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EXPERIMENTAL ANALYSIS OF DROPLET-GAS INTERACTION DURING GMAW PROCESS

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Abstract

Quality of GMAW is closely related to the behavior of the droplet from its detachment from the wire to its impingement to the weld pool. In the present research, an experimental methodology based on high speed imaging and contour detection was developed. The images are synchronized with the current and arc voltage process. The automatic detection of contour allows to track the shape for each image and to appreciate the evolution of the liquid metal for each droplet. The methodology is then applied for a set of welding parameters and two different gases (100% Argon and 92% Argon-8%CO2), in order to see how the metal transfer is modified. The profile detection allows seeing and measuring the influence of gas on the metal liquid droplet detachment and free flight motion for each period. Temperature and surface tension of the liquid metal with its interaction with the plasma are first measured and then these quantities are applied to explain some mechanisms induced in Pulsed GMAW.

Keywords

Metal Transfer, Droplet Tracking, Pinch Pressure, Droplet Temperature, Surface tension, Gas Metal Arc Welding

Introduction

Shielding gas plays an important role on the quality of metal transfer stability and then weld quality. Depending on welding conditions, different modes of transfer can be observed: globular, spray, short circuiting and pulsing. Metal transfer can be decomposed in four different phases, (i) Droplet creation at the wire tip, (ii) droplet detachment, (iii) free flight of the droplet, (iv) impingement of the droplet in the weld pool. Understanding these mechanisms and the underlying physics in metal transfer are important to qualify GMAW in industry. The behavior of the droplet is often investigated through simulation [1]. One possible field of investigation is to observe metal transfer. Different experimental devices and procedures were developed based on high speed camera and special optical devices [2-4]. Measurements during metal transfer are uncommon. Experiments generally focus on the description of a phenomenon. Jones [2] measured the droplet speed across the plasma and was able to propose some correlation with a model. Geometry of the droplet during the transfer is rarely investigated. In this work, it is proposed to analyze the geometry of the droplet based on edge detection by the processing of images from high speed videos. An automatic profile detection toolbox has been developed to make easier the task and this was applied to appreciate the influence of shielding gas on metal transfer. The automatic image treatment can be applied to a large flow of images.

Gas shielding composition modifies the heat and the mass transfer in the plasma. The plasma interacts with the droplet while the formation. Heat flows from the plasma to the liquid metal at the wire tip. The presence of plasma around the metal modifies the surface tension.

The paper is organized as follows. First, the temperature of droplet at the wire tip is determined with different shielding gas. The value of surface tension is then estimated by observing droplet oscillations during the free flight. Finally, the pressure in the neck just before detachment is approximated. This calculation contributes to better understand the difference of droplet speed transfer that is important for the quality of the process.

Experimental setup and welding settings

Static tests were performed to analyze metal transfer. The welding torch is fixed relative to the steel target. The tests last around 2s so that the weld pool created by the deposit cannot become too big and do not interact with the metal transfer. Special data acquisition was developed at the welding laboratory to synchronize images acquired with a high speed camera and the electric signals of the process [5]. In this work, a profile detection algorithm was implemented. This algorithm allows to automatically detecting profiles in a flow of images. The algorithm mixes image processing, graph algorithm and computational geometry [6]. Profile detection and an acquired image are shown on figure 1. The transfer is observed through an arc shadow graphic technique obtained with a laser diode of 808nm lightning the transfer in front of the camera.

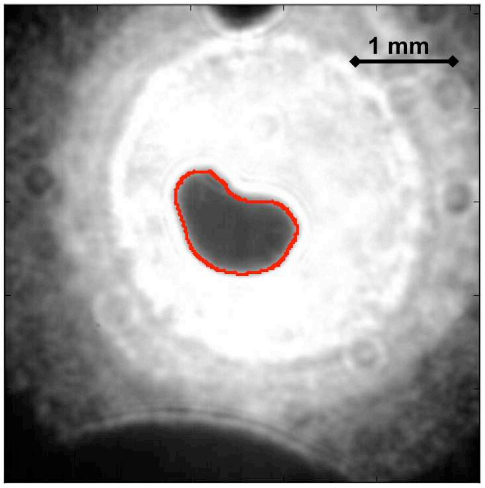

Fig. 1: Image of droplet during free flight and profile detection.

The GMAW is set in a synergistic pulsed mode. The wire speed is 3 m/min (120 ipm). The Contact Tip to Work Distance (CTWD) is 18 mm (0.7 inches). The material is ER70S-6 steel and the wire diameter is 1 mm. Two shielding gases are used in the experiments. The first one is pure Argon and the second contains 8% of CO2 in 92% of Argon.

In-Situ physical parameters

Physical properties involved in welding and particularly those involved in fluid dynamics are not so often identified. In this section, temperature and surface tension of droplet are measured directly during transfer in order to quantify how liquid metal interacts directly with the plasma. It is known that shielding gas influences heat transfer and the droplet temperature [7]. The knowing of droplet temperature is relevant to predict fume formation. To investigate the behavior of the droplet, the evolution of the liquid metal at the tip is analyzed from the time of arc extinction to its complete solidification.

An example of profile detection is shown on figure 2. The profile of the liquid metal (in black) allows several characteristics to be detected such as the volume of the droplet, the center of mass, the wetting angle and droplet oscillations by looking at the position of the extremities. To compute volume, the vertical axis is assumed to be an axisymmetric axis. Based on the contour, the center of mass and a mesh procedure, the volume can be computed. When the arc stops, the droplet at the tip of the wire remains liquid for a while. The droplet is then at a temperature higher than the melting temperature, at the temperature of overfusion $T_{overfusion}$. For a constant volume, the droplet remains in liquid phase longer time when the droplet is at a hotter temperature. The observation of the evolution of the apparent liquid phase can give insight into the temperature at the arc extinction. This initial temperature is fixed by the heat exchange between plasma and droplet and by Joule effect. Then, the droplet exchanges heat with the surrounding shielding gas and the wire.

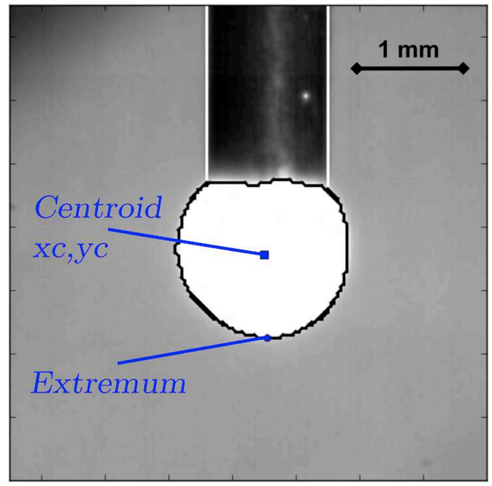

Fig. 2: Droplet at arc extinction and detected profile.

As outlined before, the power supply is set in synergistic mode. The power will not be the same between the two shielding gas. The average power delivered by the generator is shown in table 1.

Table 1: Average power delivered by the welding power supply.

Shielding gas mixture	Average Power (W)
Argon	2140
92% Argon – 8% CO2	1980

The results in table 1 show that CO2 plasma is less energetic than pure Argon one. Now, the investigation of temperature with the evolution of the apparent volume of liquid metal is analyzed. The solidification curves are shown on figure 3. Tests were repeated in order to see if arc extinction is repetitive. The curve on figures 3 can be divided in several phases. The first is due to active oscillations of the droplet followed by a maintaining of the volume of liquid phase due to a temperature higher than the melting temperature. Observation shows that solidification starts at the outer skin of the droplet and not at the wire droplet interface.

On the figure 3, the remaining droplet is bigger with the 92Ar-8CO2 shielding gas. The solidification time for the droplet depends on: (i) the heat quantity inside the liquid droplet, (ii) thermal exchange with the shielding gas, (iii) thermal exchange with the wire. The total heat in the liquid could be appreciated by:

$$Q = \rho c\left(T_{overfusion} - T_{solidus}\right)V_{droplet} + \rho L_f V_{droplet} \quad (1)$$

Where $T_{overfusion}$ is the droplet temperature at time of arc extinction and L_f *is* the latent heat of fusion.

The flux exchange could be approximated by:

$$q = h_{fil} S_{fil} \left(T_{overfusion} - T_{fil} \right) + h_{gas} S_{gas} \left(T_{overfusion} - T_{gas} \right) \quad (2)$$

The solidification time is then defined by the ratio of Q over q.

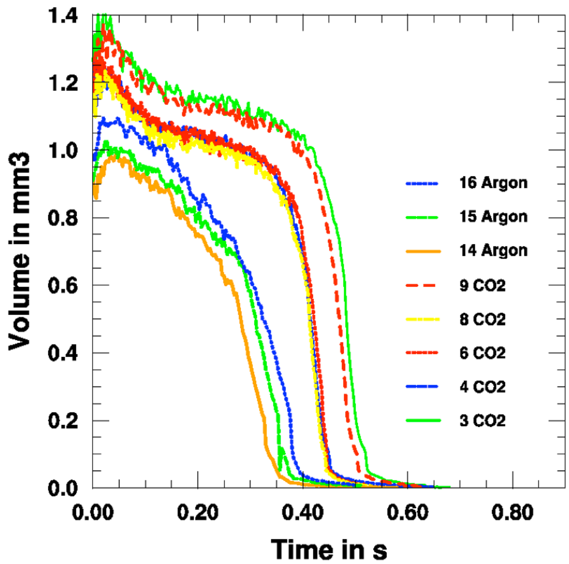

Fig. 3: Apparent volume of metal liquid for pendant droplet at the wire tip obtained with two different shielding gases.

In formulas (1) & (2) exchange coefficients have to be approximated. In figure 3, the decreasing is twice faster for the gas containing 8% of CO2 indicating a higher exchange coefficient. The heat exchange values for the two shielding gases are given in table 2.

Table 2: Heat exchange coefficient for formula (2).

Shielding gas mixture	Heat exchange W/m2	Overfusion temperature in K
Pure Argon	30	1840
92Ar-8CO2	60	1880

The overfusion temperature of the liquid is chosen such as the ratio of time over solidification time equals to 1. The results are shown on figure 4. The difference in overfusion temperatures gives the same trend as with those measured under the arc in [7]. The one of [7] are obtained for constant current at high current level. The test could be performed for this configuration also and higher temperature will be obtained. It confirms the lower heat supplied by the droplet in pulsed current mode.

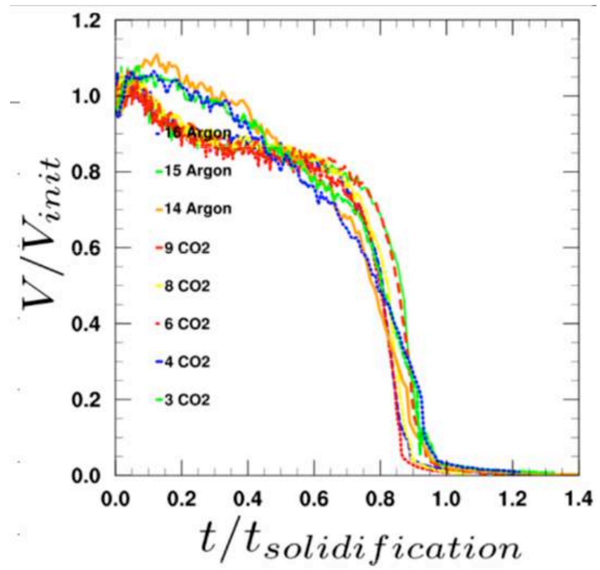

Fig. 4: Scaled curves of figure 3 with the solidification time and the initial volume.

A second important quantity is the surface tension. Subramanian and White [8] study in situ surface tension inside the plasma by observing droplet oscillations in low current during free flight. The surface tension was determined by the formula initially developed by Rayleigh [9]:

$$\sigma = \frac{3\pi\rho V_{droplet}}{8\tau^2} \quad (3)$$

Where ρ is the density of the liquid, V is the volume and τ is the oscillation period of the droplet. The density of the liquid steel was taken from published values and assumed to be 6500 kg/m3 [8].

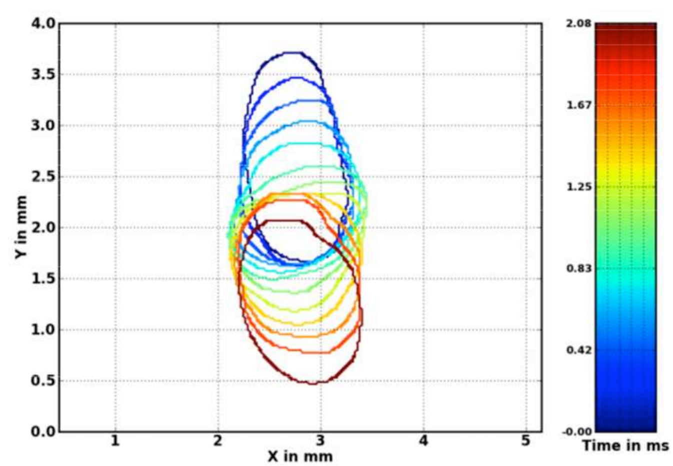

Fig. 5: Droplet tracking during free flight in GMAW with 92Ar-8CO2 gas mixture, WFS = 3m/min. and a constant CTWD = 18 mm.

To determine the oscillations, profile detection is used with a procedure developed at the welding laboratory. The profiles are shown on figure 5. The shape of the droplet is far from a sphere and looks more like an ellipsoid. In figure 5, there are around two oscillations during the free flight whatever the gas mixture is. With these oscillations, the period can be determined and then the surface tension can be approximated. The results are shown in table 3.

Table 3: Estimated values of surface tension for droplet during free flight through the plasma.

Shielding gas mixture	Surface tension N/m
Pure Argon	1.2
8% CO2	0.9

In table 3, the difference of surface tension for two experimented gases is around 30%. The order of magnitude is in agreement with all literature values of surface tension from 0.9 to 1.8 N/m [2, 8]. In the next section; these estimated values of table 3 will be used to better understand some mechanisms induced in metal transfer.

Metal transfer investigation

In this part, investigation of droplet size, droplet shape, speed of droplet into the plasma are done and explained.

One indicator for the GMAW process is the trajectory of the droplet. For the two gases under study, the trajectories are almost linear. If the successive 'y' position of the center of mass is drawn in respect to time, the droplet shows only a small acceleration just after detachment. During the free flight, the speed is constant. The average speed can be approximated and is shown in table 4 for the two shielding gases. In table 4, the droplet diameter is almost the same and the speed of the droplet is also 50% higher by using pure argon.

Table 4: Speed and diameter of droplet for two gas mixtures.

Shielding gas mixture	Droplet speed mm/s	Droplet diameter (mm)
Pure Argon	1100	1.25
8% CO2	750	1.28

Because, speed is constant all along the free flight, the difference of speed could be attributed to mechanisms induced during the detachment. The higher speed of the droplet will lead to a higher momentum when the droplet will impinge the weld pool. Now, profile detection is done during detachment. It is interesting to note that surface tension is higher for some Argon content in the shielding gas and that power is also a lit bit higher. Lowke [10] predicts the changes of droplet size during the globular to spray transition with a model which accounts Lorentz force and surface tension during the detachment. Lowke [10] proposed to approximate the pressure due to electromagnetic force in the droplet by:

$$p_E = \frac{m_0 I^2}{4\pi R_f^2}\left(1-\left(r/R_f\right)^2\right) \quad (4)$$

And the approximated pressure due to surface tension effect by:

$$p_S = \gamma\left(1/R_f + 1/R_2\right) \quad (5)$$

R_f is the radius of the neck, and R_2 is the curvature radius of the neck.

Profile detection is also used for detachment with algorithm a little bit different. Some profile detections are shown on figure 6. It is assumed that the neck and the droplet are axisymmetric. The first radius is obtained directly and the second one is fitted by a polynomial approximation as shown on figure 6. The profiles are extracted just before detachment. The synchronization of images with arc voltage and current signals allows noting that the detachment occurs at lower current for pure argon shielding gas. This could be explained by higher surface tension effects that are opposed to the fluid motion; longer time is thus needed to detach the droplet from the wire. The difference of surface tension modifies the shape and the equilibrium of the free surface.

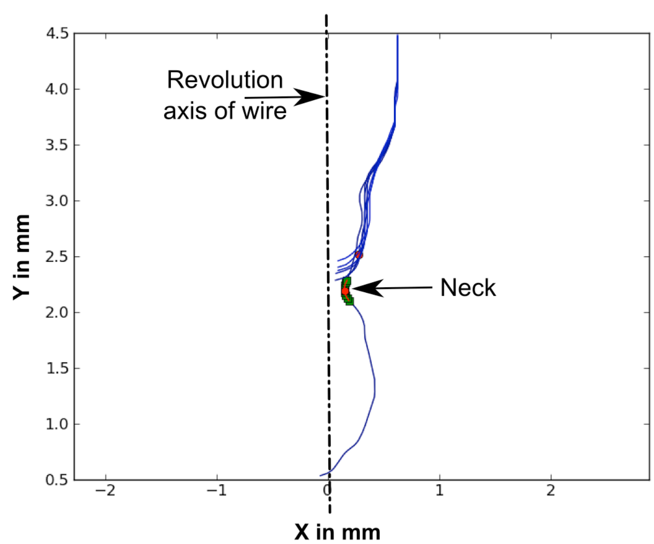

Fig. 6: Neck just before detachment of the droplet for CO2 shielding gas.

The approximation of the pressure of the droplet are calculated and shown in table 5. The images to identify the profile are the ones just before detachment.

Table 5 shows some of the parameters measured and used to approximate the pressures in equations 4 and 5. The radius of the neck is lower for the pure argon gas due to the capacity of surface tension to maintain the neck. In this case, the pressure near the free surface (P_S) and the pressure inside the neck (P_E)

are larger for the argon shielding gas. The order of magnitude is the one found by Wang *et al* [11]. To complete this analysis, the energy release rate must be computed. Due to higher pressure in a thinner neck, the energy release rate could be assumed to be higher for the pure argon shielding gas. If a force balance is computed in the middle of the neck the force is lower for the pure argon gas due to the thinner radius.

Table 5: Values used to compute pressure from profile and current for the two shielding gases.

	I (A)	R_f (mm)	R_2 (mm)	P_E (Pa)	P_S (Pa)
Argon	80	0.075	0.214	31955	14945
CO2	114	0.15	0.2925	19360	6048

Finally, profile detection on images can be used to detect bad transfer as spatters or as bad droplet motion in the plasma. Figure 7 shows a bad transfer where the droplet goes out of the weld pool.

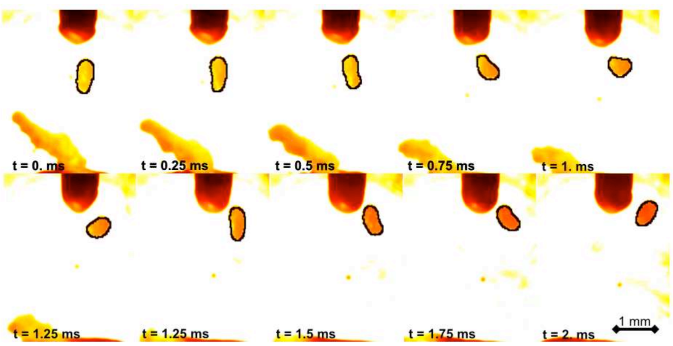

Fig. 7: Profile detection for monitoring the transfer

Conclusions

In this work, temperature and surface tension of droplet were approximated during P-GMAW with two gases. These physical properties are in closed agreement with results found in the literature [7, 8] for free flight metal transfer mode. The metal transfer analysis shows that speed of droplet with argon leads to higher speed with the same droplet size and will contribute to lead to higher momentum in the weld pool. More, by using the estimated temperature and surface tension of droplet and with the measure of the radius evolution of the wire neck, the pinch pressure has been calculated. Combining all results, the higher droplet speed for pure argon versus the 92Ar-8CO2 could be explained by higher energy release rate with the pure Argon due to higher pressures in the neck due to geometry and surface tension.

Acknowledgments

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