

# Analysis of Metal Transfer in Gas Metal Arc Welding

*This study shows that the transition of metal transfer mode in gas metal arc welding occurs much more gradually than is generally believed*

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**ABSTRACT.** Droplet sizes produced in GMAW are predicted using both the static force balance theory and the pinch instability theory as a function of welding current, and the results are compared with experimental measurements. The causes for the deviation of predicted droplet size from measured size are discussed with suggestions for modification of the theories in order to more accurately model metal transfer in GMAW. The mechanism of repelled metal transfer is also discussed. The transition of metal transfer mode has been considered as a critical phenomenon which changes dramatically over a narrow range of welding current. This transition has been investigated experimentally using high-speed videography which shows that the transition is much more gradual than is generally believed. The mechanism of the transition is discussed using a modified static force balance theory.

## Introduction

In gas metal arc welding (GMAW), there are various modes of metal transfer such as globular, repelled globular, projected spray, streaming, and rotating

transfer. These transfer modes show different arc stabilities, weld pool penetrations, spatter production, porosity population and level of gas entrapment. Lesnewich (Ref. 1) showed that the mode of metal transfer depends on many operational variables such as welding current, electrode extension, electrode diameter and polarity. Later, A. A. Smith (Ref. 2) reported that an entirely different type of metal transfer mode is produced when using carbon dioxide gas shielding as compared with argon shielding.

With many factors influencing metal transfer, theoretical models such as the static force balance theory (Refs. 3–5) and the pinch instability theory (Refs. 6–8) have been proposed to explain the

metal transfer phenomenon. These have had limited success.

In this study, the droplet size and droplet transfer frequency are analyzed both theoretically and experimentally. In the first section of this paper, the equilibrium drop sizes are calculated using the static force balance analysis and the pinch instability analysis. In the second section of this paper, measurements of droplet size at different welding currents are compared with the theoretical predictions. The limitations of the static force balance theory and the pinch instability theory in the prediction of the droplet size are discussed. In order to account for the deviation between these theories and the experimental data, a modification of the static force balance theory is proposed. The modified theory is tested using a pulsed current welding experiment.

## KEY WORDS

Modeling  
GMAW Metal Transfer  
Droplet Size Predict  
Transfer Frequency  
Taper Formation  
Shielding Gas  
Electrode Extension  
Static Force Bal. Theory  
Pinch Instability Theory  
Measurement

## Previous Studies

### Factors Affecting Metal Transfer Modes

The operational variables affecting the mode of metal transfer are the welding current, composition of shielding gas, extension of the electrode beyond the current contact tube, ambient pressure, active element coatings on the electrode, polarity, and welding material. Among these variables, welding current is the most common variable that the welder adjusts to obtain the desired metal transfer mode. At low welding currents, globular transfer mode occurs,

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transfer analysis postulates that the pinch force on the liquid column of molten metal due to the self-induced electromagnetic force enhances the break-up of the liquid column into droplets. An approximate analytical solution of the critical wavelength of this instability has been derived (Ref. 24) :

$$\lambda_c = \frac{2\pi\alpha}{\left(1 + \frac{\mu_0 I^2}{2\pi^2 R_y}\right)^{1/2}} \quad (8)$$

As seen in Equation 8, the welding current reduces the critical wavelength of the instability of the liquid jet and thus decreases the droplet size. In this way, the pinch instability theory claims to explain the general trend of decreasing drop size with increasing welding current.

Anno (Ref. 25) derived the frequency of fluctuation for a viscous jet with a surface charge and showed that viscous effects and surface charges have stabilizing effects. Allum (Ref. 8) showed that the viscous effects are negligible in liquid metal, but the stabilizing effects of surface charge are significant in the low welding current range.

The pinch instability theory suffers the same problems as the static force balance theory. These include difficulties in explaining the effect of electrode extension, and the repelling mode of metal transfer.

3) *Other Theories.* When using steel electrodes with argon shielding, the transition of metal transfer mode from globular to spray transfer has been reported to occur over a very narrow current range: less than 10 A (Ref. 1). In an attempt to explain the sharp transition in metal transfer mode as found by Lesnewich (Ref. 1), Needham, *et al.* (Ref. 19), using the static force balance theory, has proposed that the transition occurs when the welding plasma starts to exert a drag force on the drop.

#### Calculation of Equilibrium Drop Size

From the static force balance theory, the droplet size can be calculated under the assumption that the drop detaches from the electrode when the sum of the detaching forces equals the holding force :

$$F_y = F_{em} + F_g + F_d$$

(holding force) (detaching force) (9)

In calculating these forces acting on the liquid drops, a number of assumptions are made. Firstly, in calculating the electromagnetic force on the droplet, the electrons are assumed to condense uniformly on the liquid droplet only and

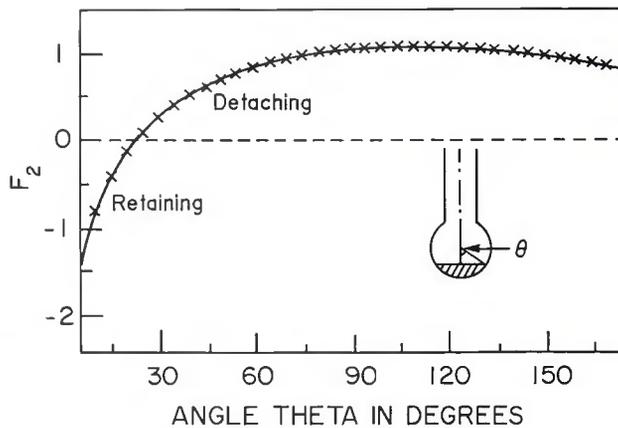


Fig. 1 — Variation of  $f_2$  as a function of  $q$  value.

$\theta$  is assumed to be 150 deg, which is the conduction zone angle when the droplet size is twice the size of the electrode. As seen in Fig. 1, the value of  $f_2$  does not change significantly when  $\theta$  is larger than 60 deg. Thus, this assumption will not cause any significant error in the electromagnetic force calculation.

For the drag force, the value of  $C_D$  in Equation 4 depends on the Reynold's number of the shielding gas. Since the velocity of the plasma in GMAW is not available, the plasma velocity was assumed to be 100 m/s, which is the same as the plasma velocity in GTAW (Ref. 27). The Reynold's number with this velocity is calculated to be approximately 9000, which lies in the Newton's law region. Thus, the values of  $C_D$  for the plasma is 0.44 (Ref. 21). For less-developed plasma jets, 10 m/s was used for the velocity of the fluid. The value  $C_D$  for 10 m/s gas flow rate is also calculated to be 0.44.  $A_p$  is the projected area of the sphere exposed to the fluid on a plane perpendicular to the direction of the motion and is given by Equation 10

$$A_p = \pi(R^2 - \alpha^2) \quad (10)$$

For the surface tension force, it is assumed that the interface between the liquid drop and solid electrode is perpendicular to the electrode axis. Also, the diameter of the drop holding neck was assumed to be the same size as the electrode diameter. The surface tension data were assumed to be: 0.9 N/m for aluminum (Ref. 27), 1.3 N/m for titanium (Ref. 28), and 1.8 N/m for steel (Ref. 27).

The total detaching force under various droplet size at a certain welding current is the summation of the electromagnetic force, the gravitational force, and the plasma drag force. At the crossover point, where the surface tension holding force and the total detaching forces meet, the equilibrium droplet size is determined. Figure 2 shows the total detaching force at various welding currents as a function of droplet size for steel electrodes with shielding gas velocities of 10 m/s, respectively. The crossover point at each welding current defines the equilibrium droplet size from the static force balance theory. The equilibrium droplet size of the steel electrode with shielding gas velocity of 10 m/s and 100 m/s are summarized in Fig. 3.

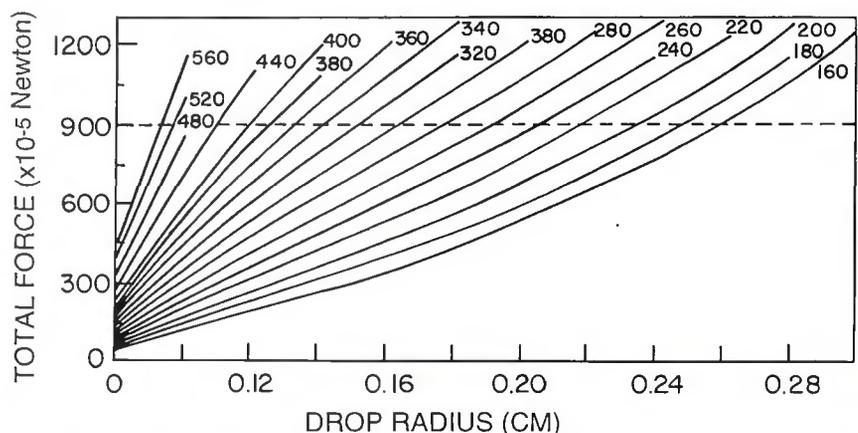


Fig. 2 — Variations of the detaching force as the droplet size at the steel electrode tip increases. The assumed argon plasma velocity is 10 m/s.











which produces the minimum droplet sizes at a given peak current. As seen in the figure, the droplet size predicted from the static force balance theory agrees within  $\pm 10\%$  with the experimental data. This experiment suggests that the cause of the deviation of droplet size in DC welding is tapering of the electrode tip.

#### Comparison between the Static Force Balance Theory and the Pinch Instability Theory

The pinch instability theory and the static force balance theory have been used in modeling metal transfer with somewhat disappointing results. The drop size predicted from the pinch instability theory as in Equation 8 is unable to predict the trends of the measured drop size as seen in Fig. 6. One of the fundamental requirements for the pinch instability phenomena to occur is that the liquid metal should be in the form of cylinder, which is at a higher state of free energy than a corresponding liquid metal sphere. However, observation with a high-speed video camera shows that as soon as the solid metal melts, it forms a spherical liquid drop, which is already in the lower free energy state as compared with a cylindrical liquid column. Thus, there is no driving force, and it is not logical to apply the pinch instability theory to a problem in which a cylindrical liquid column never exists. Also, the repelled globular transfer mode and the effect of the electrode extension is very difficult to explain by the pinch instability theory. From these observations, it is concluded that the pinch instability theory is an inappropriate way to explain metal transfer phenomena in either globular transfer or projected spray transfer.

However, in streaming metal transfer mode, a liquid column instability phenomenon is observed as seen in Fig. 18. In this case, a cylindrical liquid jet is formed at the end of the electrode, and it disintegrates into several drops away from the electrode tip. As long as the diameter of the liquid jet remains the same, the droplet size will remain the same. This may explain the plateau of drop size in the high current range of streaming transfer as seen in Fig. 6. In this case, where a cylindrical liquid column exists the pinch instability theory might be applicable.

The modified static force balance theory predicts a larger drop size than the experimentally measured value in general. One of the possible causes of this deviation is the drop movement on the electrode as seen in Fig. 19. The figure shows successive pictures of pendant drop motion over a 60 ms period. Pho-



Fig. 19 — Successive pictures of pendent drop motion prior to detachment from the steel electrode (total elapsed time: 60 ms). The shielding gas is Ar-2%O<sub>2</sub> shielding.

tographic analyses show that the peak velocity of the pendent drop reaches 20 cm/s and the dynamic force due to the pendent drop movement is calculated to be approximately  $2 \times 10^{-2}$  N. This is enough to account for the deviation of the drop size in the globular mode. Also, the surface tension value used in this study to calculate the holding force may be larger than the actual value of the system and, hence, may be incorrect. Combining these two effects, the predicted droplet size could be made to agree more closely with the experimentally measured data.

#### Conclusions

1) Metal transfer with steel electrodes shielded with Ar-2% oxygen shows a gradual transition, from globular to projected spray, followed by streaming transfer mode.

2) The static force balance theory can predict the droplet size in the globular transfer range, but it deviates significantly in the spray transfer range. The cause of the deviation is the geometry change of the electrode due to a taper formation at the electrode tip.

3) In order to analyze repelled globular transfer by the static force balance theory, it is necessary to determine another force that will act as a repelling force. A possible candidate for the repelling force is the cathode jet force on the drop.

4) When the taper is not formed, the static force balance theory can predict the droplet size very accurately in the spray transfer range, as has been shown in pulsed current welding.

5) The pinch instability theory fails to explain the effect of the electrode extension or of changes in the shielding gas on the metal transfer mode. The static force balance theory as modified by the taper formation can adequately explain metal transfer.

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