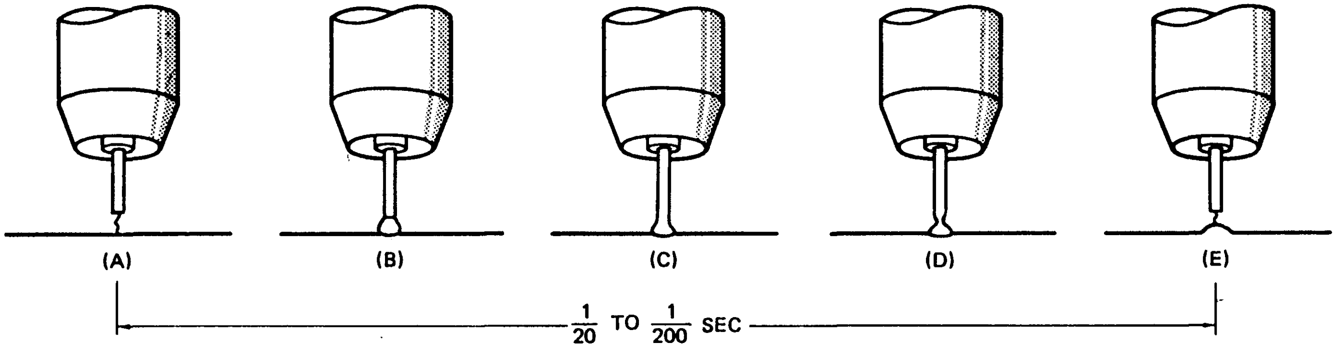


Figure 15

GMAW short-circuit arc metal transfer (Ref. 1) evaporation of molten metal with an explosive increase of volume, which makes the liquid metal splash outward.

1.3.9.2. Globular Metal Transfer

Globular metal transfer is a medium power transfe mode. This power range results in a fluidmolten pool deeply and penetrating weld. A weld penetration of 100 percent can be achieved in 3mm (1/8) inch thick, mild steel plate square butt joint. Thick sections are easily welded and have good fusion. The weld bead size and fluidity , however, reduce its ability to be used for out-of-position welding. However, this transfer mode can be used on lower power setting for some inclined or vertical welds and for a few horizontal joints, such as laps and tees.

The metal is transferred as globules, of size larger than the diameter of the electrode . Before detachment, the molten metal is held on the electrode by surface tension. The lower the metal density, the larger the globule can be formed before the globule falls.

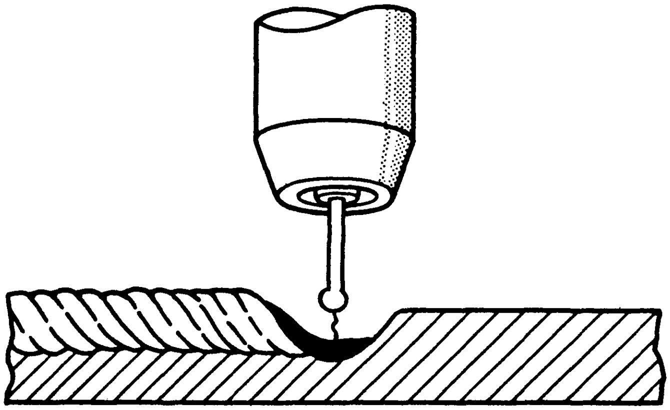
A higher voltage-to-low vapor pressure ratio is required for the arc to melt the electrode to form the globule. The arc must keep the electrode melting as fast as the wire is fed out in order to maintain the arc length. Change in the power setting will affect the arc length and the rate at which the globules are transferred. High rates of transfer will have a smooth, static sound that is similar to the sound of ripping cloth.

The arc length can be so short that it is actually below the puddle surface where the force of the arc will create a small crater and is known as buried arc globular transfer, as shown in Figures 16.

This method of globular transfer gives deeper penetration with less spatter.

1.3.9.3. Spray Metal Transfer

When both welding current and voltage are high, metal transfer in argon or argon-rich gas in generally a spray mode. At high welding voltage the arc length is long and the melted drop transfers by globular or spray mode. However, at the critical welding current (transition current), electromagnetic force exerts a pinch force to cause necking at a region close to the molten droplet. The high current density at the neck may also cause metal vaporization and the gas pushes the melted drop away from the electrode. Furthermore, Weisman (2) mentioned



Figures 16

Buried arc globular metal transfer (Ref. 1) that only argon has the plasma properties (thermal conductivity, mobility, etc.) thatpromotes the vectorial magnetic force field conducive to axial spray transfer.

Since it is free from spatter and short-circuits, spray transfer is quiet and stable.

1.3.10. The Stability of Metal Transfer in GMAW

Manz(17) suggested that spatter in GMAW occurs when the the electrode short circuits the workpiece and the molten liquid column is broken by pinch force. The pinch force is caused by an electromagnetic constriction set up by the current flowing in the circuit. When the short circuit current is not limited by the machine slope or inductance, the current will surge to very high levels and causes will generate a large pinch force. The molten metal bridge cannot carry such a high current and acts as a fuse that vaporizes. The volume expansion squeezes the metal aside and breaks the bridge. At this instant most welding spatter is created and irregular metal transfer occurs.

Jeffus et al (1) proposed an acceptable stable operational range for gas metal arc welding as shown in Figure 17. The acceptable welds should be the area between those two lines indicated. As current increases, voltage

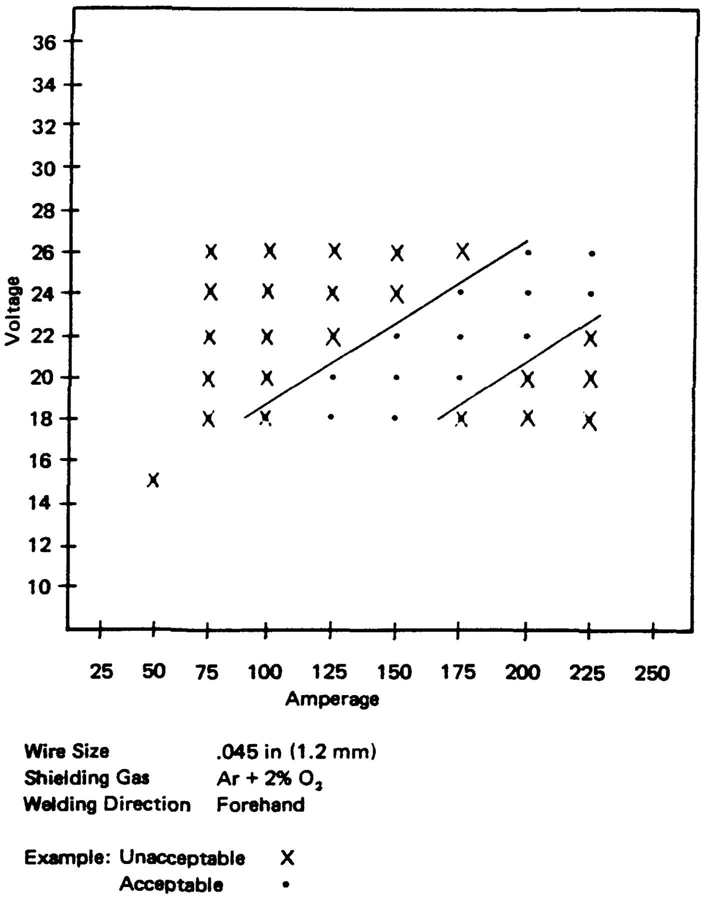


Figure 17

Welding Voltage and Current Data for GMAW with Argon Oxygen Shielding Gas (Ref. 1) also needs to be increased in order to obtain stable operation.

When the load changes on a power supply, the current takes a finite time to attain its new level. The circuit parameter which is mainly responsible for such a time lag is the inductance. The effect of inductance can be illustrated by analyzing a transient response curve. The solid line in Figure 19 shows a typical current-time curve as the current rise from zero to a final value. The broken line shows the path which the current would have taken if there was no inductance in the circuit.

The shape and height of the solid curve in Figure 19 is due to the effect of the total circuit inductance L as well as its resistance R (slope). The ratio of total circuit inductance and resistance is called L/R ratio or " circuit time constant" and represented by the symbol T.

The time constant is one of the criteria used to judge the stability of metal transfer in GMAW. Time constant is the period of time it takes for the current to reach 63 percent of its final value. The time constant can be changed by adjusting the value of either inductance or equivalent slope resistance. Making L larger or R smaller will increase the time constance and cause the current to take longer to reach steady state. However, it is more

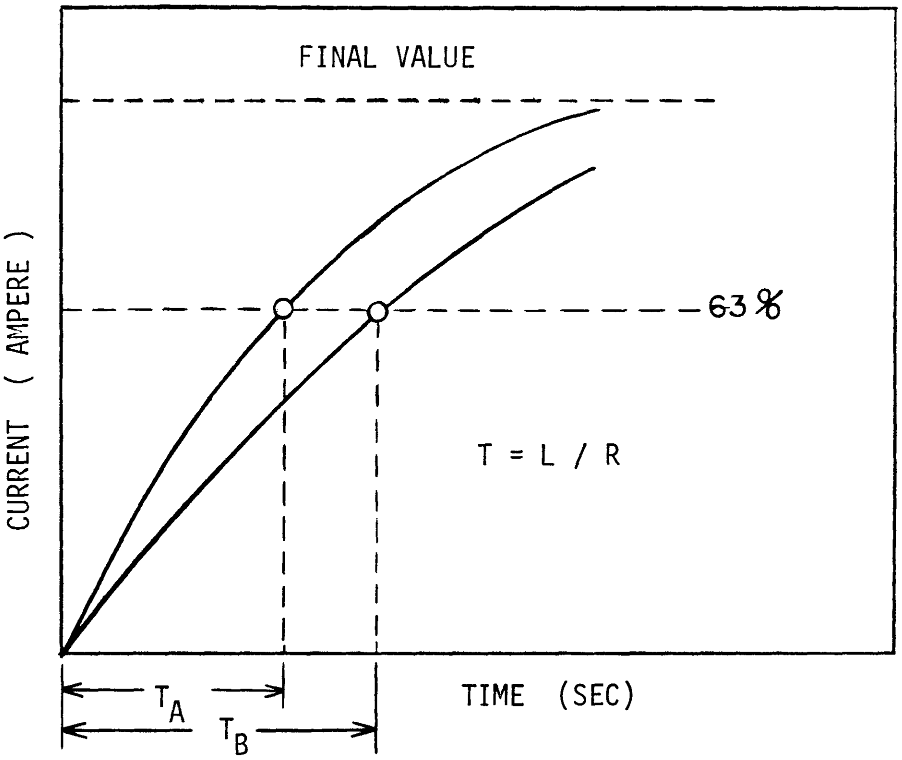


Figure 18

Definition of time constant of a power supply with inductance (Ref. 21) convenient to use inductance instead of slope.

Kolasa et al (19) proposed the criteria for good performance of GMAW by evaluating the dynamic properties of power supplies. They suggested the following conditions for will produce good GMAW performance.

(1) The time constant T_c of power supply short circuit current waveform (short circuit from open circuit or resistance load) should be set within the range : $5ms \leq T_c \leq 15$ ms for the whole range of welding parameter adjustment.

(2) The minimum mean value of voltage amplitude ripple in power source output waveform should not be less than 12 volts.

(3) A stable power supply should provide a short-circuit current peak value not less than 2.5 times of average welding current.

Furthermore, Liu and Siewert (25) together have clarified the influence of welding parameters on the metal transfer behavior by means of a droplet-rate isopleths map, shown in Figure 20.

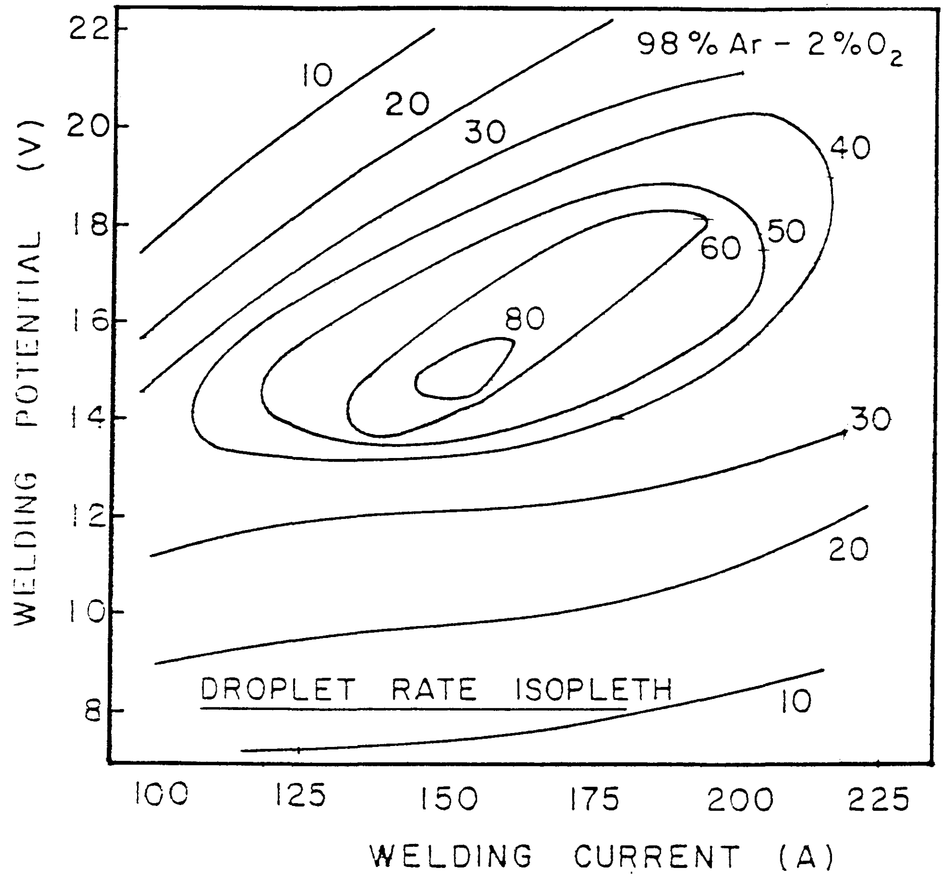


Figure 19

Droplet Rate Isopleths determined for Ar-O_2 short circuiting welding with 1.6 mm (1/16 inch) diameter steel electrode. (Ref. 25)

This diagram shows that in short circuiting welding a high droplet rate area always produce a stable performance welding condition. When current is kept constant and the voltage is increasing, droplet rate increases to a given high value and then decreases. A similar phenomenon of increasing and decreasing droplet rate with current, at constant voltage, is also observed.

2. EXPERIMENTAL PROCEDURE

1.2mm diameter E70s-3 electrode was used in this experiment. The shielding gas was a mixture of 25 percent CO_2 and 75 percent Ar at a flow rate of 1.0 m^3/hr (35 ft^3/hr). A direct current welding machine was used for the power supply. The direct current from the welding machine was regulated by a DC transistor current regulator, shown in Figure 20, which smoothed out the fluctuations of the rectified direct current and stabilized the voltage. The electrode extension was fixed at 15.8 mm (5/8 inch).

The test matrix covered a wide range of voltage and current settings, which are shown in Figure 21. The current range was from 70 to 370 Amperes and voltage was from 16 to 40 Volts. A total of 79 welds were conducted in this work.

For each of the voltage and wire speed settings, there was a corresponding pair of current and voltage welding condition. The actual current and voltage were monitored and recorded with a Nicolet high speed digital oscilloscope, shown in Figure 20.

A high speed video (Figure 22) was used to record

Figure 20

300 / 600 Ampere DC transistor current regulator and high speed digital oscillogram used in this research.

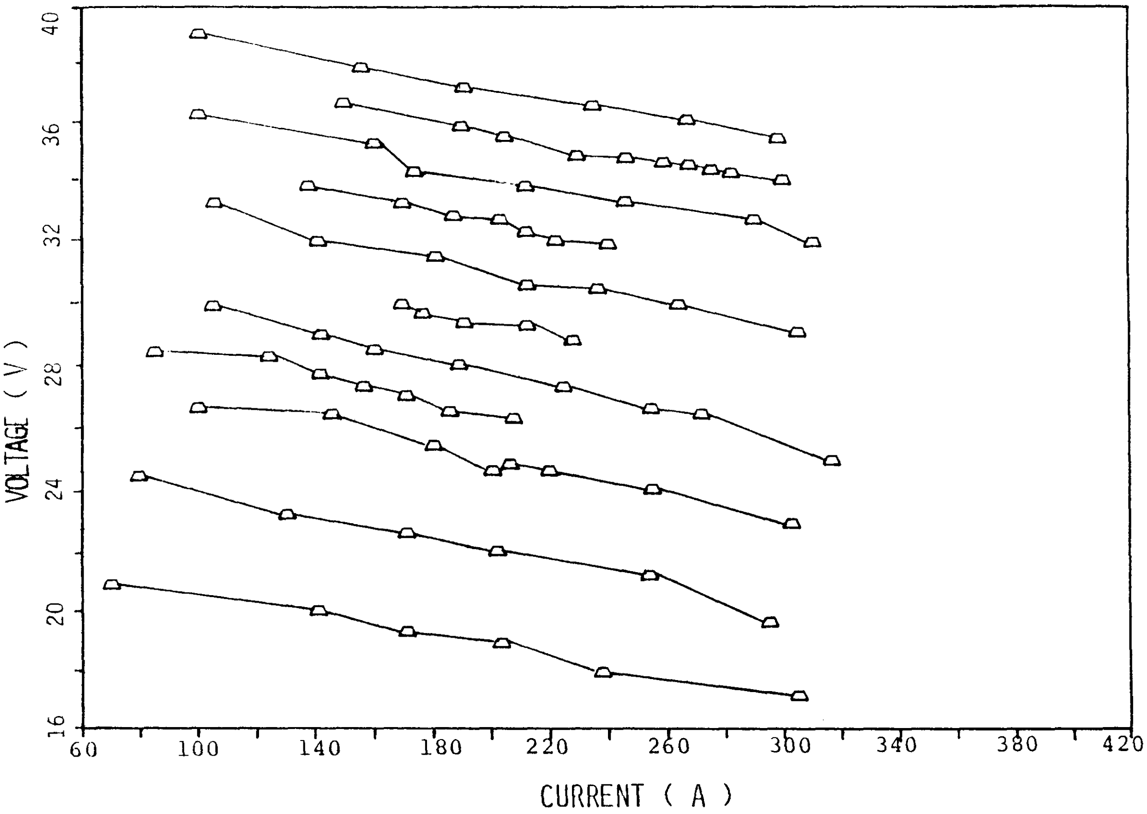


Figure 21

Welding Current and Voltage pair

used in this research

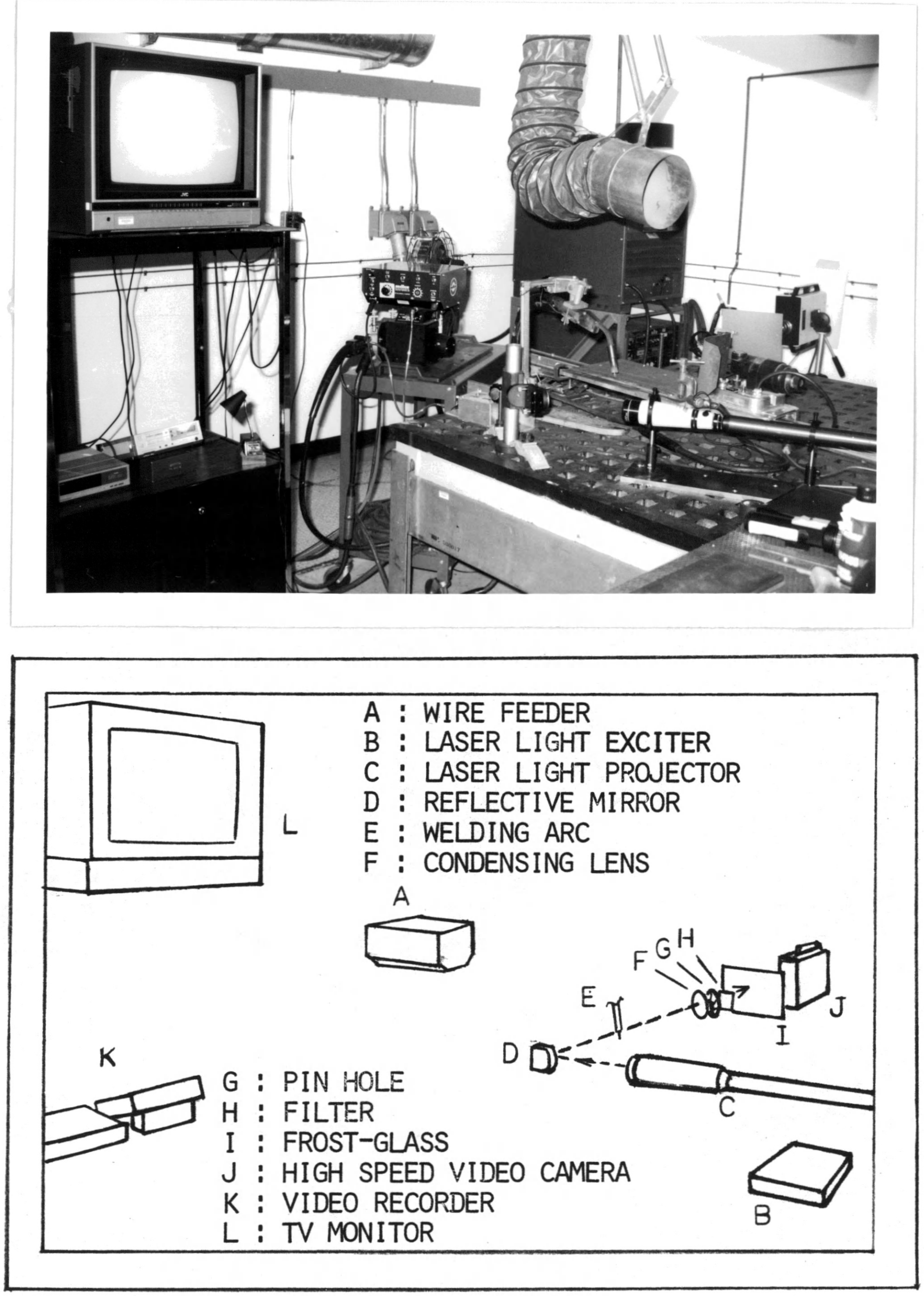


Figure 22

Laser light used to study the metal droplet transfer in a GMA welding arc the welding arc and metal transfer concurrent with oscilloscope observations . The laser light used in this study is a intense Helium-Neon light with a power of 10 mW and wavelength of 632.8 nm produced by a laser light exciter and projector (Model no. Spectra-Physics Model 106-1). The intense laser beam was emitted from a projector hitting a reflective mirror, crossing through the welding arc and passing through a series of optical accesories before reaching the camera. Then, the silhouette of the metal transfer and welding arc from the laser beam is displayed on a piece of frosted glass which is captured by the high speed video camera. The feature of instant replay of the metal transfer and arc was important in the correlation of process variables and the metal transfer mode.

Figure 23 shows a typical oscillogram of a 295 Ampere and 19.6 Volt welding arc. The upper and lower curves describe the instantaneous voltage and current, respectively. The differences between the voltage peak and valley are called the voltage variation (Δ V). The stability of metal transfer in arc welding was related to the voltage variation which was depicted by the oscillogram. From the weld current and voltage recording, the effects of current and voltage on droplet transfer

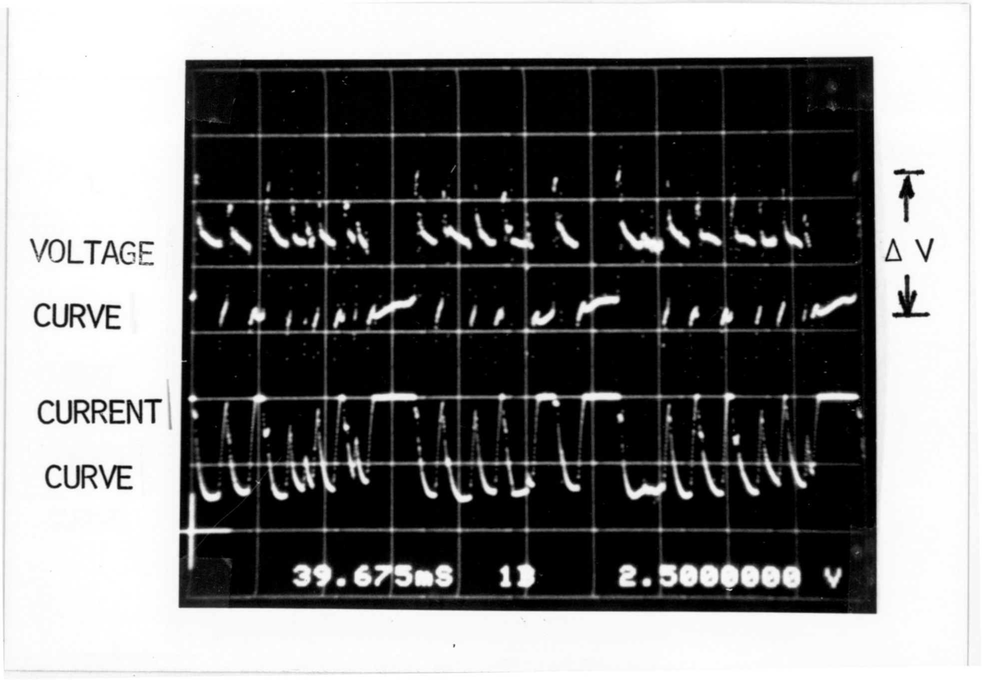


Figure 23

Typical oscillogram showing instantaneous arc voltage, current and Δ V.

rate were determined. Additionally, the metal transfer mode was determined for each combination of current and voltage using the oscillograms and slow motion video pictures.

For studying the stability of metal transfer, the transfer rate for different ranges of voltage variation (ΔV) were counted from the oscillograms. Then , the relative percentage of transfers corresponding to each ΔV is drawn on diagrams of percentage versus voltage for different ranges of current. From these diagrams the percentage of a given mode of metal transfer in a mixed mode can be determined. In order to have an overall view of the effect of current and voltage on metal transfer mode and droplet transfer rate, a metal transfer mode map is plotted. Additionally, charts of distribution of frequency as a function of welding voltage for the entire range of current were also prepared and analyzed.

3. RESULTS AND DISCUSSION

3.1 Voltage Variation and Metal Transfer Mode

The relationship between the arc length and welding potential was shown in Fig.2. Any change in the plasma resistance or distance between two electrodes will change the welding voltage. During welding, the electrode tip is melted to form small drop or large globules before being transferred to the weld pool. If the melting rate and wire feeding rate are in a dynamic steady state, when a melted droplet is formed the distance between the tip of electrode and weld pool may be sligtly shortened. When the droplet is transferred, the arc length will increase. If the droplet is large, the distance change must be larger than that of the small drop, Figure 24 and 25 Recalling that arc voltage V_b can be represented as arc length,as indicated in Figure 2, at constant current the change in arc length will cause the variation of the welding voltage. In other words, the welding voltage will possibly decrease with the formation of a globule on the electrode tip, and when the globule is transferred, the voltage should rebound to a higher value.

Figures 24 and 25 show the distances between the electrode and weld pool are 6.0 mm and 2.4 mm, with

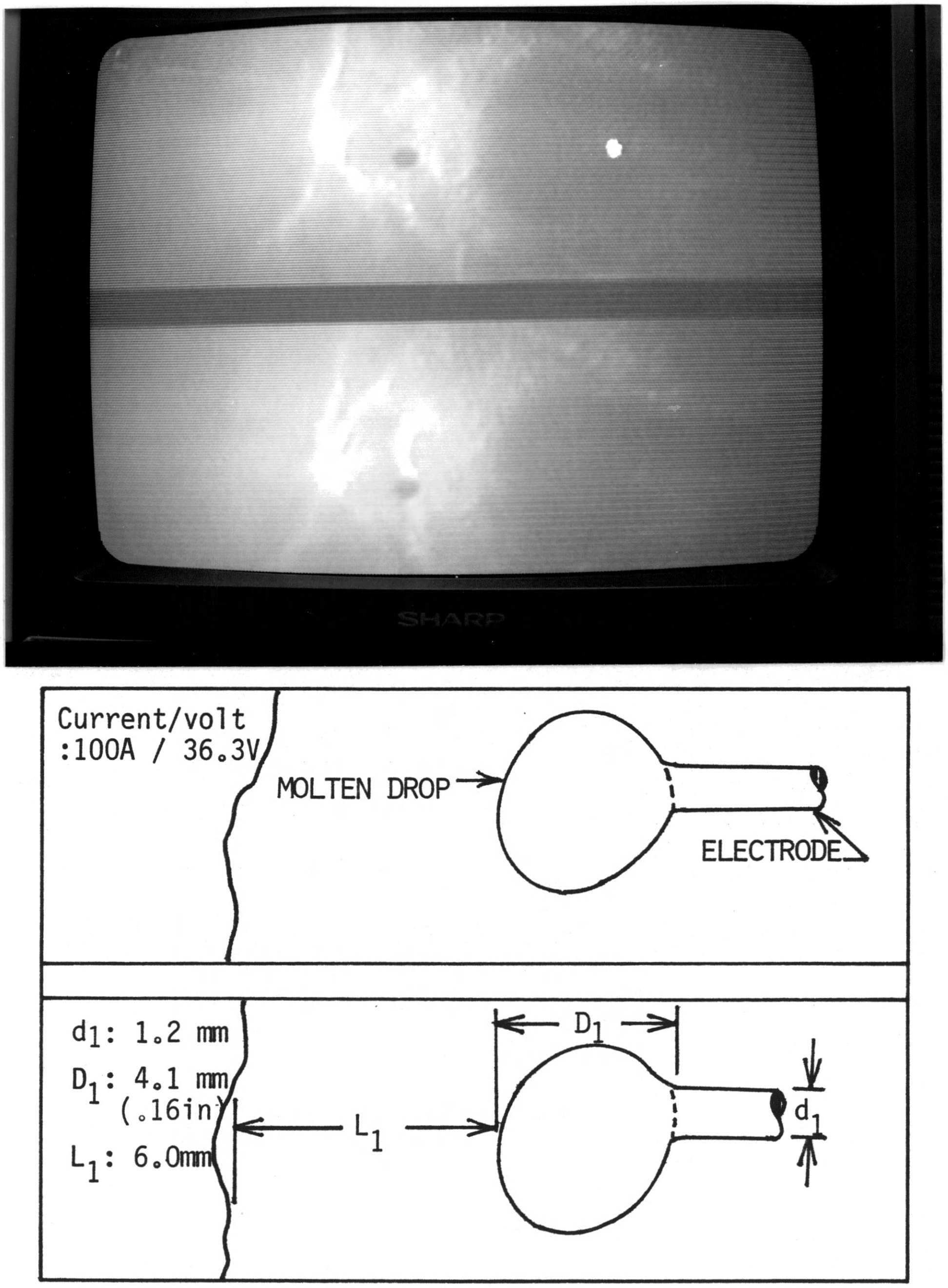


Figure 24

Schematic drawing of a metal globular at the electrode tip. The video is a still picture of a large globule on the electrode tip.

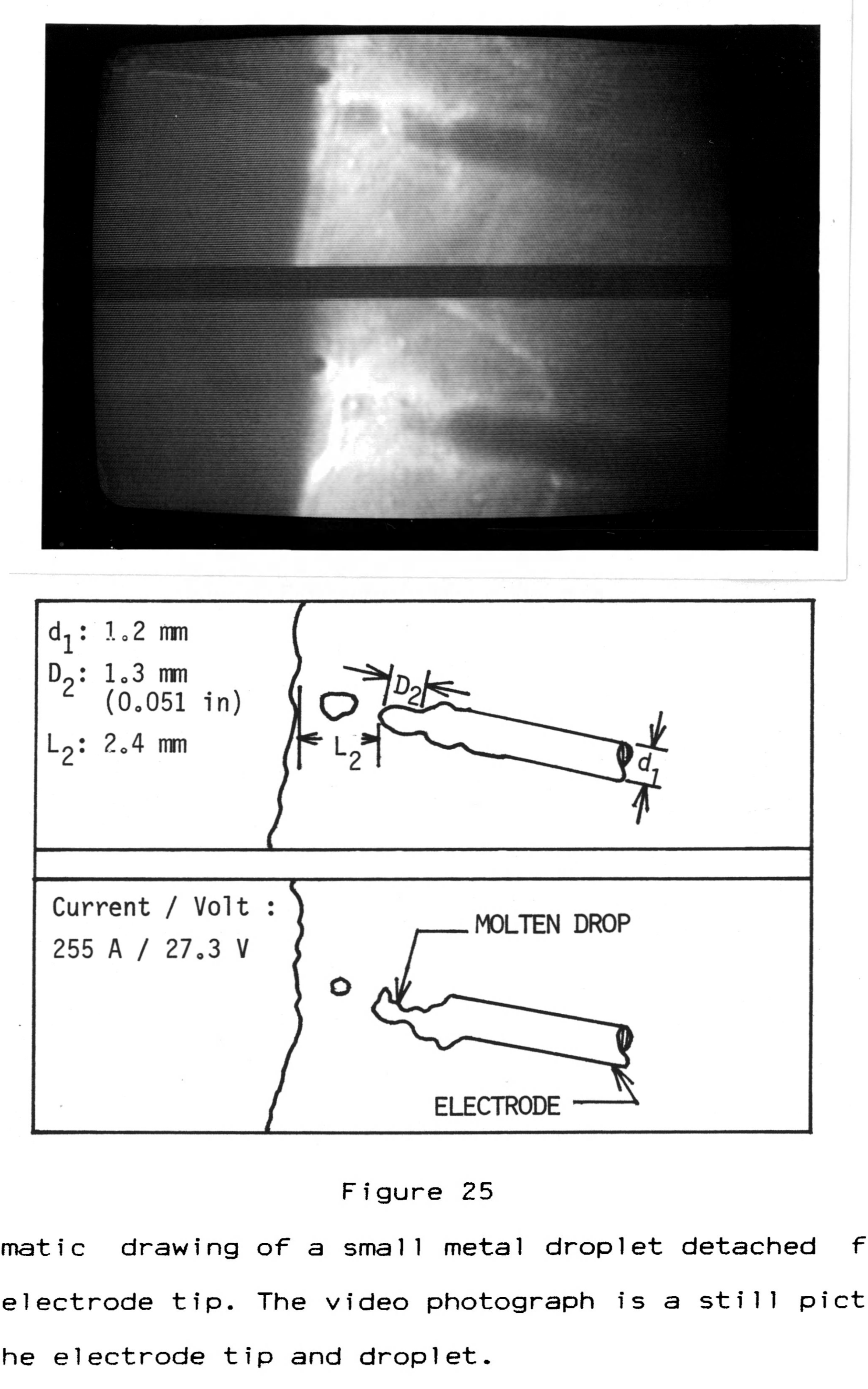


Figure 25

Schematic drawing of a small metal droplet detached from the electrode tip. The video photograph is a still picture of the electrode tip and droplet.

globule sizes are 4.1 mm and 1.3 mm in diameter. Using this set of data and Figure 2, the voltage changes (Δ V) due to the transfer are estimated to be 3.6 Volts and 1.2 Volts. Thus, a globule diameter of 4.1 mm is equivalent to a voltage change of 3.6 Volts and a diameter of 1.3 mm equivalent to 1.2 Volts change. For the above reason, a molten drop with a diameter larger than three times of diameter of electrode is a globular transfer, and a droplet with a diameter of between half and one diameter of electrode is a spray transfer.

Based upon these observation a set of criteria using volotage variation and droplet size to characterize metal transfer mode is stabilized.

Small variations in voltage change may be caused by oscillation of the level of weld pool, the globule fluctuations, and the transfer of tiny globules smaller than half of the electrode diameter All of these variations are included as $\Delta V < 0.5$ Volt. In the contact tube, minor arcing occurs between the contact tube and electrode, which also causes fluctuations in current and a change in voltage. Besides this change of current , there is the fluctuation of wire speed which directly affects the arc length. The overall variation from the contact tube is estimated to less than 0.5 Volt. Furthermore, when the globule is short circuited with the weld pool and a new arc reignited, a voltage drop of 8 to 20 volts or more is observed. Therefore the variations of voltage can be classified into four classes as $\Delta V < 0.5$ Volt ; 0.5 Volt $< \Delta V < 1.0$ Volt; 1.0 Volt $< \Delta V < 8.0$ Volts and $\Delta V >$ 8.0 Volts, representing noise, spray ; globular and short circuiting transfer. The characterization of metal transfer mode in this work is based upon this established criteria.

However, this criterion is based on the electrode size of (1.2 mm) 0.045in. As for larger diameter electrodes the droplet size may change substantially. A larger drop will produce a larger arc length fluctuation or voltage variation when the globule is formed and transferred. The definition of droplet size and transfer mode classification as a function of the electrode diameter may need to be reexamined. However, in GMAW with 0.9 mm (0.035 inch), 1.2 mm (0.045 inch) and 1.6 mm (0.062 inch) diameter electrodes, the criteria developed and proposed is expected to apply well. In SAW where much larger electrodes are used, the criterion may require revised. Nevertheless, the metal transfer modes will be different due to the presence of molten fluxes, possibly enveloping the droplets. length will produce its correspondent voltage variation so that the voltage variation is a function of globule size and independent of electrode size.

3.2 Current-Voltage Oscillogram of Gas Metal Arc Welding

For the short circuiting transfer mode there are four steps in one complete cycle as shown in Figure 27. These are (1) arcing, (2) short circuiting, (3) necking and (4) reignition. The electrode is melted to become a globule on the tip in the first step of arcing. In the arcing period, step (1), the current affects the slope of the voltage curve . When the current is low, the time required to melt and form a globule must be long because of a low melting rate and weak pinch and axial repulsion force. Therefore, even though the arc length is long enough to avoid any short circuit between the tip of electrode and weld pool, the low melting rate in this long arcing period may create an unacceptable welding condition.

At the end of arcing the globule short circuits with the weld pool. After contact, the metal bridge starts to

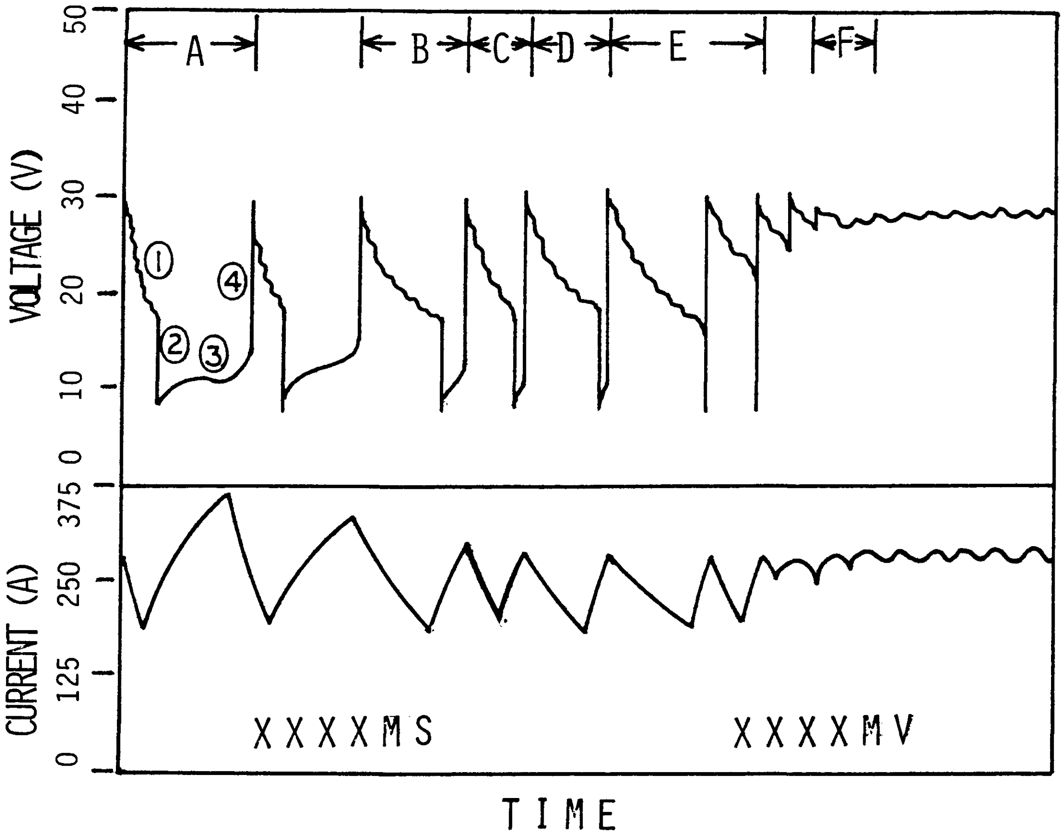


Figure 26

Idealized oscillogram of G MAW showing the different stages of metal transfer. In section A, (1) is arcing period, (2) shorting period, (3) necking period, (4) reigniting period.

neck, and the melted metal deposits to the weld pool. From step (1) to (2) the arcextinguishes and from step (2) to (3) current drastically rises up. After necking, voltage rises to reignite the arc. In this experiment it was found that the period of step (3) is very important in controlling the stability of the welding arc.

Section A in Figure 27, shows that for high current and low voltage welding condition, Volts the distance between the tip and the weld pool is short. Since there is little melted metal on the tip when the tip of electrode tip shorts with weld pool, current passes through the cold electrode and starts to melt the electrode for deposition. Thus step (3) takes a long time to rupture the bridge between the electrode and weld pool. With this short tip-weld pool distance a large quantity of current can be conducted (or the resistance can be reduced) between the tip and weld pool. Yet, the long necking period produces a lot of spatter, unsteady welding arc and metal transfer. This also makes the complete cycle period longer or the droplet rate lower. This is also illustrated in Figure 28 and 29.Compared with steps (1) and (3), steps (2) and (4) take negligible time to accomplish. Either the long arcing or the long necking period will lead to a long period of short circuiting cycle and unacceptable welding. This also explains why an acceptable welding condition is always accompanied by a high droplet frequency .

In section B of Figure 27, the conditions for a higher voltage and moderate current, a longer arc for accomodating the globule is created before it is repelled to the weld pool. As the globule grows, it contacts and transfers to the weld pool in a shorter time than that shown in section A. However, the shorter necking time result in a lower and slower rise in the current which leads to stable welding.

This is illustrated in Figures 29 and 30. When the voltage and current are both moderately high, with suitable arc length, melting rate, pinch force, and axial force to repulse the droplet, a good welding arc is in a transition mode (mesospacemode) between the short circuit and the globular modes. The characteristics of section D; E of Figure 27 represent this condition. Comparing B to C, B takes a longer time than C to melt the electrode to become a globule and drop.

However, when the voltage and current are both high, the high current can melt a globule in a short time and eject the globule from the electrode, making it fly through the arc and into the weld pool. This kind of

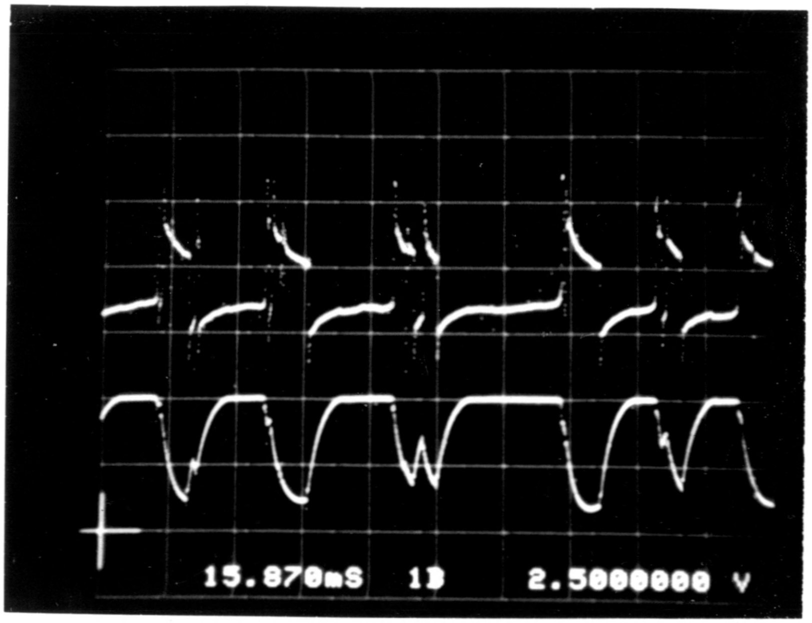


Figure 27

Arc current and voltage oscillogram for 383 A and 16.0 V welding condition.

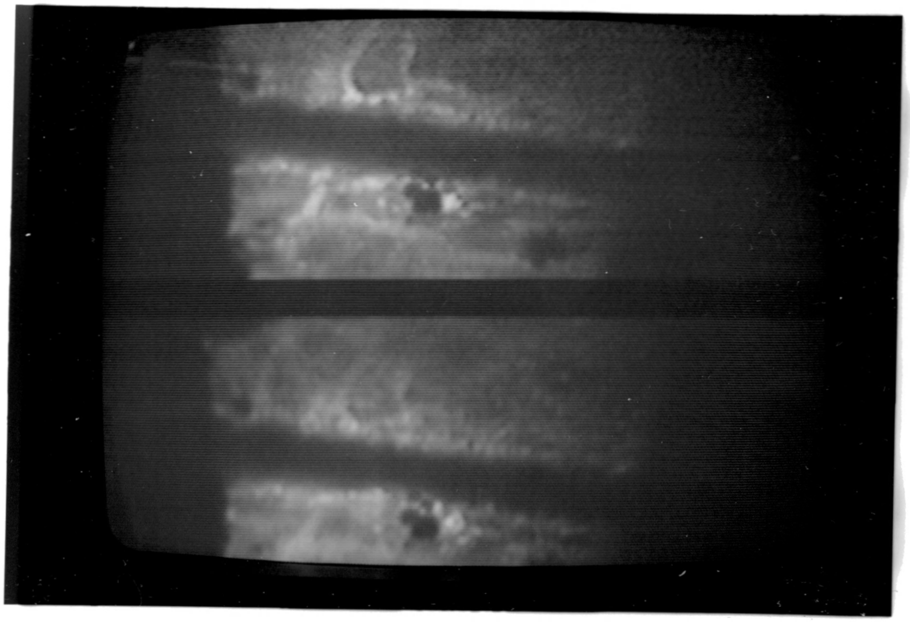


Figure 28

Still video picture of 383 A / 16.0 V arc

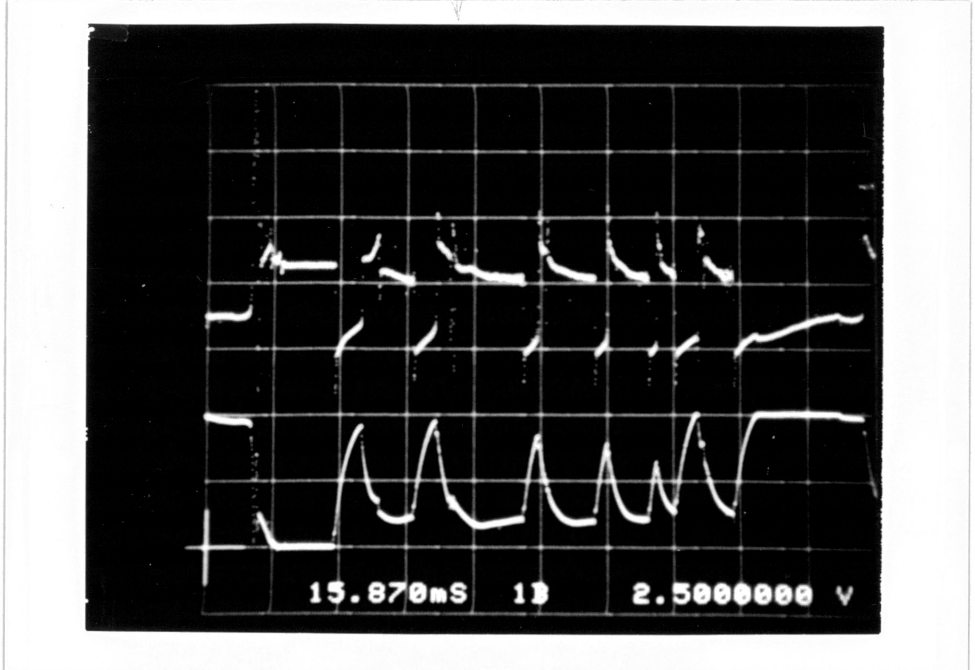


Figure 29

Arc current and voltage oscillogram for 238 A and 18.0 V welding condition.

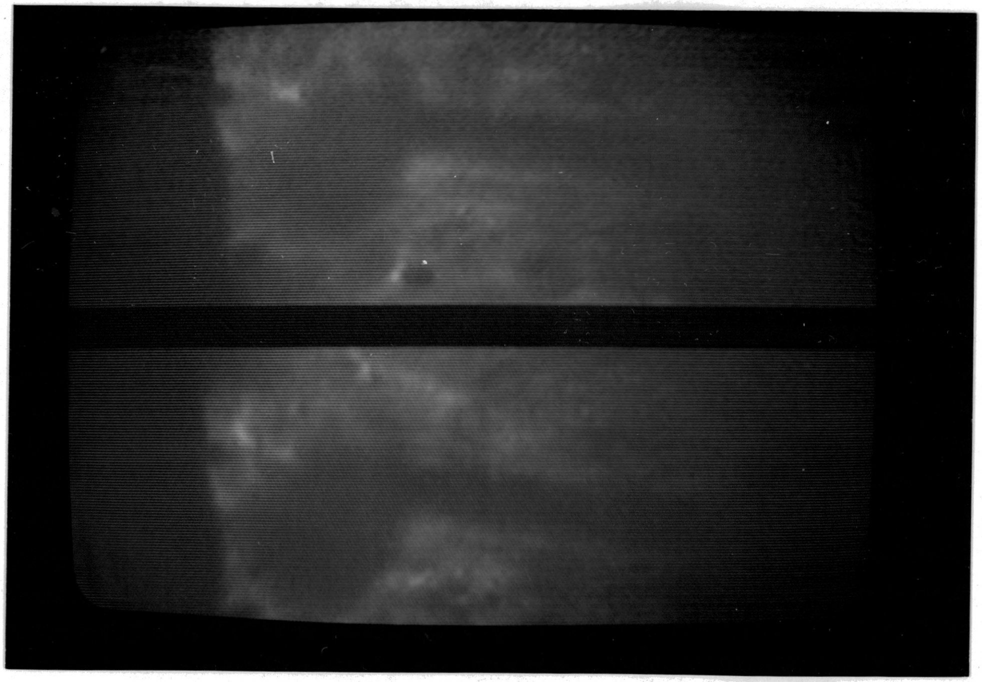


Figure 30

Still video picture of 238A / 18.0 V arc

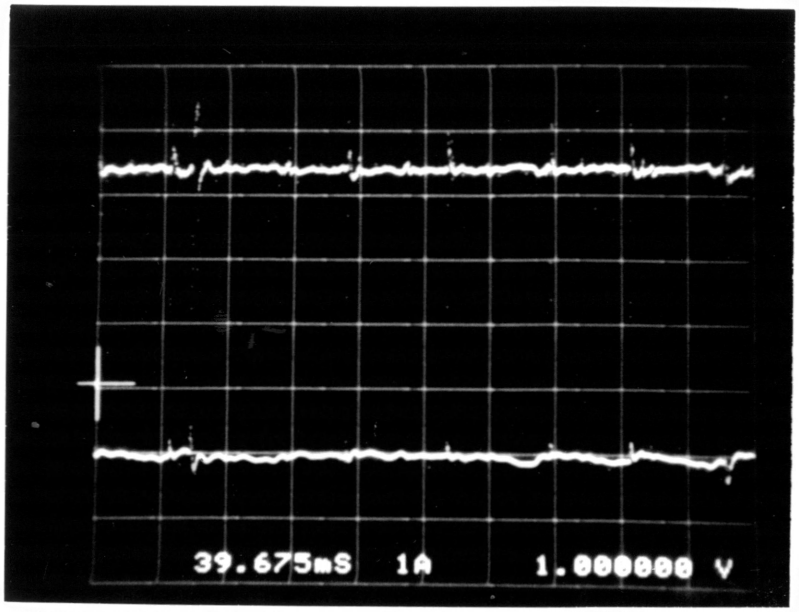


Figure 31

Arc current and voltage oscillogram for 246 A and 33.0 V welding condition.

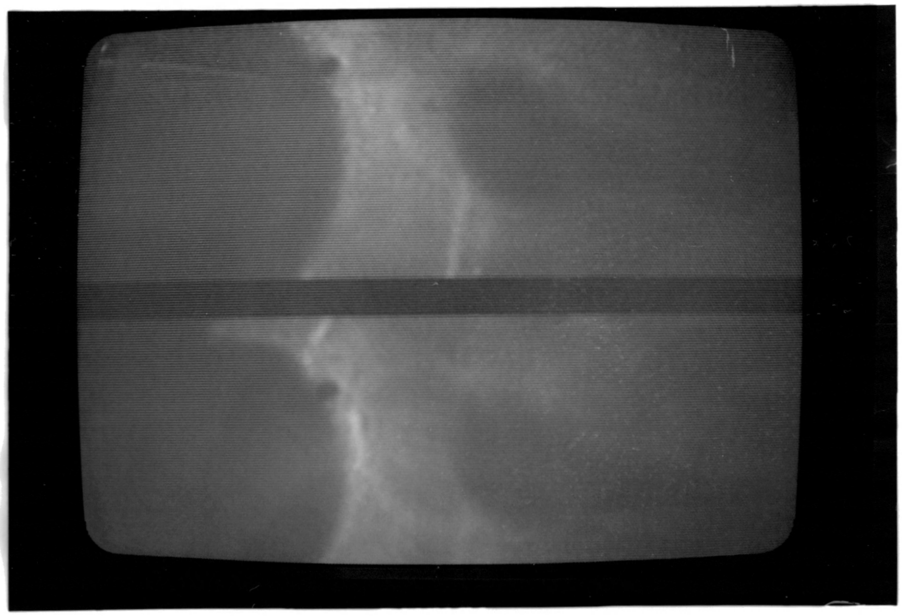


Figure 32

Still video picture of 246A / 33.0 V arc

transfer is found, for example, in welding condition of 246 Amperes / 33.3 Volt, (refer to Figure 32,33) The characteristics of oscillogram are shown in section D of Figure 27. At the moment the globule contacts the weld pool, the arc is momentarily extinguished, making the current fluctuate of about twenty Amperes. But, the current is much less than that of short circuit. The main reason is that a hot globule posseses higher resistance than that of a cold electrode in short circuiting. Furthermore, when the voltage and the current are at even higher values and the distance between the electrode tip and weld pool is appropriate, the high current can exert a very powerful pinch force and axial force to drive a smaller droplet toward the weld pool as soon as it is formed on the electrode tip.

3.3 The Stability of Gas Metal Arc Welding

In the short-circuiting mode, the melted metal globules are often in contact with the weld pool. The growth of molten metal globule is due mainly to the melting action caused by Ohmic heating. Before short circuiting can occur the globule must get close to the weld pool. So the distance between the weld pool and the tip of electrode prior to short circuiting are important for a stable metal transfer. However, the distance between the electrode tip and the weld pool is determined by the arc length and is controlled not only by the arc voltage but also by the arc current. Figure 2 shows that in the range of current higher than 200 Amperes, voltage increase with current in order to maintain the same arc length. During welding, if the current (set by the wire feeder rate) is increased and voltage is kept constant, the arc length will shorten, and the growth rate of globule will increase, according to eq.(7). On the other hand, if only voltage is increased, and current is kept constant,the distance should increase. Actually this behavior obeys Ohm's law , E(voltage) = I (current) x R (resistance), for the arc length is related to the plasma resistance.

Due to the above reasons the optimum welding condition must be in the diagonal area of Figure 18 or in a area with the highest droplet rate in Figure 20. In these regions, the voltage, current, and wire speed will always yield a proper arc distance for a stable short-circuit transfer mode that gives a maximum droplet rate in welding. Experimental oscillogram (Figure 33) and video picture (Figure 34) show a regular short circuit mode within this optimum area. The welding condition is 171

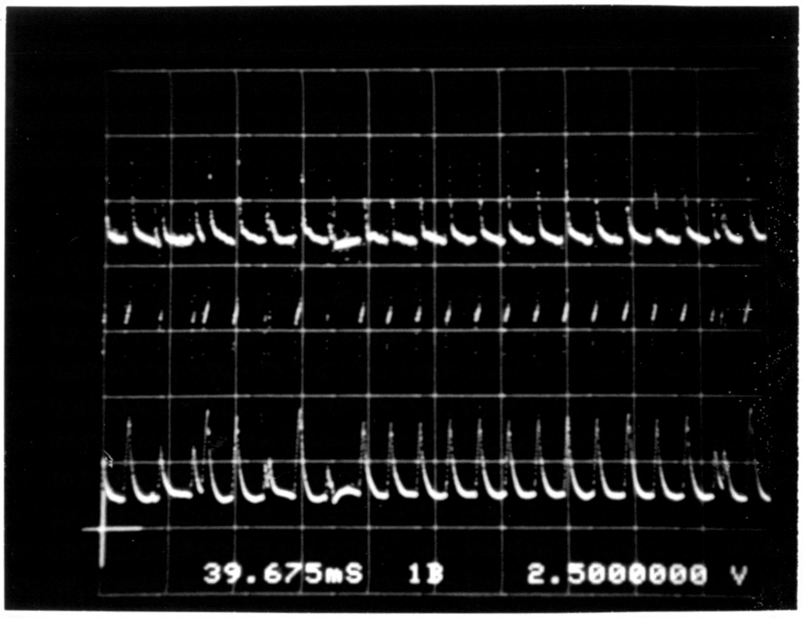


Figure 33

Arc current and voltage oscillogram for 171 A and 22.6 V welding condition.

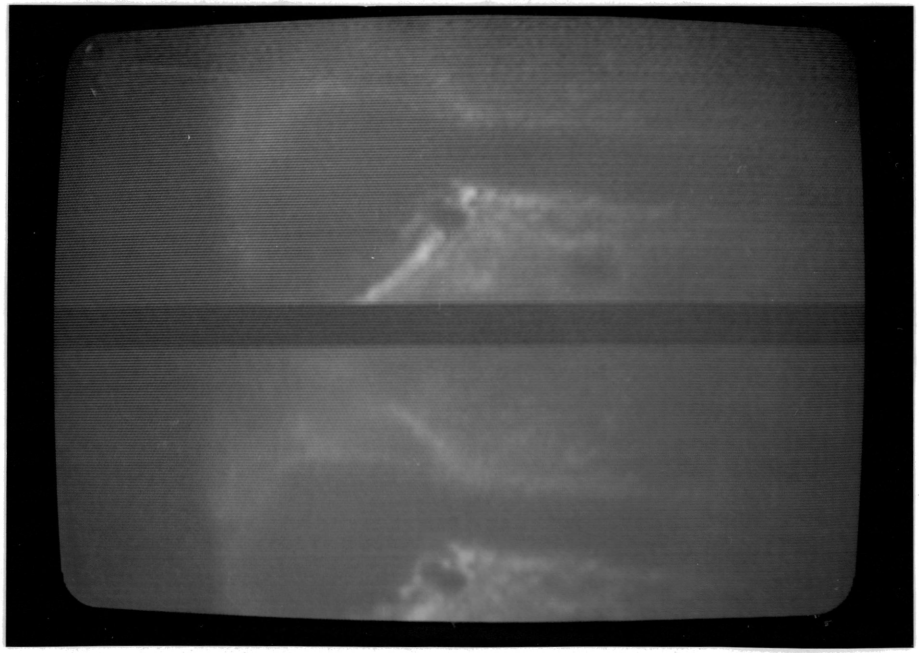


Figure 34

Still video picture of 171A / 22.6 V arc

Amperes / 22.6 Volts.

When welding at high voltage and low current, Ohm's law, $E = I \times R$, must still be satisfied by increasing the resistance (R) and increasing the arc length. Once the arc length is long, the heat dissipation through irradiation is more significant because of the large surrounding area around the plasma. When heat loss to the surrounding is significant, the ionization of metal vapor and shielding gas is poor, thus the conductance of plasma becomes low, reducing the current. In this case, the melting rate is lowered according to equation 7 , and the pinch force repulsing the droplets will also be weaker. Under this condition the metal transfer is dominated by the globular mode. In Figures 35, 36 and 37 the oscillogram and video picture show a typical globular mode, and the condition of welding is 100 Amperes /36.2 Volts.

When the current is high, and the voltage is not high enough to yield a long arc, or the distance between the electrode and weld pool is short, the transfer mode can be a mixture of spray and short circuit mode. The welding condition of 328 Amperes /31.9 Volts shows a mixture mode of spray and short circuit. The oscillogram and video picture are shown in Figure 38, 39 and 40.

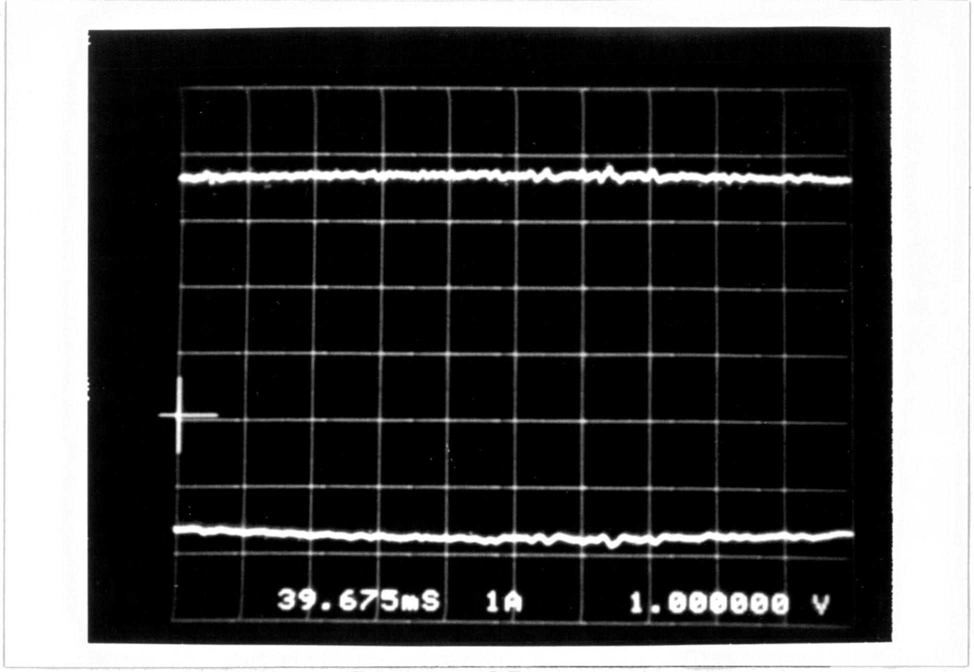


Figure 35

Arc current and voltage oscillogram for 100 A and 36.2 V welding condition.

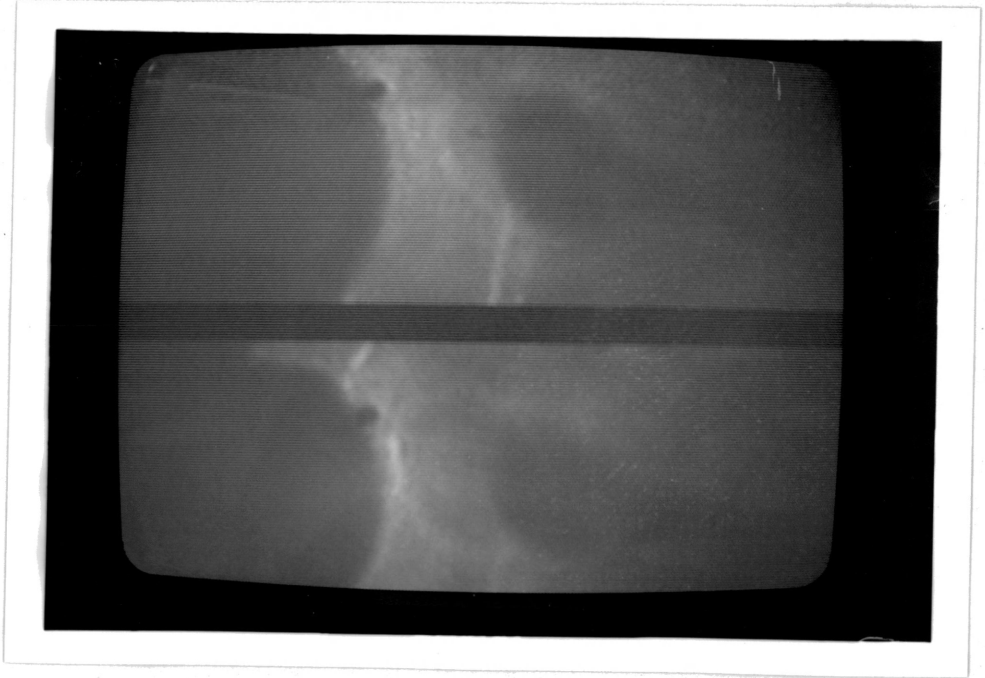


Figure 36

Still video picture of 100 and 36.2 V arc

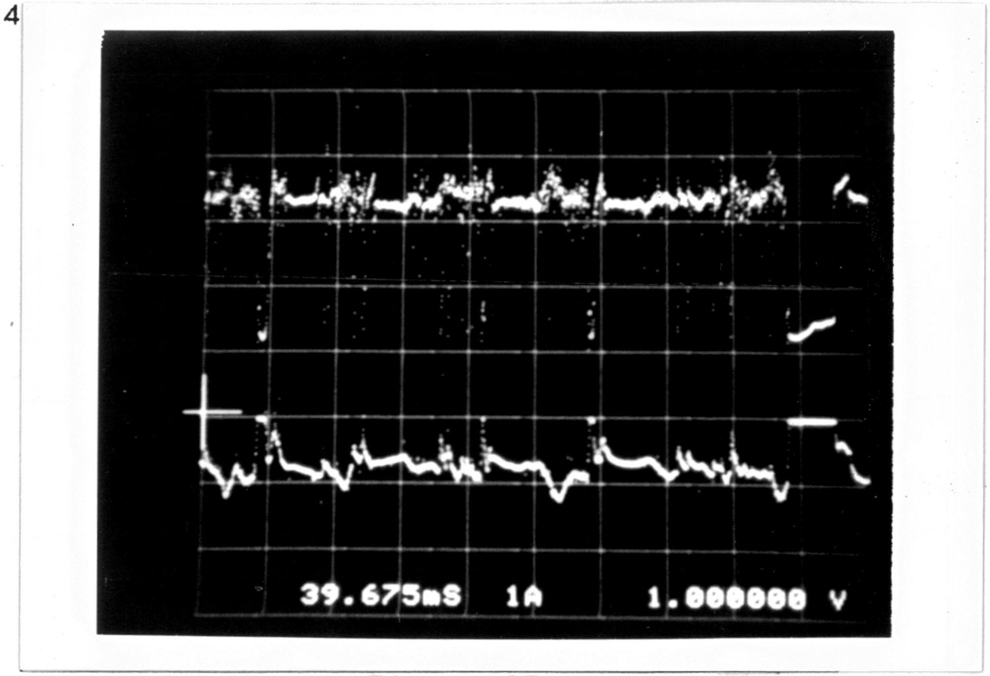


Figure 37

Arc current and voltage oscillogram for 328 A and 31.9 V welding condition.

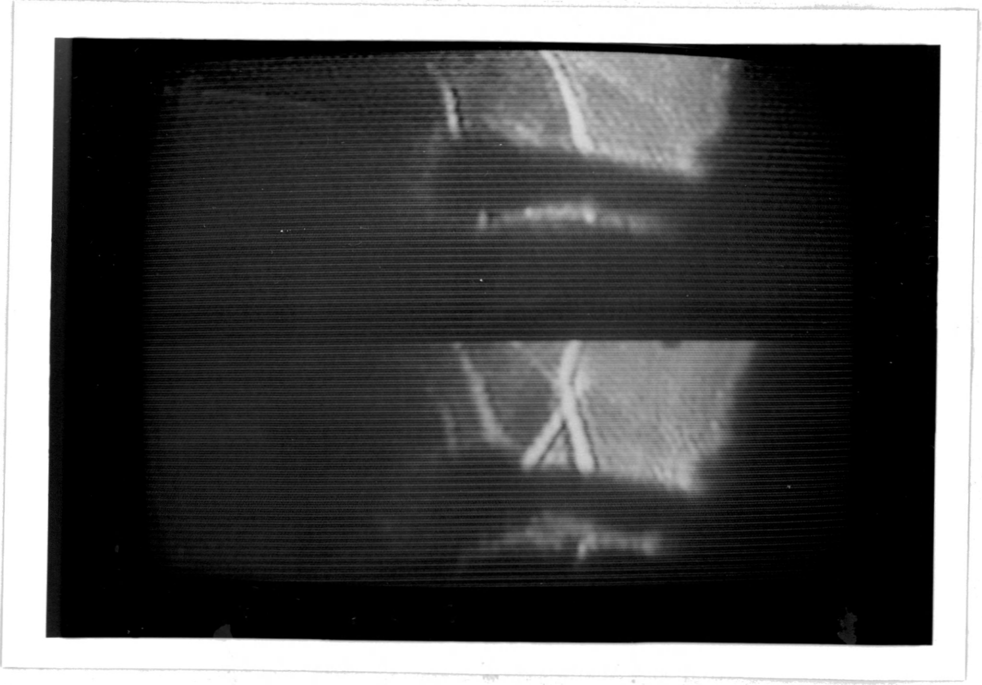


Figure 38

Still video picture of 328 and 31.9 V arc

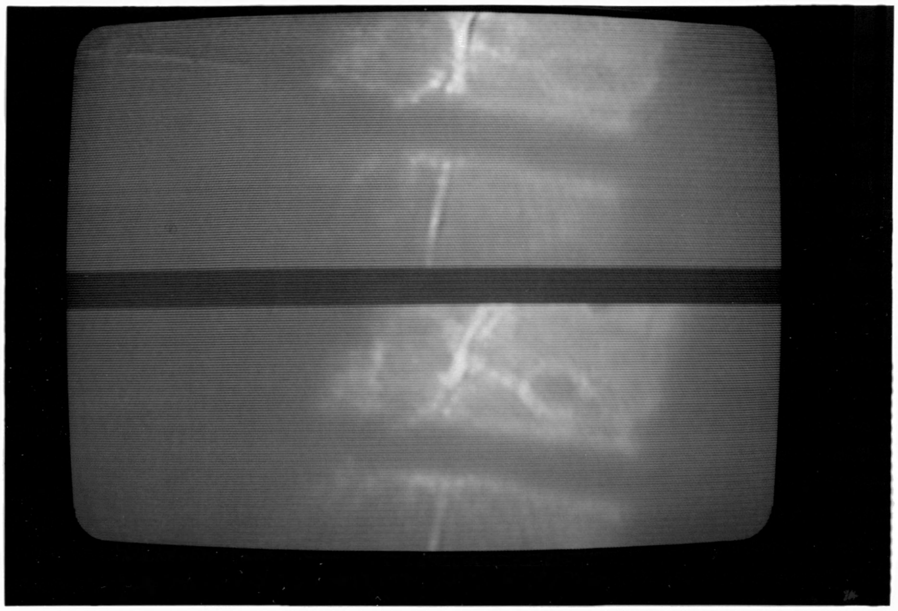


Figure 39

Still video picture of 328 and 31.9 V arc

When the welding current and voltage are both high , such as 249 Amperes / 33.8 Volts the arc length can match well with the melting rate and pinch force the transfer mode is spray as Figures 40,41.

When the welding current is extremely high and welding voltage is low, such as the condition of 383 Amperes / 16 Volts (Figures 40, 41) the plasma resistance must be extremely low in order to satisfy Ohm's law. In this experiment, the arc actually occurred under the base metal. In this way the resistance is very low, and the arc can be observed not only from the electrode tip to the weld pool that is under the plate surface, but also to the electrode surface and the wall of the weld puddle below the plate surface. An extended arc with a cone shape was also observed above the plate surface extending to about 6.76 mm (0.266 inch) up to the side of the electrode.

3.4 The Effect of Voltage on Droplet Transfer Distribution

The effects of voltage on droplet transfer is illustrated in Figures 42, 43 and 44. These diagrams cover current ranging from 140-320 Amperes. Each diagram corresponds to a different voltage change and consequently different metal transfer mode. Figure 42 shows the frequency distribution of ΔV = 0.5-1.0 Volts and frequency

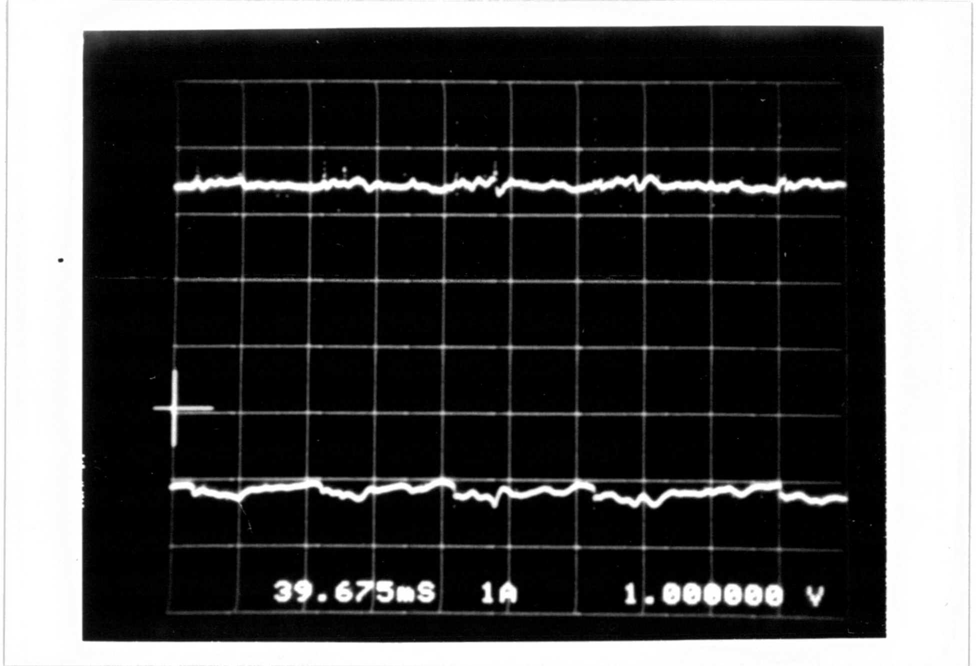


Figure 40

Arc current and voltage oscillogram for 249 A and 33.0 V welding condition.

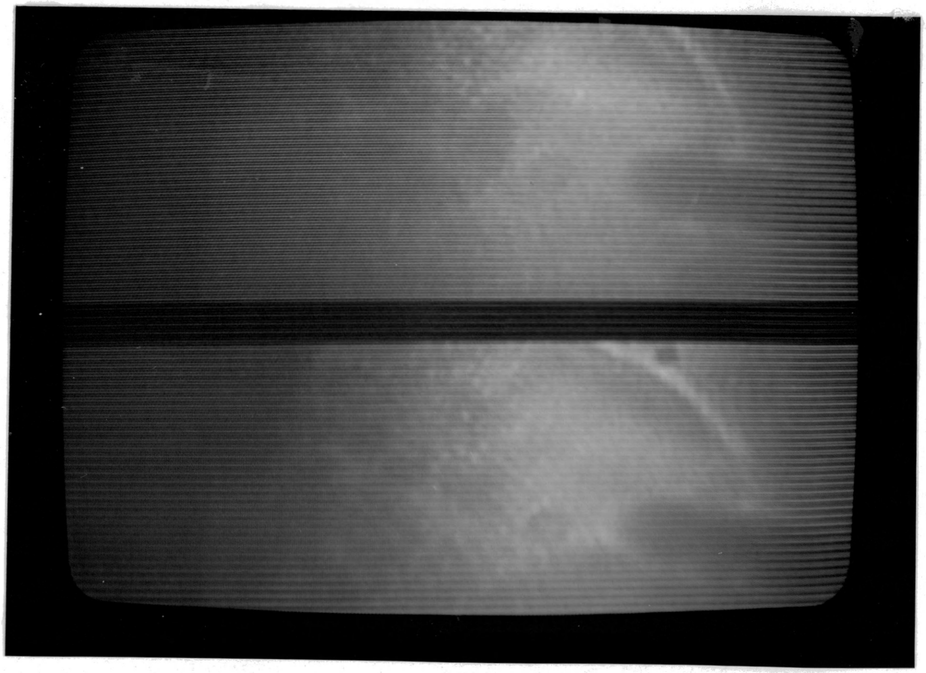


Figure 41

Still video picture of 249 A and 33.0 V arc

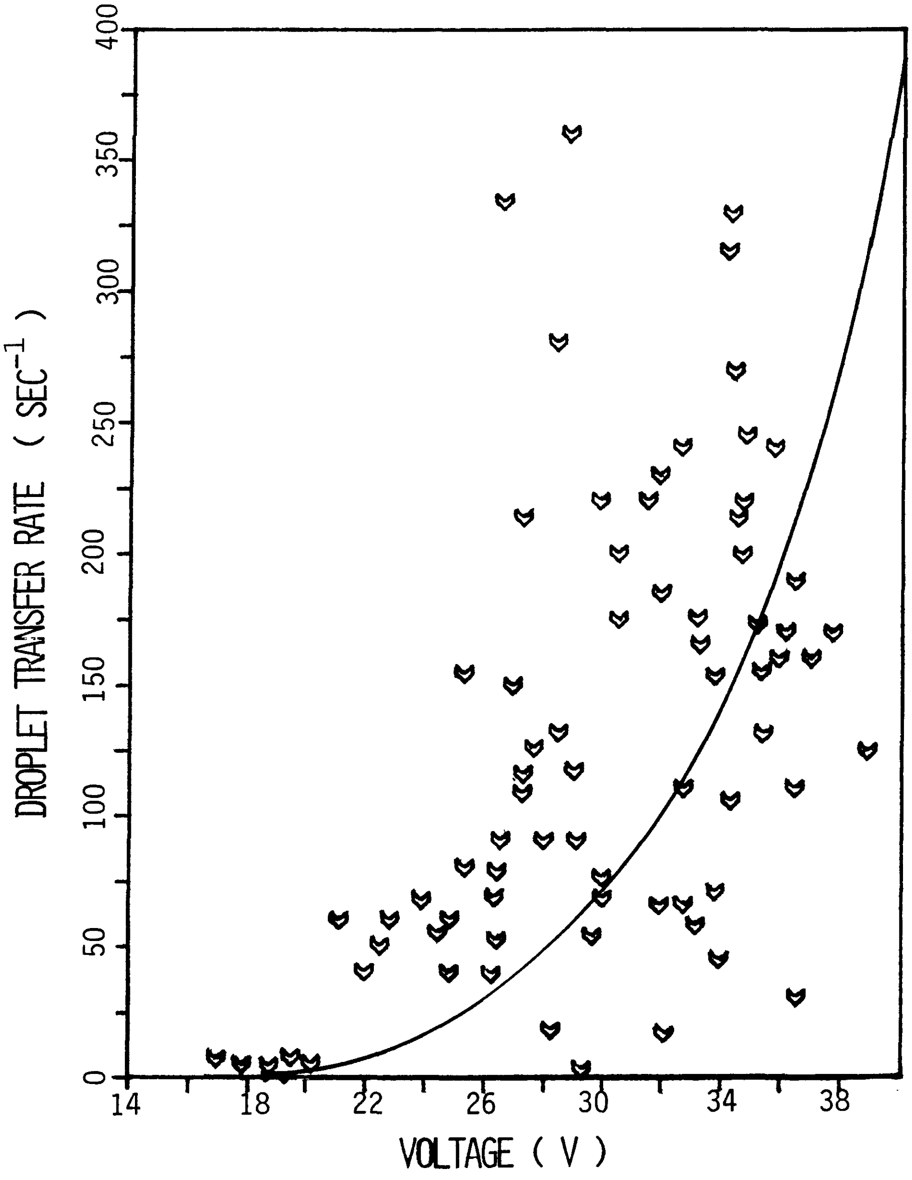


Figure 42

The effect of Voltage on the distribution of spray droplet transfer

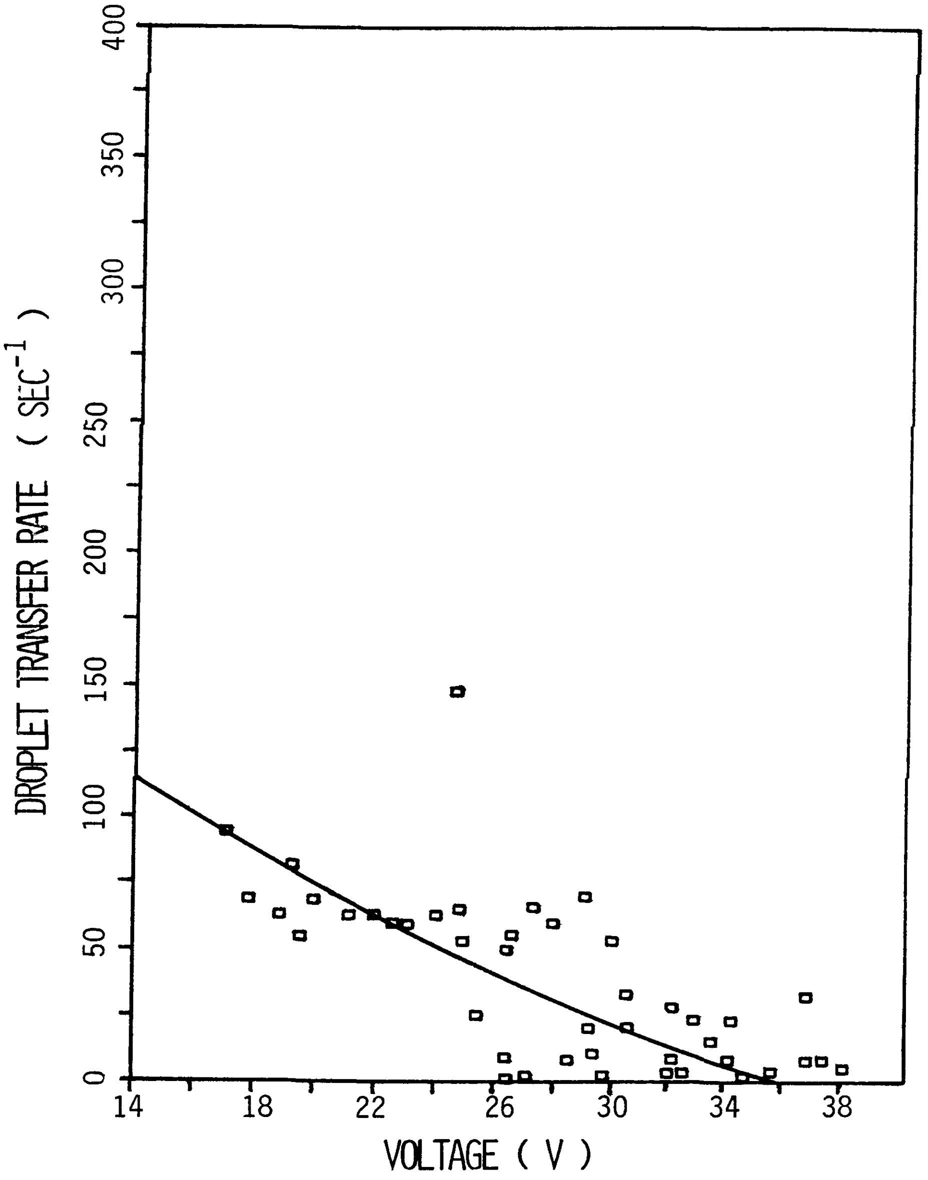


Figure 43

The effect of Voltage on the distribution of short circuiting droplet transfer

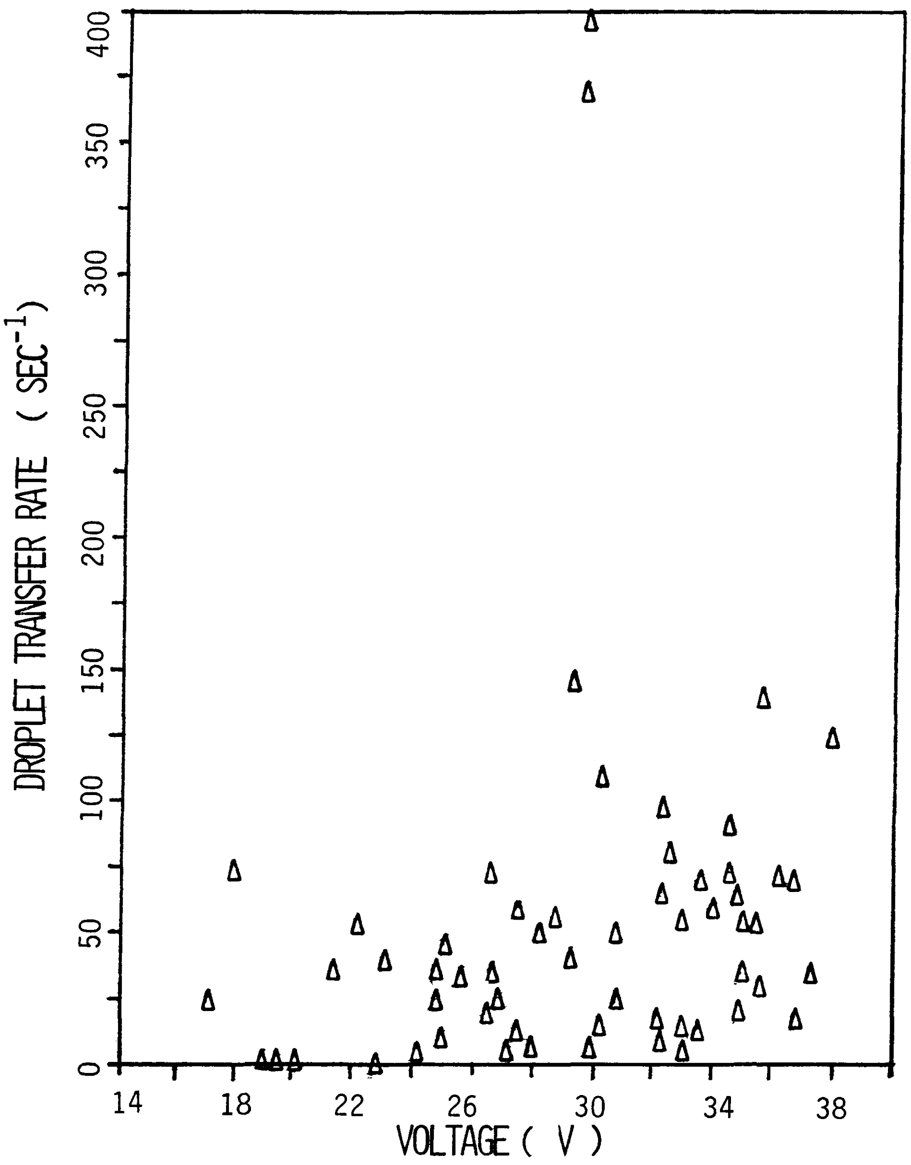


Figure 44

The effect of Voltage on the distribution of globular droplet transfer has an ascending trend from about 10 at 18.0 Volts to 325 at 34.0 Volts. This indicates that the spraying process is significant at high voltage ranges. The scatter of the data increases as the voltage goes up. This phenomenon can be attributed to the fact that the spray mode only happened in long arc length welding. According to the relationship of arc length and welding voltage, shown in Figure 2, the voltage for a long arc length must be high. For a good welding condition, a high voltage must be accompanied by a high current but not too high. Following the same reasoning a low voltage should also match with a low current so that the welding condition may be located in the acceptable region. However a low current usually produces a large globule instead of a small drop, equivalent to $\Delta V = 0.5-1.0$ Volts. Therefore the droplet rate is low. If the voltage is low enough, short circuiting will be the predominant mode. If the voltage is high and current is low, plasma resistance is high and the arc behaves erratically.

In figure 43 the distribution of frequency for $\Delta V >$ 8.0 Volts is shown to have the least value among the three voltage ranges Also, the frequency has the least random distribution and a decreasing trend from 100 at 17 Volts to 0 at 34 Volts. It indicates the short circuiting process is less common under a high voltage or long arc length.

In Figure 44 the frequency distribution of ΔV= 1.0-8.0 Volts, globular mode, has a medium random distribution and has no clear pattern of trend.

3.5 The Frequency Percentage of Different Metal Transfer Modes.

The relative percentage of each metal droplet transfer mode corresponding to the different voltage variations are shown in figure 45-48. Lines 1, 2 and 3, in these Figures, represent the percentage of transfers with ΔV = 0.5-1.0 Volts (spray), ΔV =1.0-8.0 Volts (globular), and ΔV > 8.0 Volts (short circuiting), respectively. The frequency percentages corresponding to ΔV < 0.5 V are not included in these figures.

Figure 45 shows the percentage of the different modes for the current range of 140-180 Amperes. For example, at 19.5 Volts the percentage of short circuiting mode is approximately 40 percent ,and the modes of globular and spray are almost zero. Here, through checking the percentage of small voltage variation, the percentage is approximately 60 percent. In other words, the transfer mode at 19.5 Volts is pure short circuiting. For another

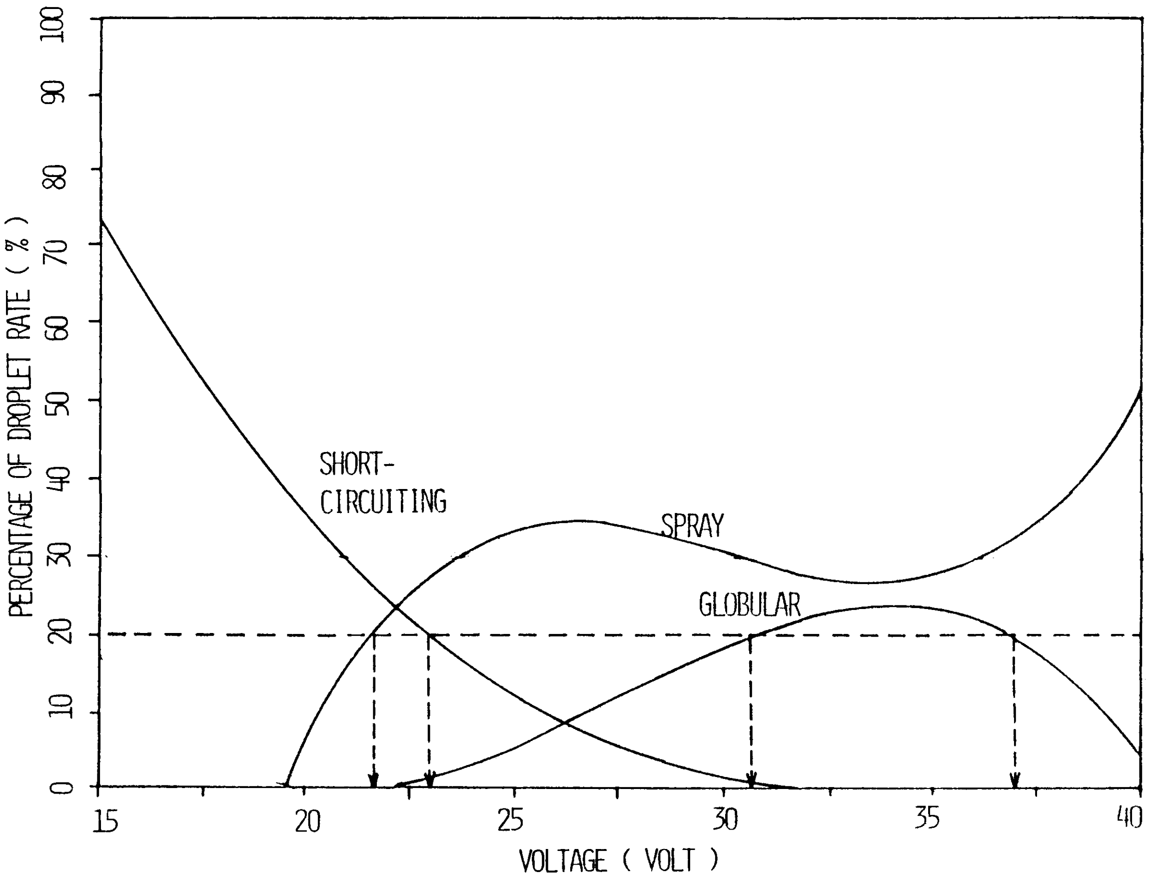


Figure 45

The Effect of Voltage on Percentage of Frequency for Current range of 140 A-180 A

example at 26 volts, the percentage of spray mode is 33 percent, and the globular and short circuiting modes have percentage of roughly 8 percent each .So the spray mode is predominant, but the globular and short circuiting modes are also in existence. Again, the percentages of small voltage variation is estimated to be about 51 percent.

In the same way, Figures 46-48 all show that the percentage of the three modes are affected by voltage. For the spray mode, except for Figure 45, in which a shallow " basin in plateau" is present, the other three diagrams show an ascending trend as voltage increases to the limit of the diagram. For the short circuiting mode, except in the case for I = 220-260 Amperes in Figure 47 ; the other current ranges show decreasing frequencies with increasing voltage, In general, as the voltage increases the percentage of spray mode will increase and the percentage of short circuiting will decrease. This observation agrees with a previous statement in section 1.3.9 which shows the relative position of each transfer mode.

3.6 Isopleths of Different Metal Transfer Modes

3.6.1 Distribution of Isopleth for Each Transfer Mode

An isopleth has been constructed for each of the metal transfer modes: the spray mode has a small voltage variation due to its small droplet and a globular has a large voltage drop caused by a large globule, for short circuiting, a 8-20 volts of voltage variation from the shorting of globular to the weld pool. Each line on the isopleth represents a given droplet transfer rate. In Figure 49,the isopleths for spray are broadly scattered for frequencies ranging from 50 to 300 $\sec^{-1}$. The distribution of isopleths covered a current range from 140 to 320 Amperes and a voltage range from 22 to 33 volts.

In Figure 50 there is a maximum droplet rate region of 350 s^{-1} located at 190 Amperes / 28 Volts. This loop is surrounded by other lower frequency ranges decending from 300 to 50 s^{-1} There are also two small medium high frequency region with 100 $\sec^{-1}$ located at 300 Amperes, 38 Volts. These areas represent the most stable globular transfer mode.

In Figure 51 there are a few lines representing frequencies of 100, 80, 60, 40, 20 (no./sec). There is an increasing trend from lower-left corner to upper-right corner. These area shows the stable area of short

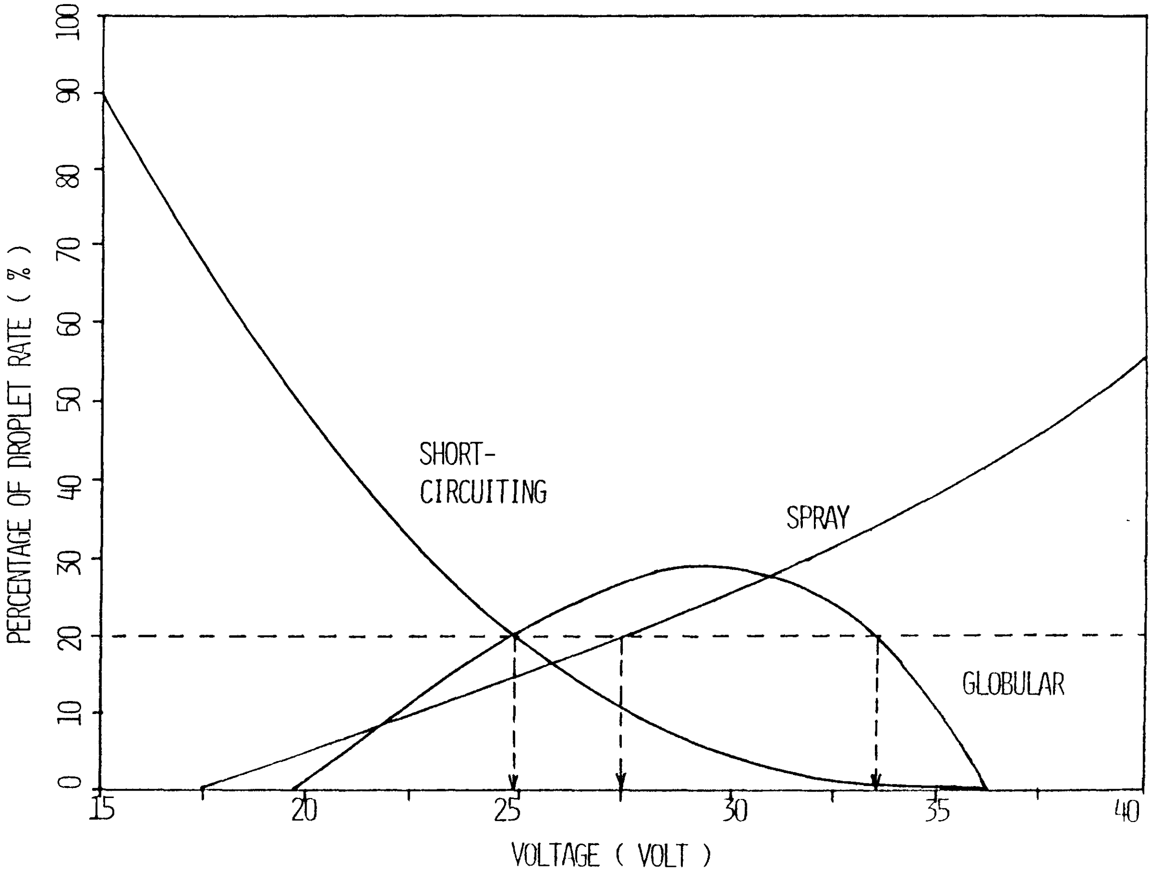


Figure 46

The effect of Voltage on Percentage of Frequency for Current range of 180 A-220 A

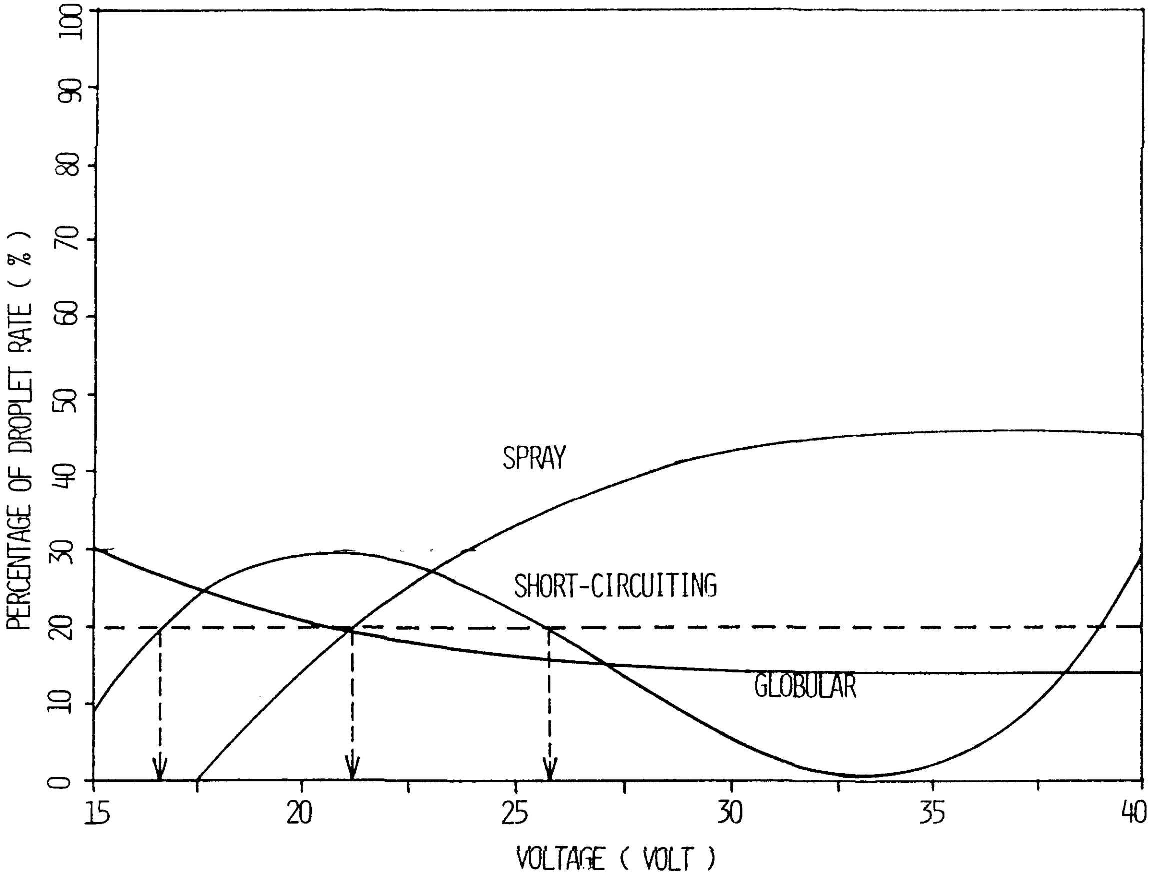


Figure 47

The effect of Voltage on Percentage of Frequency for Current range of 220 A-260 A

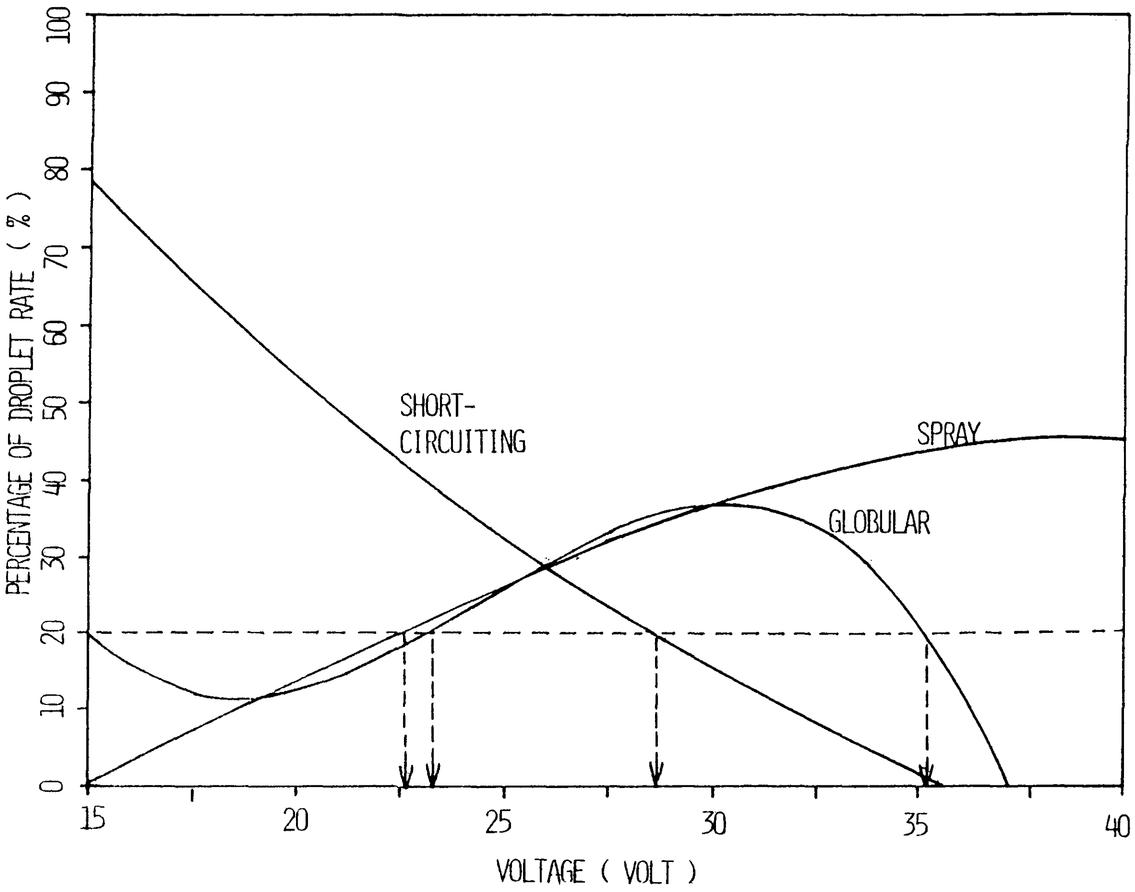


Figure 48

The effect of Voltage on Percentage of Frequency for Current range of 260 A-320 A

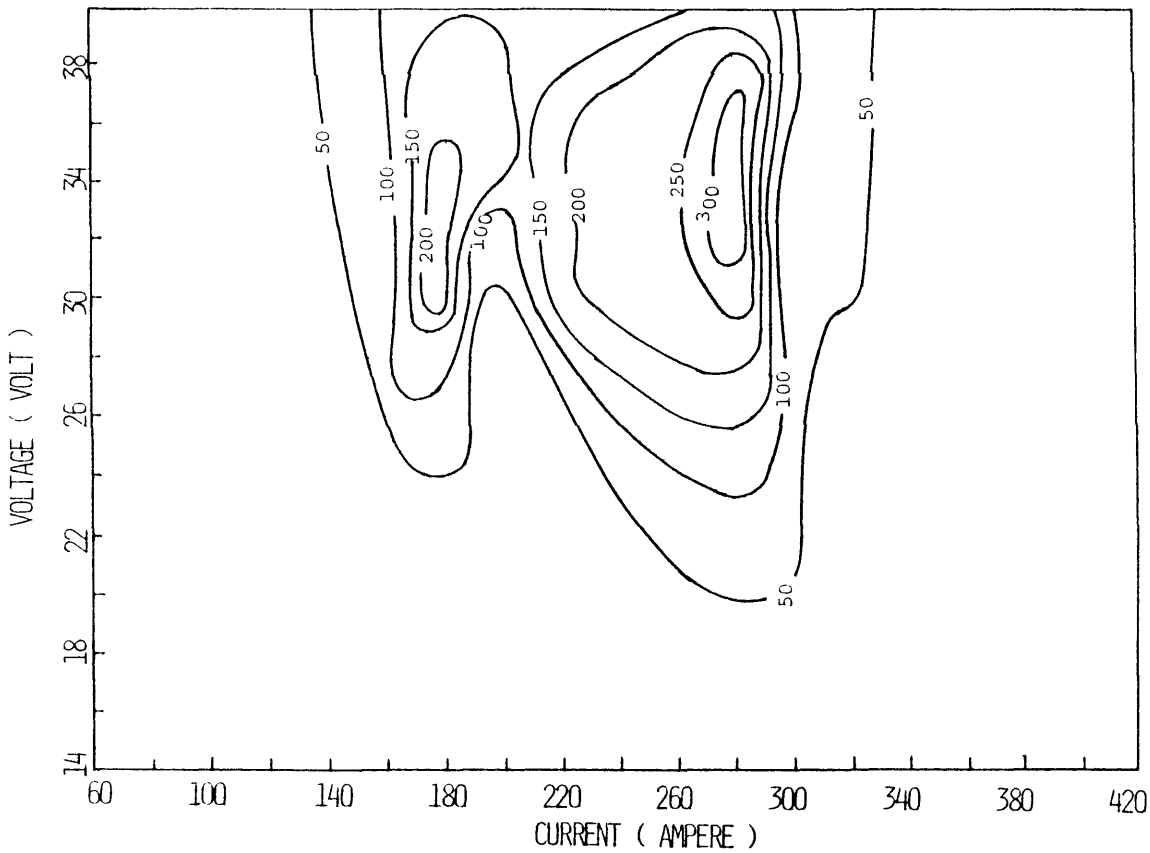


Figure 49

The isopleths for the spray mode in GMAW

The number in the diagram is the

isopleth of droplet.

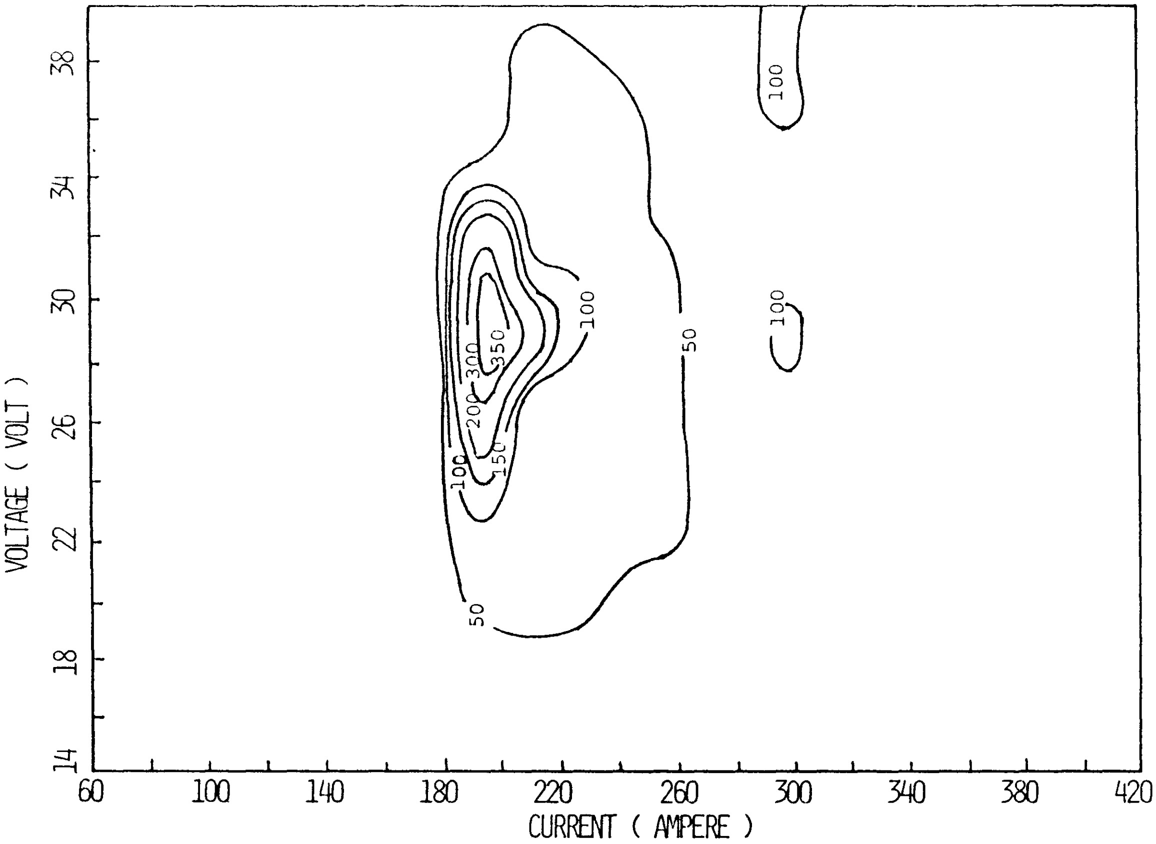


Figure 50

The isopleths for the globular mode in GMAW

The number in the diagram is the

isopleth of droplet.

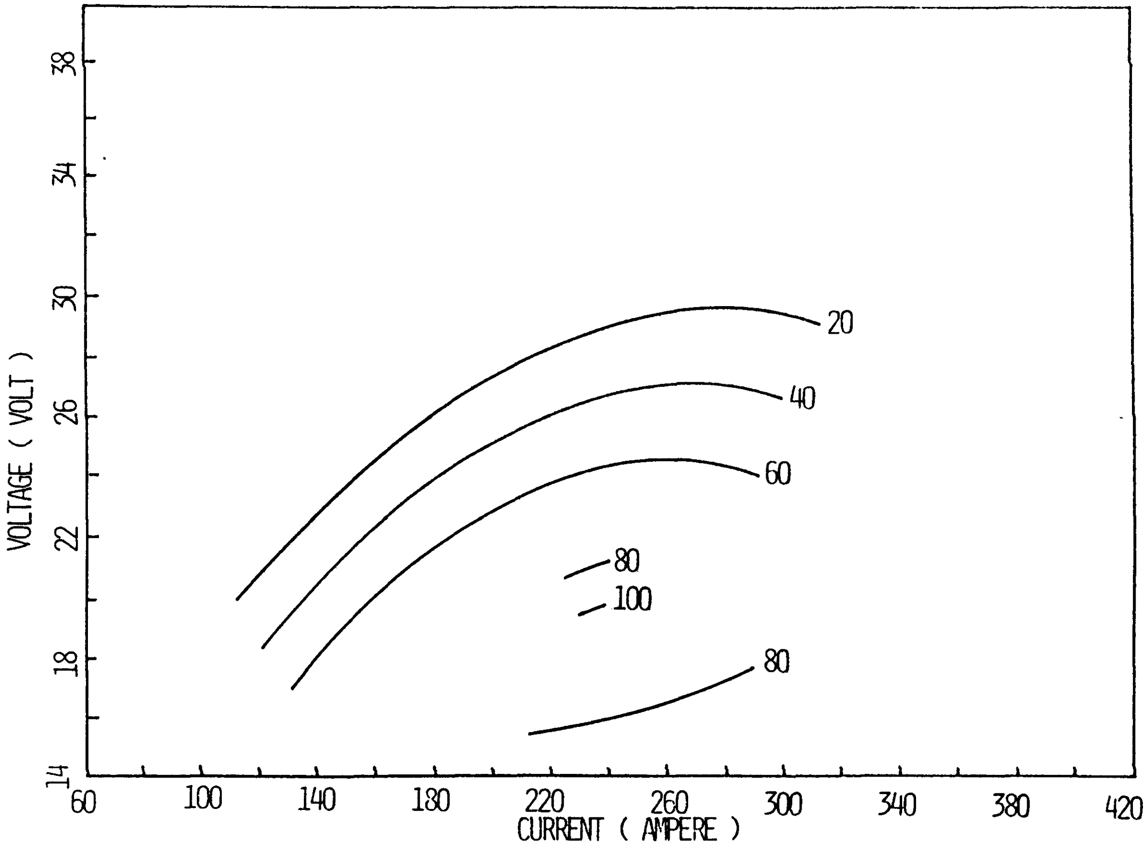


Figure 51

The isopleths for the short circuiting in GMAW

The number in the diagram is the isopleth of droplet.

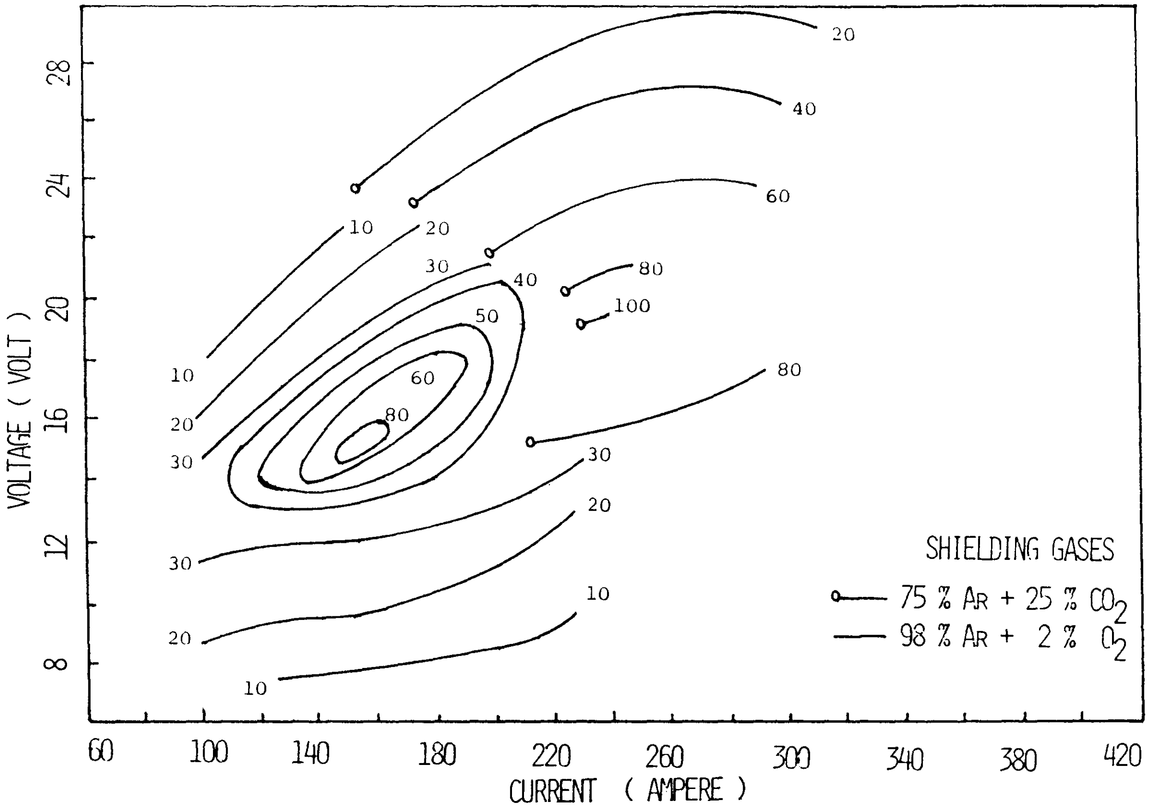


Figure 52

A comparison of isopleths of two tests with different current ranges and shielding gases. The number in the diagram is the isopleth of droplet.

circuiting. By combining this result with that of former work by Liu and Siwert (Ref.25) Figure 52 is obtained composing of different testing ranges of Figure 51 and Figure 19. Due to the diffrerent shielding gas and current-voltage range the optimum regions are shifted slightly but they are all located along the diagonal direction.

3.6.2 Relative positions of high frequency isopleth line for each transfer mode in GMAW.

From Figure 45-48 the voltage ranges that have frequency percentage larger than 20 percent of the total (indicating they have a substantial contribution to the overall transfer process) are obtained and used to draw a map that represent the position of each mode in Figure 49-51.

To develop this data for the various modes, a horizontal line was drawn across at the 20 percent level for Figure 45-48. The intersection points of this line with curves of spray, globular and short circuiting give voltage ranges that have percentages larger than 20. If the percentage for a voltage range is below 20 percent, the mode was neglected. Therefore, in Figure 44, the spray mode with percentage higher than 20 exists when the voltage larger than 22 volts. For globular the voltage is

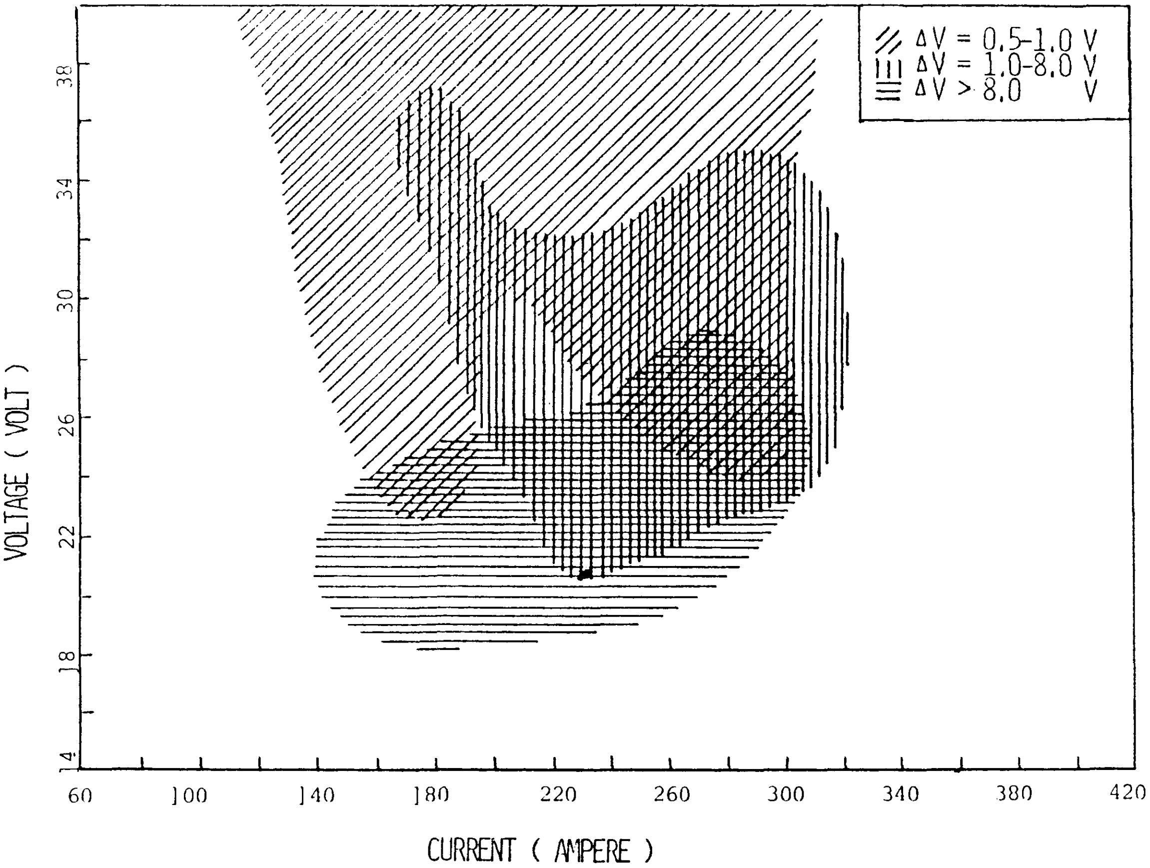


Figure 53

A distribution map of three metal transfer modes in GMAW from 30.5 to 37.0 Volts. The voltage range for short circuit is below 22 volts. In the same way the voltage range for a certain mode with percentage larger than 20 percent in other current range can be found and used to draw a map for each mode with dotted line in diagrams of 47-49. These maps well represent the position of dominance for each mode in diagrams of voltage vs. current.

Figure 53 is a compilation of Figures 49, 50 and 51 which shows the relative position of each transfer mode. In figure 53 the shaded vertical line indicates the position of spray mode which covers a relatively large area mainly in the higher voltage areas. The horizontal lines represent the region of the short circuiting transfer mode which is located at lower voltages and has some portions which overlap with the spray mode. The overlap occurs at current ranges larger than 220 Amperes and Voltages from 22 to 30 Volts. The area with slanted lines represent the globular transfer mode. It also overlaps with the other two modes at current ranges from 180 to 260 Amperes and voltage ranges from 18 to 38 volts.

It is interesting to notice that even in Ampere-Volt ranges traditionally defined as pure, spray, globular, or short circuiting mode, there is actually a mixed nature. No matter how stable the arc will be, or how uniform the arc noise is, the predominance of one of the mode determines the stability of that transfer mode.

3.7 The importance of conception of the effect of voltage on metal transfer mode

Through the conception of voltage variation the metal transfer mode can be selected by operator monitor and controlled by computer. Once these coputerized welding machine is constructed, a fast, stable and precise welding work can meet the requirement of morden welding industry.

4. CONCLUSIONS

1. The voltage fluctuation given by the oscillogram can be used to estimate the mode and the drop size of metal transfer.
2. A criterion to define metal transfer mode is established using voltage variation. It is that the spray mode is equivalent to $0.5 \text{ Volt} < \Delta V < 1.0 \text{ Volt}$; globular mode is equivalent to $1.0 \text{ Volt} < \Delta V < 8.0 \text{ Volts}$; Short circuiting mode $\Delta V > 8.0 \text{ Volts}$.
3. The short circuiting cycle curve recorded on the oscillogram is indicative of the welding conditions. The shorter the necking period and steeper the arcing curve, the more stable the welding and higher the droplet frequency. The maximum number of droplets per second represents is a stable welding condition.
4. The diagrams of frequency percentage versus voltage show the effects of voltage on the distribution of frequency and indicate, under most welding conditions, a mixed transfer modes occurs in GMAW.
5. The transfer rate isopleths for each type of metal transfer mode indicates the stable welding condition of current / voltage. The overlapped area

of these isoplethes represent a mixed but stable transfer mode.

6. The relationship between voltage variation and metal transfer mode can be incorporated into modern welding system that monitor and control the metal transfer mode automatically.

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