Globular-to-Spray Transition in Cold Wire Gas Metal Arc Welding

CW-GMAW transitions faster to a spray transfer regime

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ABSTRACT

The electrical current required for a transition from globular to spray droplet transfer during gas metal arc welding (GMAW) is determined by the specified wire feed speed in the case of constant-voltage power supplies. Generally, in narrow groove welding, spray transfer is avoided, because this transfer mode can severely erode the groove sidewalls. This work compared the globular-to-spray transition mechanism in cold wire gas metal arc welding (CW-GMAW) vs. standard GMAW. Synchronized high-speed imaging with current and voltage samplings were used to characterize the arc dynamics for different cold wire mass feed rates. Subsequently, the droplet frequency and diameter were estimated, and the parameters for a globular-to-spray transition were assessed. The results suggest that the transition to spray occurs in CW-GMAW at a lower current than in the standard GMAW process. The reason for this difference appears to be linked to an enhanced magnetic pinch force, which is mainly responsible for metal transfer in high-current welding conditions.

KEYWORDS

- Gas Metal Arc Welding (GMAW) • Cold Wire Gas Metal Arc Welding (CW-GMAW) • Globular-to-Spray Transition • Transition Current • Metal Vapor Production • Thermal Balance

Introduction

Understanding the phenomena controlling metal transfer in gas metal arc welding (GMAW) is fundamental to identifying the correct specifications and process parameters used in a welding procedure. The use of incorrect parameters may impair the quality and reliability of welds in service.

While studying metal transfer, a key parameter is the critical arc current at which globular transfer transitions to

spray transfer. Presently, this is poorly understood due to the complexity of the underlying physics. For instance, Lowke (Ref. 1) proposed an equation to calculate the transition current, but this model is only applicable to welding using 100% argon shielding gas, while a wide range of welding applications use mixed gases or CO₂ shielding.

Moreover, the model only takes into account the steel wire diameter, the surface tension of the molten metal, and the magnetic permeability of free space. Lowke (Ref. 2) subsequently extended the equation to aluminum and copper electrodes. Methong et al. (Ref. 3) reported that during the transition in a binary shielding gas (argon and carbon dioxide), the metal vapor concentrates toward the edges of the arc as the welding current increases.

Ribeiro et al. (Ref. 4) reported that in cold wire gas metal arc welding (CW-GMAW), the increase of the cold wire feed rate leads to a significant increase in current compared to the standard GMAW when in spray transfer mode. Moreover, Ribeiro et al. (Ref. 5) reported CW-GMAW operating in spray transfer can be used for narrow groove welding (NGW) with no sidewall erosion, because the arc is pinned preferentially to the cold wire.

The CW-GMAW process involves an increase in current when the cold wire feed rate increases. However, unlike GMAW, when this occurs the area of the heat-affected zone (HAZ) decreases. It is worthwhile to study the influence of this phenomenon on the globular-to-spray transition to clarify how metal transfer mechanisms differ from conventional GMAW before it can be used in practical applications. This work seeks to identify the conditions under which CW-GMAW transitions to spray transfer in comparison to GMAW using the same welding parameters.

Methodology

Bead-on-plate welds were deposited on AISI 1020 plain carbon steel with a thickness of 6.35 mm (¼ in.) using a Lincoln Electric Power Wave® R500 power source operating in

Fig. 1 — General setup for welding experiments.

constant voltage (CV). ER70S-6 was used as electrode wire and cold wire, with nominal diameters of 1.2 mm (0.045 in.) and 0.9 mm (0.035 in.), respectively. Table 1 presents the nominal chemical composition of the welding wire and the base metal. The shielding gas mixture used for all welds was Ar-15% CO₂ at the flow of 40 ft³/h (19 L/h).

The equipment and gun layout for welding is presented in Fig. 1, where the cold wire feed position can be seen as relative to the electrode wire and the device used to feed the auxiliary wire. During welding, the current and voltage were recorded at a frequency of 10 kHz for 2 s to assess the electric properties of the arc in-situ. Moreover, synchronized high-speed imaging was used to monitor the dynamic behavior of the arc at 5000 frames/s for 2 s with a shutter speed of 25 μs, while a 900 nm ± 10 nm filter was used to visualize the arc. To determine the welding parameters used in this study, preliminary welds were performed to identify parameters that caused metal transfer to be fully globular and fully spray. Hence, the transition current range from globu-

lar-to-spray was identified for standard GMAW.

Subsequently, a cold wire feed was introduced to determine if the globular-to-spray transition occurred at a different arc current in CW-GMAW. Table 2 presents the welding parameters used to determine the range of globular-to-spray transition that occurs in standard GMAW along with their response in current and voltage. It was found the range for the transition current for GMAW is 265 to 293 A.

After determining the globular-to-spray transition parameters, the same parameters were used to carry out the CW-GMAW welding using cold wire feed rates of 20, 80, and 140%. These feed rates refer to mass feed rate in units of kg/s as a fraction of the welding electrode wire mass rate. For all the cold-wire-assisted welds, the contact to work distance (CTWD) was kept the same (17 mm).

The images obtained using a 900 nm filter were manually processed to measure the droplet detachment frequency (Hz). However, prior to the manual measurement of droplets, the fast Fourier transform (FFT) of the voltage signal was performed to estimate the droplet frequency. Due to a 2–12% margin of error between the manually counted and FFT estimated droplet frequency, the reported droplet frequency in this work refers to the manually counted value. Moreover, the FFT determined value of frequency cannot be statistically treated to provide the mean and variation range, because it is only one value of frequency. The droplet diameter was estimated from the detachment frequency. The droplet frequency was counted in five intervals of 0.36 s each, summing in total 1.8 s of the total 2 s sampled during welds. The values presented are thus the average of five measurements, which consider approximately the whole sampled time, and the error bars represent a 95% confidence interval.

Based on the droplet diameter measurements, the transition from globular to spray could be identified based on when the droplet was smaller than the nominal electrode diameter (which was 1.2 mm in the present work). Table 3 presents the welding parameters for cold wire welds and the current and voltage machine response after welding. The droplet diameter was calculated from the measured values of drop detachment frequency (Ref. 6):

$$d = (WFS \times d_e^2 / 40 \times f_d)^{1/3} \quad (1)$$

Table 1 — Nominal Composition of the Welding Wire and Base Metal

Material	Nominal Chemical Composition (wt-%)						
	C	Si	Mn	P	S	Cr	Fe
AISI 1020	0.18	—	0.30	—	Max. 0.005	—	Bal.
ER70S-6	0.15	1.15	1.85	0.025	0.035	0.05	Bal.

Table 2 — Welding Parameters Used to Determine the Globular-to-Spray Transition Along with Their Response Average Voltage and Current

Welding Process	WFS (in./min) [m/min]	U (V)	TS (in./min) [cm/min]	CTWD (mm)	Transfer Mode Observed	Avg. U (V)	Avg. I (A)
GMAW	250 [6.35]	25			Globular	24.54	239.61
GMAW	270 [6.86]	26			Globular	25.84	242.15
GMAW	290 [7.36]	27			Globular	26.81	243.81
GMAW	310 [7.87]	28	25 [63.5]	17	Transition	27.79	264.94
GMAW	330 [8.38]	29			Transition	29.20	292.81
GMAW	350 [8.89]	30			Spray	29.81	294.65

Fig. 2 — Oscillograms for standard GMAW conditions: A — 250 in./min; B — 270 in./min; C — 290 in./min; D — 310 in./min; E — 330 in./min; F — 350 in./min. Plot for the entire sampling.

where d is the droplet diameter, WFS is the wire feed speed, d_e is the diameter of the wire electrode, and f_d is droplet frequency.

The instantaneous arc resistance (R_i) was estimated using the values of the instantaneous voltage (U_i) and instantaneous current (I_i) according to the following:

$$R_i = U_i / I_i \quad (2)$$

The values of R_i were averaged over the sampled period of 2 s and presented in the average resistance of the arc plasma section.

Results

Metal Transfer Dynamics

Figure 2 shows the oscillograms for the standard GMAW conditions used to identify the transition zone between globu-

lar and spray modes. High-speed images are shown only at the transition, which occurred between 310 and 350 in./min, and the spray condition at a wire feed speed of 350 in./min.

Figure 3 shows representative high-speed images of the two conditions in which globular-to-spray transition occurs, namely Fig. 3A and B; and the fully spray condition is shown in Fig. 3C. As noted, the criterion adopted to distinguish between those was based on whether the droplet diameter is larger than the electrode diameter, corresponding to globular transfer. A droplet diameter lower than the electrode diameter indicates spray transfer mode. However, during transition the droplet size may fluctuate lower or higher than the electrode diameter.

The conditions shown in Fig. 2B and C transition from globular transfer mode to short circuit, which Scotti et al. (Ref. 7) described as interchangeable metal transfer (ITM). This can be ascribed to the following: 1) a variation in specific resistivity of the arc column, and 2) a higher post short-circuit current. These two features in ITM come from a higher increase in wire feed speed compared to a small increase in voltage, as can be

Table 3 — Welding Parameters Used for CW-GMA Welds to Investigate the Globular-to-Spray Transition Along with the Response in Voltage and Current

Welding Process	WFS (in./min) [m/min]	CW Percent (%)	U (V)	TS (in./min) [cm/min]	CTWD (mm)	Avg. U (V)	Avg. I (A)
CW-GMAW	310	20	28	25 [63.5]	17	28.12	270.28
	[7.87]	80				28.12	274.42
		140				28.17	275.41
		20				29.14	279.55
	330	80	29			29.14	283.01
	[8.89]	140	29.14			299.07

Fig. 3 — A, B — High-speed images of transition from globular to spray; C — the fully spray condition.

noted from the welding parameters in this study. As soon as the energy in the arc is sufficient to sustain a spray transfer, then interchangeable transfer ceases.

The spray transfer current in standard GMAW is, on average, 294.7 A (as reported in Table 2). Figure 4 shows the high-speed images of the welds in the transition region with cold wire feed. The droplet size was close to the wire diameter when 20% cold wire feed rate was used — Fig. 4A. When 80% cold wire feed rate was used, there was an instantaneous decrease in droplet diameter, showing the transition from globular to spray began at this cold wire feed rate — Fig. 4B. Further increasing the cold wire feed rate led to a full axial spray transfer mode with droplets smaller than the wire diameter. In fact, the current applied for the spray regime condition is, on average, 275.4 A, which is smaller than the current for fully spray transfer for standard GMAW using the same wire feed speed and voltage.

It is also interesting to note that when the cold wire was introduced at a feed rate of 20%, there was an instability of voltage and current signals, which are reflected in the current oscillation in Fig. 5A. When the cold wire feed was increased to 80%, that led to a stabilization of the current and voltage signals, as shown in Fig. 5B. However, at a cold wire feed rate of 140%, an instability in the voltage and current signal was caused by the injection of more cold wire than could be accom-

modated by the arc. This caused part of the cold wire to emerge out of the pool and disturb the arc — Figs. 4C and 5C. In Fig. 5C, this disturbance was a short circuit caused by the cold wire tip; when this happened, the voltage decreased to levels below 10 V.

Figure 6 shows the high-speed images for the CW-GMAW welds using a feed rate of 330 in./min. Figure 6A shows that when 20% cold wire feed was introduced, the droplet diameter was about the size of the wire diameter, causing behavior similar to that shown in Fig. 5. When 80% cold wire was introduced in the arc, the droplet diameter started to decrease to levels lower than the electrode diameter. Again, for this particular feed rate, there was a stabilization of the arc phenomena, which reflected the stabilization of the measured signals of voltage and current. The arc position regarding the cold wire was intermediate; the arc was not completely pinned to the secondary wire as reported by Ribeiro et al. (Ref. 4).

Further increasing the cold wire led to instabilities due to insufficient energy levels in the arc to sustain the extra wire, as observed in Fig. 5C. At the cold wire fraction (140%), part of the cold wire again emerged out the pool. The cold wire emerging out of the pool can short circuit the arc (refer to Fig. 7C), briefly causing the values of voltage to drop to levels below 10 V. It can be seen that the arc was completely attached to the cold wire.

Fig. 4 — High-speed images of CW-GMAW-310 in./min-28 V-25 in./min-17 mm: A — 20%; B — 80%; C — 140%.

Figure 8 shows the oscillograms for 350 in./min, which was a fully axial spray transfer mode. A cold wire feed rate of 80% could be accommodated by the energy supplied by the arc so no instability could be detected. In fact, it appeared the arc stabilized, because the spread of voltage and current were reduced.

It was also observed that increasing the cold wire feed rate to 140% did not cause instabilities — Fig. 8C. The transition current for spray in standard GMAW using 350 in./min was 294.7 A (refer to Table 2).

Cyclogrammes

Cyclogrammes show the voltage plotted against the current to elucidate operational modes/points during welding operation. They can be used to determine process stability as well as transfer mechanism based on the shape of the cloud of points (Ref. 8). The experimental conditions employing 270 and 290 in./min, Fig. 9B and C, respectively, presented interchangeable metal transfer between spray and short circuit, which is consistent with the previous results. Once this range of 270–290 in./min was passed, the metal transfer across the arc moved toward spray, improving stabilization as indicated by the reduction of the area in the cyclogrammes for standard GMAW.

Figure 10 shows a cold wire feed rate of 80% stabilized

the metal transfer, as indicated by the reduction of the cyclogramme area in comparison to standard GMAW — Fig. 10A. However, further increasing the cold wire fraction led to short circuits, which can be seen in Fig. 10C, where some points fall below 10 V.

During unstable conditions, the cluster of the points increases, as a response of the power source feedback to stabilize the welding operation. However, certain points fall close to 10 V, experiencing short circuit, as seen in Fig. 10C. This attempt to stabilize voltage/current response was caused by feedback in the welding source to maintain operation at a constant voltage (CV). This mechanism serves to keep the arc close to the set-point voltage and current through inductance control, which accounts for the current variation in time after a short circuit to reignite the arc. In fact, this cluster of points could become a supplementary indication of stability of a welding process parameter in addition to the sole area of the cyclogramme, which represents the total area formed by points in a cyclogramme irrespective of the cluster occurrence (Ref. 9).

Figure 11 shows cyclogrammes in the 330 in./min condition. A 20% cold wire feed rate stabilized based on the reduced area of the cyclogramme, Fig. 11A, compared to Fig. 9E. In contrast, the cold wire feed rate of 80% caused a small increase that can be considered within the stability limits — Fig. 11B. However, at a 140% cold wire feed rate, the weld-

Fig. 5 — Oscillograms for CW-GMAW with WFS equal to 310 in./min with progressive values of cold wire feed rate: A — 20%; B — 80%; C — 140%.

CW-GMAW-330ipm--28V-25ipm-17mm-20%

CW-GMAW-330ipm--28V-25ipm-17mm-80%

CW-GMAW-330ipm--28V-25ipm-17mm-140%

Fig. 6 — High-speed images of CW-GMAW-330 in./min-28 V-25 in./min-17 mm: A — 20%; B — 80%; C — 140%.

ing stability was compromised by the short-circuit events, causing the cold wire contact with droplets still hanging on the electrode wire.

At a cold wire feed rate of 140%, the cluster of points increases as a result of the power source feedback system, which attempts to stabilize the arc after short circuits. Figure 12 shows the cyclogrammes for the 350 in./min condition, which corresponds to fully developed spray mode. When 20% cold

wire feed rate was used, there was a reduction of the cyclogramme area, as seen by comparing Figs. 12A to 9E. The reduction of area is most pronounced when higher cold wire fractions were used, for instance, 80 and 140%.

In contrast to the previous situations, the increase in the cluster of data points in Fig. 12 was not related to instabilities in the electric arc or short circuits caused by the cold wire emerging out of the weld pool. Rather, this was due to a higher

Fig. 7 — Oscillograms for CW-GMAW with WFS equal to 330 in./min with progressive values of cold wire feed rate: A — 20%; B — 80%; C — 140%.

Fig. 8 — Oscillograms for CW-GMAW with WFS equal to 350 in./min with progressive values of cold wire feed rate: A — 20%; B — 80%; C — 140%.

stabilization of the welding process with the progressive stabilization of the arc due to arc pinning to the cold wire when the cold wire feed rates increased, and provided there was enough energy in the melt pool to sustain this extra wire.

Droplet Frequency and Diameter

The frequency of the droplets and their estimated diameter are presented in Fig. 13. Figure 13A and B show the droplet frequency for the 310 in./min condition. Introducing the cold wire increased the droplet frequency. Though specifically for Fig. 13A, the droplet frequency appeared unaltered in comparison to the standard GMAW, given the limits of variation represented by the confidence level at 95%. The current for fully developed spray at 350 in./min was 295 A.

The increase in detachment frequency corresponded to a decrease in droplet diameter, which was caused by the increase in the tapering Lorentz force, which varied directly with the current (Ref. 10). Figure 13B shows the trend in droplet detachment frequency (Fig. 13A) was maintained with the droplet starting to transit to a spray condition at 80% cold wire feed rate. This was due to the increase in current to melt the extra wire introduced in the arc. At a cold wire feed rate of 80%, the transition to spray occurred in a much lower current than the fully spray condition as reported in the metal transfer dynamics section.

Figure 13C and D show the droplet frequency and the droplet diameter for 330 in./min, respectively. Similar to the case described in the previous paragraph, the transition for

spray started at 80% cold wire feed rate, in which the error bars indicate the droplet frequency was higher than the droplet frequency of reference. Using a WFS value of 330 in./min, the transition to spray was more gradual than when using a WFS of 310 in./min. Similarly, the transition to spray started at the cold wire feed rate of 80% when compared to the reference level — see Fig. 13C and D. The reason for the difference in slope behavior of these two cases remains unclear and is worthy of future study.

Average Resistance of the Arc Plasma

Figure 14 presents the arc resistance for the welds using 310, 330, and 350 in./min wire feed speed. The arc resistance was estimated using Equation 2 as described in the methodology. Valensi et al. (Ref. 11) reported in the transition from globular to spray, the conductivity of the plasma column increased due to the metal vapor generation rate increase. The resistance of the plasma column in a fully developed spray condition (350 in./min) is equal to 0.1028Ω — Fig. 14C. Comparing the resistance for the conditions of 310 and 330 in./min to this standard value, the resistance limit to allow a fully spray transfer for the conditions was mapped out in this work. According to Fig. 14A, the resistance for 80% was 0.1025Ω , which is lower than the reported value for spray using 350 in./min. Also, according to Fig. 14B, the resistance for an 80% feed rate was 0.1030Ω , which was close to the value reported in Fig. 14A. This indicates the results of arc resistance were consistent with the droplet fre-

Fig. 9 — Cyclogrammes for standard GMAW conditions: A — 250 in./min; B — 270 in./min; C — 290 in./min; D — 310 in./min; E — 330 in./min; F — 350 in./min. Color bar indicates density of data.

quency measurements. For the CW-GMAW conditions in which the WFS was 310 and 330 in./min, the transition to spray suddenly occurred at an 80% cold wire feed rate, with arc current values of 274.42 and 283.01 A, respectively (Table 3). These currents are inferior to the average current of 294.65 A, reported in Table 2, for a fully spray regime transfer in standard GMAW.

The size of the variation around the average arc resistance at 140% in Fig. 14A and B was due to the short circuit (disturbances) caused by the excessive amount of cold wire in the arc. The arc resistance plots indicate that increasing the cold wire fraction led to pinning of the electric arc to the cold wire for high cold wire fractions (> 100%), provided there was enough energy to accommodate this high cold wire fraction. When there was enough energy to accommodate the cold wire (350 in./min), the resistance variation was lower than in the standard GMAW for 80 and 140% cold wire feed rates — Fig. 14C. The decrease of the resistance indicated an improvement in arc conductivity, which accounted for stability and an increase in current, leading to higher values of detachment force from the self-induced magnetic field.

Discussions

Metal Transfer and Globular-to-Spray Transfer Mechanism in CW-GMAW

There are basically two theories that try to explain the phenomena of metal transfer in welding: The static balance force theory (SBFT) by Waszink and Graat (Ref. 12) and the pinch instability theory (PIT) proposed by Allum (Refs. 13,

14). The SBFT accurately predicts the droplet diameter in globular transfer mode while the PIT performs better in spray transfer. However, neither can predict the globular-to-spray transfer. Recently, Zhao and Chung (Ref. 15) reported the phase field method can approximate the globular-to-spray transition current, along with the droplet sizes in the transition regime.

During metal transfer, the droplets are subjected to three forces: electromagnetic force (F_{em}); gravitational force (F_g); and surface tension force (F_s). In this analysis, the viscous drag force of the plasma and the arc pressure are disregarded because they account for only 10% of F_s , according to Waszink and Graat (Ref. 12). In globular transfer, droplet detachment is governed by F_g because the droplet diameter is large, while in spray mode, detachment is governed by the electromagnetic force.

The mechanism of hastening the onset of the globular-to-spray transfer in CW-GMAW is related to the current increase caused by higher total wire feed (both electrode and cold wire feed rate) applied in CW-GMAW. This mechanism is similar to the one proposed by Kim and Eagar (Ref. 10). The total power delivered to the anode ($\dot{Q}_{total}$) can be written as follows:

$$\dot{Q}_{total} = (3/2 kT/e + V_a + \phi)I + (\bar{\rho} L/A I^2) \quad (3)$$

where k is the Boltzmann constant, T is the electron temperature, e is the electron charge, V_a is the anode voltage drop, ϕ is the work function of the electrode material, $\bar{\rho}$ is the average resistivity of the electrode material, L is the electrode extension, A is the cross-sectional area of the electrode, and I is the welding current. The first parenthesis is the power imparted by the electron condensation, while the second

Fig. 10 — Cyclogrammes for CW-GMAW conditions using WFS = 310 in./min: A — CW-20%; B — CW-80%; C — CW-140%. Color bar indicates density of data points.

Fig. 11 — Cyclogrammes for CW-GMAW conditions using WFS = 330 in./min: A — CW-20%; B — CW-80%; C — CW-140%. Color bar indicates density of data points.

Fig. 12 — Cyclogrammes for CW-GMAW conditions using WFS = 350 in./min: A — CW-20%; B — CW-80%; C — CW-140%. Color bar indicates density of data points.

parenthesis is the power due to Joule effect. The total wire feed in CW-GMAW causes the Joule power to increase, acting similar to an increase in electrode extension. Thus, the electrode melting occurs at reduced arc currents in CW-GMAW compared to standard GMAW, leading to electrode tapering at lower currents compared to standard GMAW. From the SBFT theory, the only holding force in the electrode droplet is the surface tension (F_s), which is as follows:

$$F_s = \pi d_e \gamma \quad (4)$$

where d_e is the electrode diameter and γ is the surface tension coefficient of the molten electrode. Thus, as tapering of the electrode proceeds, d_e decreases and, consequently, F_s decreases as well, which cause smaller droplets to be formed, accounting for the sooner globular-to-spray transition in CW-GMAW.

Fig. 13 — Average droplet frequency and estimated average droplet diameter: A — Average droplet frequency for WFS of 310 in./min; B — average droplet diameter for WFS of 310 in./min; C — average droplet frequency for WFS of 330 in./min; D — average droplet frequency for WFS of 330 in./min. The percentages in the graph indicate the cold wire feed rate. Standard GMAW is to 0% cold wire feed rates.

Arc Stability and Arc Resistance

The methodology proposed to assess arc stability using the cyclogrammes in the results section uses the following: 1) the area of the cyclogramme and 2) the cluster of points in the cyclogramme. These two features are complementary in the sense that when the welding operation is stable, the area of the cyclogramme decreases along with the cluster of points — see Fig. 9A, E, and F for standard GMAW. When the cold wire feed rate reaches 80%, the stability in CW-GMAW is comparable to the standard GMAW — Figs. 11B, 12B. The increase in cluster of points, observed for instance in Figs. 10C and 11C, is caused by the feedback mechanism in the welding power source to maintain the instantaneous voltage/current near the values of current and voltage set before the welding operation.

The transition to spray transfer is accompanied by a reduction in resistance (increase of conductivity) of the arc column, as shown in Fig. 14. This mechanism is likely due to higher ionization caused by the increase in metal vapor (from electrode and cold wire derived). Lancaster (Ref. 16) reported that in iron or steel arcs, the ionization is due to small amounts of metal vapor originating from the electrode. The introduction

of cold wire causes a reduction in CTWD resistance, which is the sum of electrode extension resistance and arc resistance (Ref. 17). This decrease in arc resistance likely facilitates the flow of charge inside the arc. This facilitation in current flow likely increases the current density, which might explain why the electromagnetic force becomes increasingly dominant with additional cold wire feed rates (Ref. 18).

Conclusions

Standard and cold wire GMAW welds at constant voltage were performed to identify the current at which the transfer mode transitions from globular to spray regime. The transition to spray was studied using high-speed imaging and high frequency of sampling electrical signals. The following conclusions were reached:

1. The transition from globular to spray in cold wire GMAW occurs at 4 to 7% lower current level when compared to standard GMAW for the same process parameters;
2. The transition from globular to spray occurs due to an increase in current with the increase of cold wire feed rates, which leads to an increase in tapering of the electrode by elec-

Fig. 14 — Arc resistance values based on instantaneous values of current and voltage for three distinct WFS conditions: A — 310 in./min; B — 330 in./min; C — 350 in./min. Error bars show 95% confidence intervals.

tron condensation, which reduces the surface tension force (only droplet holding force); and

3. The resistance of the arc plasma column seems to decrease with the increase of cold wire feed rates, which accounts for an increase in current. This is probably due to higher metal vapor fraction generated by the cold wire.

Acknowledgments

The authors would like to acknowledge Natural Sciences and Engineering Research Council of Canada (NSERC) and TransCanada Energy (TCE) for financial support of this project. They would like to also acknowledge the Centre for Advanced Materials Joining (CAMJ) of the University of Waterloo, where all the experiments were performed. Lastly, P. D. C. Assunção would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) of the Brazilian Ministry of Education for the scholarship to visit the University of Waterloo.

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