INEEL/CON-98-00695
CONF-980657--

Stability of a Pendant Droplet in Gas Metal Arc Welding

P. E. Murray

Lockheed Martin Idaho Technologies Company
Idaho National Engineering and Environmental Laboratory
Idaho Falls, ID 83415-2210

RECEIVED
JUL 14 1998
OSTI

Abstract

We develop a model of metal transfer in gas metal arc welding and compute the critical mass of a pendant droplet in order to ascertain the size and frequency of droplets detaching from the consumable metal electrode. These results are used to predict the mode of metal transfer for a range of voltage and current encompassing free flight transfer, and the transition between globular and spray transfer. This model includes an efficient method to compute the stability of a pendant droplet and the location of the liquid bridge connecting the primary droplet and the residual liquid remaining after detachment of the primary droplet.

Introduction

Gas metal arc welding uses a consumable metal electrode which melts in the presence of an electric arc. Droplets are expelled from the consumable electrode and impinge the weld pool in order to reinforce the weld. In some cases the electrode melts to produce a liquid globule that detaches from the electrode. In other cases the electrode melts to produce a liquid stream that breaks into droplets. Hence the stability of a pendant droplet in the presence of electromagnetic, gravitational, viscous and interfacial forces is an important theoretical issue in arc welding research. In particular, an understanding of the stability of a pendant droplet is needed to ascertain the characteristics of mass transfer such as the size and frequency of droplets impinging the weld pool and the transition between mass transfer by liquid globules and mass transfer by a spray of droplets.

The stability of droplets forming at a welding electrode determines the mode of metal transfer, but we are interested in the larger issue of process modeling. In particular, the objectives of process modeling are to ascertain the range of process variables that leads to a stable electric arc, and determine the dynamic response to a change in process variables. Therefore, a process model must include the interaction between the dynamics of metal transfer, plasma arc, electrical circuit and weld pool. A process model may be used to create a map of metal transfer which identifies the range of voltage and current at which free flight, spray and globular metal transfer occur. Within the range of voltage and current needed to sustain a stable metal transfer, a process model may be used to determine the mode of metal transfer, the voltage and current at which a transition occurs, and the effect of changes to the size and type of metal electrode and changes to other processing variables. For the welding researcher, this capability may be used to establish a sound approach to develop optimal welding procedures and assess strategies for process control.

This study stems from earlier research on modeling of gas metal arc welding (Watkins et al.[1]; Reutzel et al.[2]). The former includes a "mass on a spring" representation of an oscillating spherical droplet forming on a welding electrode. The latter retains the model of an oscillating spherical droplet and includes models of the electrical circuit, arc and electrode in order to compute the instantaneous arc length, electrode extension and melting rate. In these cases, the use of a lumped parameter representation of a pendant droplet leads to an efficient simulation of the growth and detachment of droplets. However, two deficiencies have been identified. First, the "spring" force was a constant determined empirically, but actually represents the force due to expansion and contraction of the surface of a droplet (Jones[3]). This force is related to the change of surface energy that accompanies deformation of the droplet. Second, the assumption of a spherical droplet precludes computation of the location of the liquid bridge connecting the primary droplet and the residual liquid remaining after detachment of the primary droplet. In fact, the location of the liquid bridge determines the masses of the primary droplet and the residual liquid remaining on the electrode. Hence the shape of a pendant droplet at the instant of detachment is needed. This introduces a dilemma for process modeling. Simulation of the exact shape of a growing, pendant droplet requires a detailed computation of the forces acting to deform the droplet. This issue was investigated by Jones[3] who constructed a model of a pendant droplet by blending shapes consisting of ellipsoids and polynomial volumes. The overall shape satisfies a macroscopic force balance, and detachment occurs when the "neck" of the droplet becomes very thin.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.

In this study we investigate the issue of efficiently computing the stability of a growing, pendant droplet on a welding electrode. Although Jones'[3] model resolves the problems associated with the earlier models due to Watkins et al.[1] and Reutzel et al.,[2] the problem of computing the motion and stability of pendant droplets without introducing complex shapes is unresolved. In fact, the electromagnetic force acting on a pendant droplet involves integrals that may be evaluated in closed form in the case of spherical droplets, but not in the cases of ellipsoids and polynomial volumes. We resolve this issue by appealing to previous experimental and theoretical studies suggesting that an elongated droplet at the instant of detachment may be represented by a spherical primary droplet, a spherical droplet attached to the electrode, and a liquid filament connecting the two droplets. We call this the idealized configuration of the free surface of the droplet. Large deformation of the free surface and elongation of the droplet lead to formation of a liquid filament and detachment of the primary droplet. Simulation of growth, deformation and detachment is used to determine the frequency of detaching droplets for a range of current encompassing globular and spray transfer. In order to validate the model, we gather experimental data on gas metal arc welding and create a map of metal transfer which identifies the range of voltage and current at which free flight, spray and globular metal transfer occur. The model is assessed by comparing numerical predictions and experimental measurements of the mode of metal transfer, the frequency of droplets detaching from the electrode, and the current at the transition from globular to spray transfer.

Background

Several forces cause droplets to detach from the metal electrode in gas metal arc welding. These include electromagnetic, gravitational and drag due to flowing plasma (Waszink and Graat[4]). Experimental observations suggest that at low current the electrode melts to produce a liquid globule that detaches in the manner of a pendant droplet growing at the end of a capillary tube. In this case the process of detachment may be assumed quasi static and so the criterion for detachment may be obtained from a balance of forces (Kim and Eagar[5]). However, the exact shape of the droplet is needed to determine the critical mass because the pressure inside the droplet depends on the radius of curvature of the surface. Although methods to compute the equilibrium shape of pendant droplets have been known awhile, Kim and Eagar[5] used an approximate condition of equilibrium:

$$F = 2\pi r\gamma , \tag{1}$$

where F is the total downward force on the droplet, r is the radius of the electrode and γ is the surface tension. Assuming an axisymmetric droplet, the correct relation is:

$$F = 2\pi r\gamma(\sin\theta - r\kappa), \tag{2}$$

where θ is the contact angle at the liquid solid interface and κ is the mean curvature at the liquid solid interface. However, quasi static shapes are precluded in arc welding because the fluid is always in motion due to the presence of electromagnetic forces. Notwithstanding the limitations of the quasi static theory, the static shape of a pendant droplet in gas metal arc welding was recently computed (Nemchinsky[6]), but the efficacy of this approach is limited to arc welding at low current.

Experiments suggest that at high current the electrode melts to produce a liquid stream that breaks in the manner of an unstable liquid jet. In this case breakup is caused by a capillary instability known as the Rayleigh instability (Lamb[7]). The classic result due to Rayleigh is

$$\lambda = (9.016)R , \tag{3}$$

where λ is the wavelength of maximum instability and R is the radius of an undisturbed, cylindrical column of liquid. In arc welding, however, breakup is assisted by the presence of electromagnetic forces that pinch the liquid stream. A criterion for the stability of an inviscid, cylindrical column of liquid in the presence of an electromagnetic force was obtained by Allum[8]:

$$\lambda = 2\pi R\left\{0.625\left(\frac{\mu_0 I^2}{\pi^2\gamma}\right)^{0.278}\right\}^{-1} , \tag{4}$$

where μ_0 is the permeability of free space and I is the current. The critical mass of the droplet satisfies the following relation:

$$m_c = \rho\pi R^2 L , \tag{5}$$

where m_c is the critical mass of the droplet, ρ is the density of the droplet, L is the critical length, and R is the radius of an undisturbed, cylindrical column of liquid. Setting the critical length equal to 0.75λ (Allum[8]), this equation may be solved to obtain the critical mass.

The critical mass of liquid may be inferred from the preceding criteria, but the mass of the primary droplet, the residual mass remaining on the electrode, and the presence of satellite droplets must be obtained from the shape of the droplet at the instant of detachment. Hence a computation of the dynamic shape of droplets in gas metal arc welding was recently undertaken by Simpson and Zhu[9] and Haidar and Lowke[10]. However, the dynamics of the liquid filament connecting the primary droplet and the residual mass is not well understood. A recent study examined the time to break this filament and suggested that the time follows scaling laws that are independent of boundary and initial conditions (Eggers[11]). Moreover, viscous and interfacial forces that affect the resistance to breakup may be important in thin liquid filaments.

The stability of pendant droplets is relevant to other technologies, and so experiments have been performed to examine the forces that lead to elongation and breakup of pendant droplets and the motion of droplets before breakup (Zhang and Basaran[12]). These experiments and related ones using pendant droplets forming at the end of a capillary tube had shown that growth, oscillation and elongation of the droplet leads to formation of a liquid bridge. This bridge becomes a filament that breaks. The recoil accompanying breakup may lead to creation of satellite droplets. These observations had been supported by detailed numerical simulations of growth and breakup of inviscid droplets (Schulkes[13]) and simulations of growth and oscillation of viscous droplets (Basaran and DePaoli[14]). Moreover, the primary droplet, satellite droplet and the residual droplet that remain after detachment are approximately spherical, but are slightly deformed from the spherical shape at the instant of detachment.

Method

In this study we develop a model that includes an efficient method to compute the motion and stability of a pendant droplet and the location of the liquid bridge connecting the primary droplet and the residual droplet remaining after detachment of the primary droplet. The results of the studies previously cited suggest an idealized configuration consisting of a pendant spherical cap and a sphere connected by a liquid bridge, which is shown in Fig. 1. The length of the liquid bridge can be positive, zero or negative, and so this idealized configuration may be used to represent pendant droplets that are elongated or compressed. Moreover, the idealized configuration may be used to represent droplets at equilibrium or droplets that have a thin liquid "neck" at the onset of detachment, as shown in Fig. 1.

To obtain the mass, momentum and position of the droplet during growth, we formulate the equation of motion of a pendant droplet that grows by melting an electrode in the presence of an electric arc. The equation of motion is a one dimensional, macroscopic force balance that ensures efficiency of computation:

$$m\ddot{x} + \dot{m}_{out}V_{out} - \dot{m}_{in}V_{in} = mg + F_{em} + F_{drag} + F_{viscous} + F_{surface}, \quad (6)$$

where m is the mass of the droplet, x is the center of mass of the droplet and so $\ddot{x}$ is the acceleration of the droplet, $\dot{m}_{out}$ is the rate of mass leaving due to detachments, $\dot{m}_{in}$ is the rate of mass entering due to melting of the electrode, V_{out} is the velocity of detaching droplets, V_{in} is the velocity of the electrode entering the electric arc, g is the gravitational acceleration, F_{em} is the electromagnetic force, F_{drag} is the viscous drag due to the flowing shielding gas, $F_{viscous}$ is the viscous force due to flow inside the droplet, and $F_{surface}$ is the interfacial force due to expansion and contraction of the surface of the droplet.

We include a few remarks concerning the electromagnetic force acting on the pendant droplet. The electromagnetic force due to the flow of current in a spherical droplet was formulated by Green[15] and was generalized by Amson[16]. In case the shape of the droplet and the location of current flow through the surface of the droplet are known, the results due to Amson[16] may be used to compute the electromagnetic force on an elongated droplet. In fact, Jones[3] used experimentally observed shapes in order to compute the electromagnetic force and deduce the effect of the liquid "neck" on detachment.

In this study we assume that the pendant droplet is spherical and use Green's[15] formula to compute the electromagnetic forces acting on the droplet. We assume that the arc encompasses the surface of the droplet and the current density is uniform at the surface. In case the droplet is elongated, a liquid bridge connects the droplet and electrode. Since the electromagnetic force has a logarithmic singularity in the limiting case of a liquid bridge that vanishes, the force is large at the onset of detachment. This underscores the importance of modeling the presence of a liquid bridge. An approximation to the radius of the liquid bridge is obtained from the radius of a cylinder that has the same mass and center of mass as the droplet. Although current flows through the liquid bridge, we assume that flow of current into the arc is through the surface of the primary droplet only. The radii of the electrode, primary droplet and liquid bridge are used to compute the angle encompassing the surface of the primary droplet which conducts current. In the case of an elongated droplet, the electromagnetic force is given by the following relation:

$$F_{em} = \frac{\mu_0 I^2}{4\pi}\left(-\frac{1}{4} + \ln\frac{R\sin\theta}{r} - \frac{1}{1-\cos\theta} + \frac{2}{(1-\cos\theta)^2}\ln\frac{2}{1+\cos\theta}\right), \quad (7)$$

where μ_0 is the permeability of free space, I is the current, r is the radius of the electrode, R is the radius of the equivalent sphere of mass m, and θ is the angle encompassing the surface of the primary droplet which conducts current. This angle is obtained from the following relation:

$$\sin\theta = \frac{r_b}{R}, \quad (8)$$

where r_b is the radius of the liquid bridge which is approximated by the radius of the equivalent cylinder of mass m and length $2x$.

Other forces included in Eq. (6) are the viscous and interfacial forces. The viscous drag due to the shielding gas flowing around the droplet is approximated by Stokes' drag law for a sphere immersed in a viscous fluid (Lamb[7]). The viscous force due to flow inside the droplet is neglected since the Reynolds number is approximately equal to 500 (Waszink and Van den Heuvel[4]). The interfacial force due to expansion and contraction of the surface of the droplet is related to the change in surface energy that accompanies deformation of the droplet (Jones[3]). In this study, the interfacial force is approximated by the following relation:

$$F_{surface} = -\gamma\left(\frac{S(2\bar{x}) - S(\bar{x})}{\bar{x}}\right)\frac{x-\bar{x}}{r}, \quad (9)$$

where γ is the interfacial tension, $S(x)$ is the surface area of the droplet as a function of the center of mass, $\bar{x}$ is the center of mass of the droplet at equilibrium, and r is the radius of the electrode. The surface area of the droplet is approximated by the surface area of the droplet in the idealized configuration. Details of the computation of the idealized configuration are given below.

In the idealized configuration, the mass m is apportioned into mass m_0 attached to the electrode and mass m_1 attached to mass m_0 by a liquid filament. We require that the mass and center of mass of the idealized configuration satisfy the following relations:

$$m = m_0 + m_1, \quad (10)$$

$$xm = x_0 m_0 + x_1 m_1, \quad (11)$$

where x_0 is the center of mass m_0 and x_1 is the center of mass m_1. Assuming that mass m_0 is a spherical cap, we obtain the following relations for the mass and center of mass of the residual droplet:

$$m_0 = \rho \frac{\pi}{6} h \left(3r^2 + h^2\right), \tag{12}$$

$$x_0 = \frac{h}{2} \frac{\left(2r^2 + h^2\right)}{\left(3r^2 + h^2\right)}, \tag{13}$$

where r is the radius of the electrode, h is the height of mass m_0, and ρ is the density of the droplet. Using Eqs. (10)-(13), we obtain the following relations for the mass and center of mass of the primary droplet:

$$m_1 = \rho \frac{\pi}{3} \left(4R^3 - \frac{h}{2} \left(3r^2 + h^2\right) \right), \tag{14}$$

$$x_1 = \frac{16R^3 x - h^2 \left(2r^2 + h^2\right)}{16R^3 - 2h\left(3r^2 + h^2\right)}, \tag{15}$$

where R is the radius of the equivalent sphere of mass m.

In order to determine the stability of a pendant droplet, we find the minimum length of the droplet in the idealized configuration which satisfies the constraints on the mass and center of mass. This is obtained by finding the configuration that minimizes the distance from the center of mass of the primary droplet to the point at which the liquid filament connects the residual droplet. The condition of minimization is given by $\frac{\partial}{\partial h}(x_1 - h) = 0$. This leads to a nonlinear equation that is solved by a suitable numerical method such as Newton's method in order to obtain h, which is substituted into Eqs. (12)-(15) to obtain the values of m_0, m_1, x_0 and x_1. The minimum length of the droplet in the idealized configuration is equal to $x_1 + r_1$, where r_1 is the radius of the equivalent sphere of mass m_1.

Recall that growth and elongation of a pendant droplet leads to formation of a liquid bridge that becomes a filament and breaks. Hence we introduce the dimensionless critical length of a pendant droplet, which is defined as L_c/r, where L_c is the length of the droplet at the instant of detachment, and r is the radius of the electrode. In order to determine the critical length, we appeal to the experimental results due to Zhang and Basaran[12] which show that L_c/r takes values in the range $5-10$. The exact value depends on many variables, which include the viscosity and surface tension of the droplet, the force acting on the droplet, the growth rate of the droplet, and the radius of the electrode. In the case of gas metal arc welding, measurements of L_c/r and its dependence on welding processing variables are unavailable. However, we know that breakup occurs before the liquid bridge becomes too long and slender because the presence of a thin liquid bridge leads to a large increase in the electromagnetic force which promotes breakup of the liquid bridge (Jones[3]). This suggests that we select the lowest value of L_c/r reported by Zhang and Basaran[12], $L_c/r = 5$, and compare L_c/r and L/r, where L is the minimum length of the droplet in the idealized configuration. Hence we assume that breakup occurs in case the minimum length of the droplet in the idealized configuration exceeds $5r$.

A final note concerns the melting rate of the electrode, which is related to the current and the extension of the electrode into the arc. Details may be found in Lesnewich[17]. The melting rate correlation given by Lesnewich[17] and the equation of motion given by Eq. (6) are combined to form a set of differential equations that are integrated by a suitable numerical method such as the Runge Kutta method, in order to determine the mass, position and momentum of the growing droplet. The growth rate and stability of the pendant droplet are monitored and the stability criterion is used to determine whether detachment occurs.

Results

In order to assess the validity of the model, bead on plate welds were made on carbon steel type A36 using an automated gas metal arc welding apparatus. A Miller Maxtron 450 power supply was used in a constant voltage mode. The shielding gas was a mixture of 98% Ar_2 and 2% O_2 and the flow rate was fixed at 50 scfh. The electrode was carbon steel type AWS ER70S-6 and its diameter was 1.14 mm. The distance from the contact tip to the base metal was varied from 13 mm to 19 mm, the voltage was varied from 25 v to 33 v, and the speed of the electrode was varied from 60 mm/s to 300 mm/s, which produced a variation in current from 130 A to 380 A. The arc was filmed using a special camera designed for a high intensity light source. The mode of metal transfer was recorded for each weld. In case the transfer was globular with intermittent spray, the mode was called mixed. Hence a map of metal transfer was created and the result of this experiment is shown in Fig. 2.

The result shown in Fig. 2 identifies the range of voltage and current needed to sustain a steady state, free flight metal transfer and a stable electric arc. In particular, the "short arc" limit occurs in case the voltage is too low to sustain a stable electric arc, and the "long arc" limit occurs in case the voltage is too high to sustain a stable electrode extension. A steady state, free flight metal transfer occurs within these limits. Inside the range of stable operation, the experimental data indicates that the transition between mass transfer by globules and mass transfer by spray occurs within a range of current, but the transition between mixed and spray transfer occurs at approximately 225 A. In comparison, Lesnewich[18] reported an abrupt transition at 210 A for a 0.045 inch diameter carbon steel electrode, zero extension of the electrode, and a shielding gas of 99% Ar_2 and 1% O_2.

The model of the stability of a pendant droplet is used to compute the frequency of detachment of droplets from a 1.2 mm carbon steel electrode. These computations were made for various values of current encompassing free flight metal transfer that includes globular and spray. The result is shown in Fig. 3. We note that the computed frequency undergoes two abrupt increases, and the location of the first abrupt increase in frequency approximately coincides with the measured transition from globular to spray transfer. In particular, the model predicts that the transition occurs between 180 A and 240 A and depends on the electrode extension. Moreover, the model predicts that the transition current decreases with an increase in electrode extension, which agrees with earlier experimental findings (Lesnewich[18]). The experimental data shown in Fig. 2 indicates that the transition from globular to spray transfer occurs between 175 A and 225 A. However, this data includes the "long arc" limit in which the electrode extension reduces to zero and the "short arc" limit in which the arc length reduces to zero at the onset of short circuiting. Therefore, the measured transition current includes an uncertainty due to variations in the electrode extension. Notwithstanding this uncertainty, the computed transition current for electrode extensions in the range 5 mm to 15 mm is approximately equal to the measured range of current at the transition from globular to spray transfer.

Another noteworthy observation concerns the motion of the pendant droplet. We show in Fig. 4 a computation of the center of mass and overall length of a pendant droplet growing at the tip of an electrode. In this particular case, 200 droplets are detaching from the electrode during each second. Growth and elongation of the droplet leads to formation of a liquid bridge that connects the primary droplet and the residual liquid attached to the electrode. In fact, the presence of a thin liquid bridge leads to a large increase in the electromagnetic force which promotes detachment of the droplet (Amson[16]; Jones[3]). As the liquid bridge forms, the droplet undergoes rapid elongation and attains a critical length at the onset of detachment.

In order to further assess the validity of the model, bead on plate welds were made on aluminum alloy type 6061 using the same automated gas metal arc welding apparatus. The shielding gas was 100% Ar_2 and the flow rate was fixed at 30 scfh. The electrodes were aluminum alloy type AWS ER4043 and their diameters were 0.89 mm and 0.76 mm. The distance from the contact tip to the base metal was fixed at 20 mm, the voltage was varied from 18 v to 22 v, and the speed of the electrode was varied from 100 mm/s to 350 mm/s, which produced a variation in current from 60 A to 200 A. The mode of metal transfer and the frequency of droplets detaching from the electrode were recorded for each weld. A comparison of the measured and computed frequencies is shown in Figs. 5 and 6.

The results in Figs. 5 and 6 demonstrate that the model predicts the abrupt increase in frequency that accompanies the transition from globular and spray transfer. However, the accuracy of the computed frequency is limited, which may be due to the assumptions and approximations used to compute the forces acting on a pendant droplet, the idealized configuration, and the critical length for stability. Notwithstanding these limitations, the model may be used to predict the mode of metal transfer and the current at which the transition occurs. Although Lesnewich[18] noted an abrupt change in the frequency of detachments at the transition between globular and spray transfer, the experiments and simulations in this study show that the frequency undergoes an abrupt increase in a range of current which encompasses the transition from globular to spray.

Conclusion

We developed an efficient method to compute the motion and stability of a pendant droplet growing at the end of a welding electrode in gas metal arc welding. To accomplish this objective, we introduced an idealized configuration of a pendant droplet which was obtained from previous experimental and theoretical studies of the growth of pendant droplets at the end of a capillary tube. The position and momentum of a pendant droplet were determined by solving the equation of motion, and the stability of a pendant droplet was determined by comparing the minimum length of the droplet in the idealized configuration and the critical length. We used this model to compute the frequency of detaching droplets for a range of current encompassing globular and spray transfer. We assessed the validity of the model by comparing theoretical predictions and measurements of the mode of metal transfer and the transition from globular to spray transfer. We conclude that the computed frequency of detaching droplets is a suitable indicator of the mode of metal transfer.

Acknowledgments

Work supported by the U. S. Department of Energy, Office of Basic Energy Sciences under DOE Idaho Operations Contract No. DE-AC07-94ID13223. The author is grateful to Mr. D. E. Pace and Mr. E. W. Reutzel for the experimental data, and to Dr. H. B. Smartt for helpful discussions on this subject.

References

1. A. D. Watkins, H. B. Smartt, and J. A. Johnson, *Proceedings of the 3rd International Conference on Trends in Welding Research*, Gatlinburg, Tennessee, June 1-5 (1992).
2. E. W. Reutzel, C. J. Einerson, J. A. Johnson, H. B. Smartt, T. Harmer, and K. L. Moore, *Proceedings of the 4th International Conference on Trends in Welding Research*, Gatlinburg, Tennessee, June 5-8 (1995).
3. L. A. Jones, *Dynamic Electrode Forces in Gas Metal Arc Welding*, Ph.D. Dissertation, Massachusetts Institute of Technology (1995).
4. J. H. Waszink and L. H. J. Graat, *Welding J.*, 62, 109s-116s (1983).
5. Y. S. Kim and T. W. Eagar, *Welding J.*, 71, 269s-278s (1993).
6. V. A. Nemchinsky, *J. Phys. D*, 27, 1433-1442 (1994).
7. H. Lamb, *Hydrodynamics*, 6th Ed., Cambridge University Press (1932).
8. C. J. Allum, *J. Phys. D*, 18, 1431-1446 (1985)
9. S. W. Simpson and P. Zhu, *J. Phys. D*, 28, 1594-1600 (1995).
10. J. Haidar and J. J. Lowke, *J. Phys. D*, 29, 2951-2960 (1996).
11. J. Eggers, *Phys. Rev. Lett.*, 71, 3458-3460 (1993).
12. X. Zhang and O. A. Basaran, *Phys. Fluids*, 7, 1184-1203 (1995).
13. R. M. S. M. Schulkes, *J. Fluid Mech.*, 278, 83-100 (1994).
14. O. A. Basaran and D. W. DePaoli, *Phys. Fluids*, 6, 2923-2943 (1994).
15. W. J. Greene, *Trans. Amer. Inst. Elect. Engrs.*, 79, 194-201 (1960).
16. J. C. Amson, *Brit. J. Appl. Phys.*, 16, 1169-1179 (1965).
17. A. Lesnewich, *Welding J.*, 37, 343s-353s (1958).
18. A. Lesnewich, *Welding J.*, 37, 418s-425s (1958).

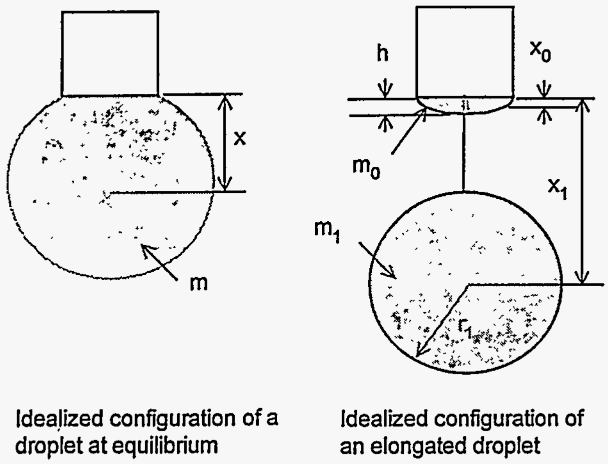

Fig. 1. The idealized configuration of a pendant droplet consisting of a pendant spherical cap and, in the case of an elongated droplet, a sphere connected by a liquid bridge.

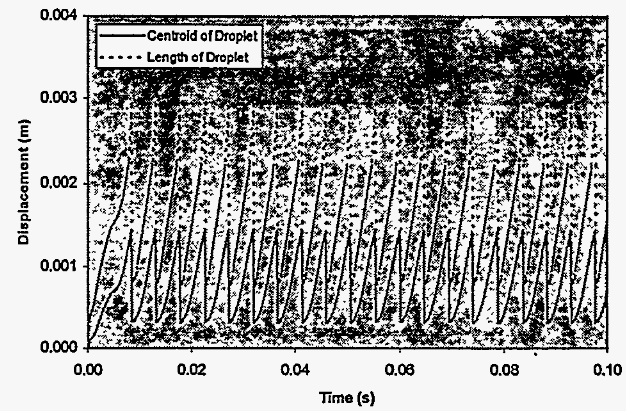

Fig. 4. A computation of the center of mass and length of metal droplets detaching from a 1.2 mm carbon steel electrode with a frequency equal to 200 droplets per second.

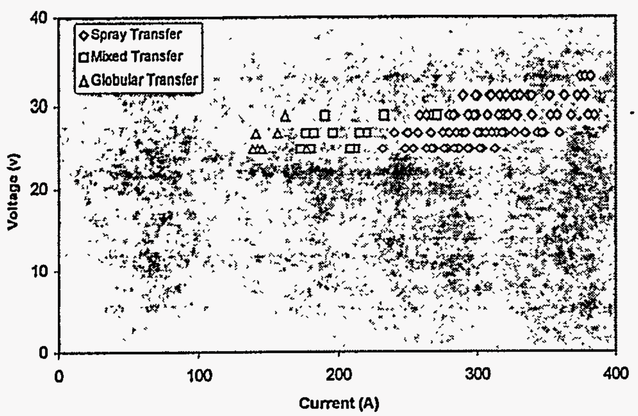

Fig. 2. The measured mode of metal transfer for gas metal arc welding using a 1.2 mm carbon steel electrode and a shielding gas consisting of 98% argon and 2% oxygen.

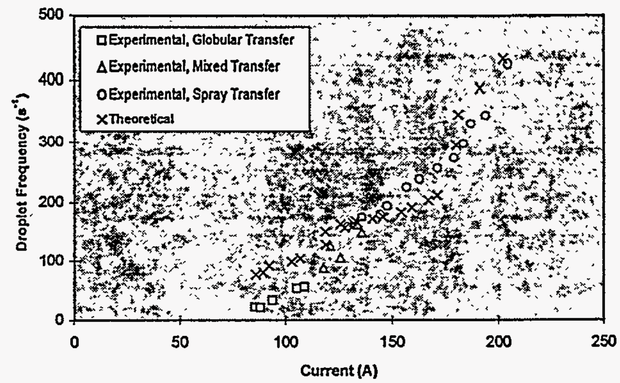

Fig. 5. The measured and computed frequency of transfer of metal droplets for gas metal arc welding using a 0.89 mm aluminum electrode.

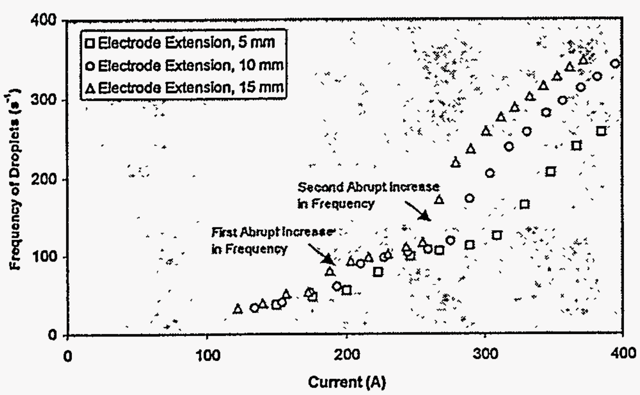

Fig. 3. The computed frequency of transfer of metal droplets for gas metal arc welding using a 1.2 mm carbon steel electrode and three values of the electrode extension.

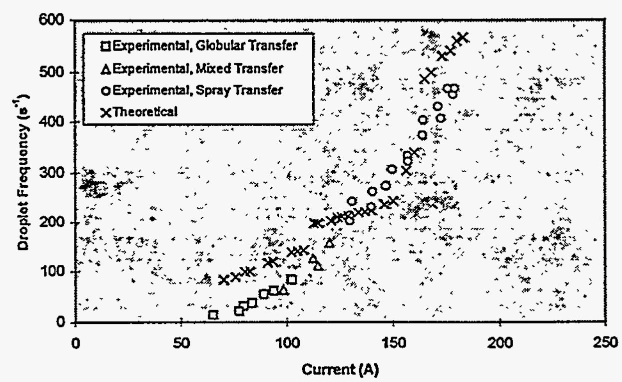

Fig. 6. The measured and computed frequency of transfer of metal droplets for gas metal arc welding using a 0.76 mm aluminum electrode.