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2014

Wong, Y.-R., & Ling, S. F. (2014). An investigation of dynamical metal transfer in GMAW—effects of argon shielding gas. *Journal of materials processing technology*, 214(1), 106-111.

<https://hdl.handle.net/10356/101140>

<https://doi.org/10.1016/j.jmatprotec.2013.08.003>

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[DOI:<http://dx.doi.org/10.1016/j.jmatprotec.2013.08.003>].

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An investigation of dynamical metal transfer in GMAW - effects of argon shielding gas

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Abstract

The unbalance radial electromagnetic force was firstly obtained by measuring the real-time input electrical impedance of GMAW. This force serves as an attaching force because it pushes the droplet aside of the welding wire and sticks on the tip of welding wire as result of surface tension force. In spray transfer mode, lower unbalance radial electromagnetic force was observed when argon shielding gas was used. The finding presented in this paper is contrary to the literature which reported that higher electromagnetic force is desirable for faster transfer rate of droplets in spray transfer mode.

Keywords: GMA welding; Real-time input electrical impedance; Electromagnetic force; Argon shielding gas; Spray transfer mode

1 Introduction

In gas metal arc welding (GMAW), the molten droplets at the tip of welding wire and weld pool are substantially above the melting temperature. At such high temperature, the oxidation of the molten material with the oxygen and nitrogen in the air are rapid. Common defects like porosity, cracking and embrittlement are usually found in the weld bead as a result of rapid oxidation. Therefore, some form of protection to prevent the oxidation is essential. One of the solutions is to supply the shielding gas to form a layer of shield which surrounds the welding arc and weld pool.

The commonly used shielding gases in GMAW are carbon dioxide (CO_2), argon gas (Ar) and their combinations. The applications of such shielding gases can provide good protection of the molten droplets and weld pool, however, they also affect the formation of welding arc, arc stability and metal transfer. The effects of shielding gases based on their physical characteristics were underlined by Suban et al. (2001). The arc initiation and stability by using argon gas is better than CO_2 because the ionization potential and electric conductivity of argon gas is higher. However, CO_2 can achieve better temperature distribution within the welding arc and weld penetration due to higher thermal conductivity.

To understand the role of shielding gas in obtaining optimal quality of weld, both numerical modeling and experimental work have been carried out based on different

shielding gases. Various modeling methods of thermal plasma were reviewed by Murphy et al. (2009). It was found that the influences of different shielding gases are vital in determining the arc constriction, metal vapor and weld pool properties. A two-dimensional axisymmetric numerical model was used to investigate the effects of adding helium, nitrogen and hydrogen to the argon shielding gas (Murphy et al., 2009). On the other hand, the transient transport phenomenon of metal transfer based on a heat transfer model was studied numerically (Rao et al., 2010). It was reported that the welding arc behaves very differently in various shielding gases due to the differences in ionization potential, thermal and electrical conductivity.

Several experimental works have been carried out to evaluate the quality of weld when different shielding gases were used. In relation to the metal transfer, pure argon shielding gas can achieve spray transfer mode easily and therefore good wettability (Carlos and Jair, 2011). In terms of mechanical property, the yield strength of weld metal for high strength low alloy steel varies according to the O_2 and CO_2 content in the argon shielding gas (Mukhopadhyay and Pal, 2006). This has been further proven by Teske and Martins (2008) when the effects of additional O_2 and CO_2 on the morphology and impact resistance of welded steel were studied experimentally.

The study of metal transfer shows that the formation and detachment of droplet is not only affected by the types of shielding gases but also the interaction of acting forces such as gravity, surface tension, electromagnetic force, viscous drag force and arc pressure. The resultant of forces actually decides the size and transfer rate of droplet. A dynamic two-dimensional arc model was developed to investigate the effects of the various forces acting on the droplet (Haidar, 1998). It was found that the gravity plays an

important role for globular transfer mode but the radial component of the electromagnetic force is the major detaching force in spray transfer mode. A liquid type pendent droplet was adopted by Nemchinsky V.A. (1994) to analyze the effects of surface tension and electromagnetic force acting on the molten tip of welding wire. This study was further enhanced by modeling the detachment of droplet at the tip of welding wire using dynamic force balance model to predict the resonant frequency and detaching size of droplet (Nemchinsky, 1996). All the numerical models work reasonably well in their respective range of welding parameters such as welding voltage and current. In fact, they provide a good reason to study the physical phenomena of metal transfer.

The use of argon shielding gas can result into smaller size of droplet and faster transfer rate of droplet which can go up to few hundreds droplets per sec (Zielinska et al., 2008). Therefore, spray transfer mode is achieved. In order to evaluate the relationship between the argon shielding gas and the formation of spray transfer mode, a comprehensive model was developed by Rao et al. (2010) to simulate the transport phenomena during the GMAW under different shielding gases. The axial component of the electromagnetic force acting on the droplet was found to be the detaching force which helps in the separation of droplet from the welding wire. Similar result and conclusion was also obtained by Magnabosco and Coppo (2011). However, no further discussion was made due to the lack of information about the total electromagnetic force which includes the radial component of electromagnetic force.

In our previous work, a new measuring method was developed to obtain the real-time and accurate resistance of welding system based on the input electrical impedance of welding processes, $Z_{in}(t)$ (Wong et al., 2013). The $Z_{in}(t)$ can be expressed as

$$Z_{in}(t) = Z_r(t) + j\omega Z_x(t) = R(t) + j\left(\omega L(t) - \frac{1}{\omega C(t)}\right) \quad (1)$$

where $R(t)$ or $Z_r(t)$ is the resistance, $Z_x(t)$ is the reactance which consists of inductance $L(t)$ and capacitance $C(t)$. They are inherently obtained from the welding system which can be represented by an equivalent circuit. According to eq. (1), the $Z_{in}(t)$ is expressed as a function of time after the two input signals, welding voltage and current are measured simultaneously and processed in time domain. Due to the self-inductance and electromagnetism of welding arc, the flow of DC current in the welding arc induces an unbalance radial electromagnetic force which surrounds the entire welding arc. This unbalance radial electromagnetic force can be correlated with the time varying $L(t)$ by modified Lorentz's Law as expressed in eq. (4):

$$L(t) = \frac{\Phi(t)}{I(t)} \quad (2)$$

$$B(t) = \frac{\Phi(t)}{A} \quad (3)$$

$$F(t) = B(t)I(t)\ell = \frac{L(t)(I(t))^2 \ell}{A} \quad (4)$$

where Φ is the induced magnetic flux, I is the welding current, B is the magnetic flux density, A is the cross sectional area of welding arc, F is the electromagnetic force and ℓ

is the arc length. Eq. (4) clearly implies that the $F(t)$ is time varying and proportional to the $L(t)$. In other words, the $F(t)$ can be evaluated by measuring the magnitude of $Z_x(t)$.

Besides electromagnetic force, there are other predominating forces aforementioned to achieve faster transfer rate of droplet. However, in this paper, only the electromagnetic force and surface tension force were evaluated. The unbalance radial electromagnetic force was firstly obtained by correlating with the self-inductance, $L(t)$ so that the relationship between the argon shielding gas and formation of spray transfer mode can be revealed. Two types of shielding gases, 100%CO₂ (CO₂) and 95%Ar + 5%CO₂ (95%Ar), were used and the experimental results were compared. In order to stimulate the metal transfer modes, mainly short-circuiting and spray transfer mode, GMAW was carried out based on different settings of welding voltage and current. The results were then validated by examining the images of metal transfer which were taken based on an image acquiring system.

2. Input Electrical Impedance, $Z_{in}(t)$

After the welding voltage and current signal are acquired simultaneously during the welding process, the $Z_{in}(t)$ is computed by taking the quotient of welding voltage, $V(t)$ to current, $I(t)$ in their analytic forms (see eq. 5 – 7):

$$\hat{V}(t) = V(t) + jh[V(t)] \quad (5)$$

$$\hat{I}(t) = I(t) + jh[I(t)] \quad (6)$$

$$Z_{in}(t) = \frac{\hat{V}(t)}{\hat{I}(t)} \quad (7)$$

where $\hat{V}(t)$ and $\hat{I}(t)$ is the analytic signal of welding voltage and current in complex-valued form. The real part of $\hat{V}(t)$ and $\hat{I}(t)$ is the original real-valued $V(t)$ and $I(t)$. The imaginary part of $\hat{V}(t)$ and $\hat{I}(t)$, $h[V(t)]$ and $h[I(t)]$ is the product of Hilbert transform (Julius and Allan, 2000) which can be obtained by shifting the $V(t)$ and $I(t)$ by $+90^\circ$. The $Z_{in}(t)$ is an accurate and reliable signature because it represents the system properties of welding system (R, L and C) without the influence of signal noises or disturbances. Furthermore, the R, L and C is inherently obtained as function of time since the $Z_{in}(t)$ is computed in time domain by using Hilbert transform. Therefore, the dynamic behavior of welding process including the metal transfer can be reflected accurately by the time variations of $Z_r(t)$ and $Z_x(t)$.

3. Experimental Setup

GMAW welding machine (3 phase, 50Hz input voltage with DC current output) was used to carry out the welding experiments. As shown in Fig. 1, the welding torch was attached to a 2-axis Cartesian Robot so that the free wire extension and welding speed were kept constant. Furthermore, this welding torch was also connected to a controller for automatic triggering of welds. In order to fix the welding torch and leading angle, a 360°

rotational torch holder with heat isolator pad made by ceramic material was designed and built. On the other hand, a steel table was constructed for mounting the robot and steel plates.

Two different shielding gases, CO₂ and 95%Ar were involved in the experiments. In order to evaluate the effects of shielding gases, Taguchi Method (Philip J. Ross, 1996) was adopted to design the experiments. As shown in Table 1, L9 array was adopted. Two factors (welding voltage and current) were set and tested at three levels, low, middle and high with single replicate. Others important welding conditions were listed in Table 2. All the welds were made on carbon steel plates, grade AH36, 10mm thickness according to the bead-on-plate test.

For the acquisition of welding voltage and current signal, a voltage probe and current probe were used to measure the signals simultaneously. The voltage probe was taped on the output terminal of power supply while the current probe was hooked on the welding cable. These input signals were sampled by a 12 bits, 8 channels DAQ system at 3 kHz. A built-in analog filter with 250Hz cut-off frequency was used for each channel to prevent signal aliasing. The measured signals were then processed by using MATLABTM program in order to compute the $Z_{in}(t)$.

Two dimensional images of droplet formation and detachment process were recorded by using the image acquiring system (see Fig. 2). A high speed camera was used in the system. The focus length of camera was kept at 355mm and the magnification of lens was set at 1.75. Due to the extremely bright light emitted from the welding arc, a costumed-made filter lens was attached to the camera in order to prevent the excessive light from deteriorating the quality of images. Unomat Super Spot Light was placed

opposite to the camera so that the shadows of welding wire, droplet and weld pool were captured by the camera. For the setting of camera, the frame rate was set at 250 frames per sec and the time interval between each image was therefore 0.004s.

Fig. 1. Schematic diagram of experimental setup.

Fig. 2. Illustration of image acquiring system.

Table 1. Setting of welding voltage, current and observed metal transfer.

RUN No	Voltage (V)	Current (A)	Transfer Mode	
			CO ₂	95%Ar
1	24	150	SCT ^a /GT ^b	SCT/GT
2	24	175	SCT	SCT/GT
3	24	200	SCT/GT	SCT/GT
4	26	150	SCT/GT	SCT/GT
5	26	175	SCT/GT	GT/ST ^c
6	26	200	SCT/GT	GT/ST
7	28	150	GT	GT/ST
8	28	175	SCT/GT	GT/ST
9	28	200	SCT/GT	GT/ST

^aShort circuiting transfer mode.

^bGlobular transfer mode.

^cSpray transfer mode.

Table 2. Important welding conditions.

Parameters	Value
Welding speed (mm/s)	7.5
Wire diameter (mm)	1.2
Free wire extension (mm)	15
Leading angle (°)	15
Shielding gas flow rate (L/min)	20
Welding time (s)	20

4. Results and Discussion

Fig. 3 and 4 illustrated two typical time record results of $Z_r(t)$ and $Z_x(t)$ based on CO_2 and 95%Ar shielding gases for 0.2s only. It showed that the amplitude of $Z_x(t)$ under CO_2 shielding gas can be higher than the 95%Ar shielding gas. Since the $L(t)$ is proportional to the amplitude of $Z_x(t)$ as expressed in Eq. (1), the difference of $Z_x(t)$ under the CO_2 and 95%Ar shielding gas indeed implies that the unbalance radial electromagnetic force can be very different. In order to evaluate the effects of different shielding gases on this force, the standard deviation of $Z_x(t)$ is computed as follows:

$$\sigma_{Z_x} = \sqrt{\frac{1}{N} \sum_{i=1}^N Z_{x,i}^2} \quad (8)$$

N is total data points which depends on the sampling rate and sampling length.

The standard deviation of $Z_x(t)$, σ_{Z_x} was computed and listed in Table 3. Based on the comparison of their differences in percentage, the σ_{Z_x} under 95%Ar shielding gas is always lower than CO_2 shielding gas. The differences can range from 23% to 53% depending on the welding voltage and current setting. In other words, the unbalance radial electromagnetic force can be lower in case of using 95%Ar shielding gas.

Fig. 3. Time varying $Z_{in}(t)$ under CO_2 shielding gas, Run No. 7.

Fig. 4. Time varying $Z_{in}(t)$ under 95% Ar shielding gas, Run No 7.

Table 3. Standard deviations of $Z_x(t)$, σ_{Z_x} .

RUN No	CO ₂	95% Ar	Difference (%)
1	0.045	0.023	48
2	0.050	0.024	53
3	0.037	0.027	28
4	0.035	0.022	38
5	0.034	0.018	47
6	0.035	0.017	52
7	0.028	0.022	22
8	0.025	0.018	28
9	0.021	0.016	23

Fig. 5 revealed that the σ_{Z_x} can vary with respect to the welding voltage and current. The σ_{Z_x} decays when the welding voltage is higher. On the other hand, the differences of σ_{Z_x} between two shielding gases are relatively large at low welding voltage. Under same level of welding voltage but except for low welding current, the σ_{Z_x} decreases when the welding current increases. These changes of σ_{Z_x} could be caused by the interactions between the welding voltage and $C(t)$, welding current and $L(t)$.

For the observed metal transfer modes, more than one metal transfer modes can happen under same welding conditions (see Table 1). Under 95%Ar shielding gas, both globular and spray transfer modes are observed at high welding voltage. If percentage is used to weight these two transfer modes, the spray transfer mode is weighted the highest at high welding current. This observation agrees with the result of σ_{Z_x} which is inversed proportional to the welding current. Therefore, it suggests that the $Z_x(t)$ has significant influence on the formation of spray transfer mode.

Fig. 5. Comparison of σ_{zx} at different RUN No.

It was reported that the axial electromagnetic force acting on the droplets serves as the detaching force to separate the droplets from the welding wire. Therefore, higher electromagnetic force is desirable so that the droplets can be separated rapidly. However, a contrary result was obtained in this paper that the unbalance radial electromagnetic force under 95%Ar shielding gas is always lower. In order to investigate how does smaller unbalance radial electromagnetic force can help to achieve spray transfer mode, the images of metal transfer were recorded and examined physically.

The images of droplet formation and detachment process were presented in Fig. 6 to demonstrate the short-circuiting transfer mode. The images are labeled from t_1 to t_{13} in sequence for a complete cycle of metal transfer. The whole process lasts for 0.048s based on the no. of frames counted. Therefore, the transfer rate of droplet is measured at 20.83Hz (1/0.048s). At t_1 , the welding arc vanishes because the welding wire is bridged

up with the weld pool by the molten droplet. After the droplet is fully detached from the welding wire, the welding arc is reformed in between the welding wire and weld pool. On the other hand, severe weld spatter is observed from t_2 to t_4 when the molten droplet is being transferred to the weld pool. Due to the continuous melting of welding wire, another droplet starts to form at the tip of welding wire at t_5 and eventually it bridges up again the welding wire with weld pool at t_{13} .

Similarly, the images presented in Fig. 7 are labeled from t_1 to t_6 in sequence for a complete cycle of metal transfer based on spray transfer mode. It is observed that a droplet forms at t_1 . It is detached quickly from the welding wire at t_5 without any weld spattering. The period of whole process is 0.016s and therefore the transfer rate of droplet is measured at 62.5Hz ($1/0.016s$).

Fig. 6. Short-circuiting transfer mode under CO₂ shielding gas, RUN No 3.

Fig. 7. Spray transfer mode under 95%Ar shielding gas, RUN No 7.

Important observations were made from Fig. 6 and 7 to prove the influence of unbalance radial electromagnetic force. As shown in Fig. 6, the droplet is pushed aside from the center of welding arc and sticks on the tip of welding wire. Similar phenomena are also observed for other cases under CO₂ shielding gas. Conversely, the droplet in Fig. 7 does not behave the same as it is quickly detached to the weld pool without moved aside from the center of welding arc. These observations are seen for all the cases under 95%Ar shielding gas.

As aforementioned, the flow of DC current in the welding arc induces an unbalance radial electromagnetic force which surrounds the entire welding arc. When this force is large, the droplet is pushed aside of welding wire and sticks on the tip of welding wire as result of surface tension force. Larger size of droplet becomes essential so that its gravity force is large enough to overcome the surface tension force and can be detached from the welding wire. It was confirmed that the unbalance radial electromagnetic force is actually attaching force which results into larger size of droplet and slower transfer rate of droplet. On the other hand, this finding is also supported by a recent work which reported that the surface tension force is insignificant in spray transfer mode (Alexei Y., 2013).

5. Conclusions

1. The unbalance radial electromagnetic force was firstly obtained by measuring the real-time input electrical impedance method. The experimental result showed that the time varying reactance of input electrical impedance, $Z_x(t)$ can be correlated with the unbalance radial electromagnetic force acting on the droplet, which is important to the formation of spray transfer mode.
2. Under 95%Ar shielding gas, the unbalance radial electromagnetic force is always lower. This result is contrary to the literature which reported that higher electromagnetic force is desirable for faster transfer rate of droplets in spray transfer mode.
3. In spray transfer mode, the droplet is not pushed aside of the welding wire and sticks on the tip of welding wire as result of surface tension force due to lower unbalance radial electromagnetic force.

Acknowledgements

This work was supported and financed by Nanyang Technological University of Singapore, Sembcorp Marine Technology Pte Ltd Singapore and Maritime and Port Authority of Singapore. These supports are gratefully acknowledged.

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