Archives of Materials Science and Engineering
Volume 33
Issue 1
September 2008
Pages 49-56
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Effect of welding current on metal transfer in GMAW

M.St. Węglowski [a,*], Y. Huang [b], Y.M. Zhang [b]
[a] Institute of Welding, ul. Bł. Czesława 16/18, 44-100 Gliwice, Poland
[b] University of Kentucky, Lexington, KY 40506, USA
* Corresponding author: E-mail address: marek.weglowski@is.gliwice.pl

Received 29.04.2008; published in revised form 01.09.2008

ABSTRACT

Purpose: The paper presents findings related to the influence of welding current on metal transfer in GMAW. The main goal was to understand how droplet diameter, droplet velocity and droplet transfer rate change with the wire feed speed which determines the welding current.

Design/methodology/approach: The experimental station was designed and built. A high speed video camera “Olympus i-SPEED” was used. The investigations were conducted on an automated GMAW platform. For each wire feed speed the images of metal transfer and welding parameters were recorded.

Findings: Research results presented in this paper indicate that the wire feed speed (welding current) has a significant influence on droplet diameter, droplet velocity and transfer rate. The new method based on narrow band filter for imaging is much more sensitive to the changes of welding conditions and should be used as a tool for monitoring of GMAW process.

Research limitations/implications: The high speed video camera is an expensive instrument and it can be used only as a laboratory tool in monitoring and optimizing of welding processes.

Practical implications: The gained experience will help to determine the further directions for the research on metal transfer in GMAW and help the authors to be prepared for studying the CMT welding process. This methodology will be particularly attractive for welded – structures manufacturing industry because it could significantly reduce the cost of production by optimizing welding parameters.

Originality/value: The new method for monitoring metal transfer based on narrow band filter does not require He-Ne laser to be placed ob the opposite of the imaging plane to generate a shadow. This method is thus more compact and easier to use. The original results of these investigations are mathematic descriptions of droplet flight trajectory and droplet velocity.

Keywords: Welding; Metal transfer; High speed camera; Sensing

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The gas metal arc welding (GMAW) is increasingly employed for fabrication in many industries. This process is versatile, since it can be applied for all position welding; it can easily be integrated into the robotized production canters. These advantages have motivated many researchers to study GMAW process in detail [1]. Gas Metal Arc welding is an arc welding process that uses an arc between a continuously-fed filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of a pressure. It is also known as MIG welding or MAG welding where MIG (Metal Inert Gas) welding refers to the use of an inert gas while MAG (Metal Active Gas) welding involves the use of an active gas (i.e. carbon dioxide and oxygen). A variant of the GMAW process uses a tubular electrode filled with metallic powders to make up the bulk of the core materials (metal core electrode).

Such electrodes may or may not require a shield gas to protect the molten weld pool from contamination. All commercially important metals such as carbon steel, high-strength low alloy steel, stainless steel, aluminium, copper, titanium, and nickel alloys can be welded in all position with GMAW process by choosing appropriate shielding gas, electrode, and welding variables. The process is illustrated in Figure 1.

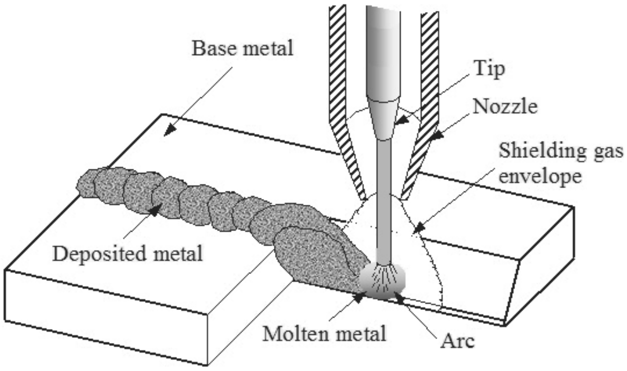

Fig. 1. GMAW process

Metal transfer in GMAW refers to the process of transferring material of the welding wire in the form of molten liquid droplets to the work-piece (Fig. 2). Metal transfer plays an important role in determining the process stability and weld quality. Depending on the welding conditions, metal transfer can take place in three principal modes: globular, spray, and short – circuiting. Globular transfer, where the droplet diameter is larger than the wire diameter, occurs at relatively low currents. Since it is often accompanied by extensive spatters, globular transfer is typically used in welding parts which has relatively loose quality requirements. Spray transfer, where the droplet diameter is smaller than the wire diameter, occurs at medium and high currents. It is a highly stable and efficient process, and is widely used in welding thick steel plates and aluminium parts. Short – circuiting transfer is a special transfer mode where the molten droplet on the wire tip makes direct contact with the work-piece or the surface of the weld pool. It is characterized by repeated, intermittent arc extinguishment and re-ignition. It requires low heat input and hence is commonly used in welding thin sheets [1].

Metal transfer has been a subject matter of many investigations. In [2] the welding process control and metal transfer were controlled and its mode was detected by monitoring current and voltage of the power supply. Many papers described methodology of mathematical analysis for the formation of droplets, and analysed and calculated the effects of individual forces acting on metal droplets at the tip of the wire in GMAW [3]. In order to determine the dominant factors, which affect the metal transfer mode, a dimensional analysis has been conducted in previous studies. Several dimensionless numbers are derived on the basis of the surface-tension force are the Weber (W_e), Bond (B_o), N_{SE}, N_{SV}. The subscripts S and V denote the surface tension and viscosity. These numbers represent the relative effects of electrode melting, gravitational, electromagnetic and viscous forces with respect to the surface-tension force, respectively. The N_{SE} number was found to be the most important dimensionless number influencing the characteristics of metal transfer [4]. Most of recent investigations focused on studying the effect of waveform parameters on the mode of metal transfer in pulsed gas metal arc welding (GMAW-P) [5-9]. The metal transfer mode is also an interesting subject matter in newly developed welding methods such as double electrode gas metal arc welding (DE-GMAW) developed at the University of Kentucky [10]. Some studies focused on detailed analysis of droplet velocity and developed model based only on the electromagnetic pinch force. Many efforts have been made to optimize welding parameters to achieve one droplet per pulse (ODPP – GMAW) [11]. Further, a non-isothermal numerical model has been developed to simulate the metal transfer process in GMAW. Experiments with high-speed photography and laser-shadow imaging show that the simulation results were in broad agreement with the actual welding process [12]. There are also studies which cover the subject matter of short circuit gas metal arc welding process [13]. The newest investigations about metal transfer even allow to create a new classification of mode of metal transfer modes [14]. The new classification is simpler, but does not loose the logic of numbering, from both fundamental and technological points of view. The melting of the wire, which is fundamental and influences process stability and productivity, has also been a main topic of some investigations [15]. Recently, hybrid laser-MIG welding methods have also been studied [16].

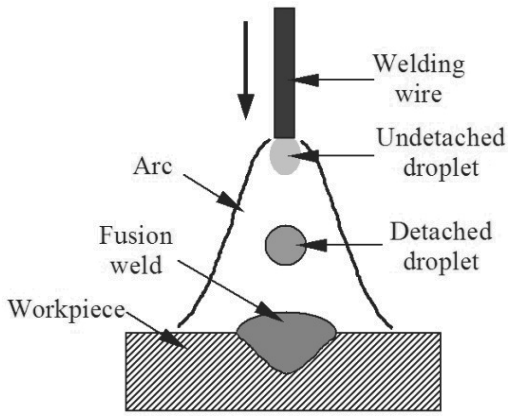

Fig. 2. Schematic of metal transfer process in GMAW

However, the investigations that were carried out up to date have not covered subject matter of mathematic description of droplet flight trajectory and droplet velocity. This paper describes detailed mathematical analysis of droplet flight trajectory and droplet velocity based on polynomial regression of experimental data. In previous investigations the shadowgraph technique has been used to image the metal transfer process using He-Ne laser [17]. In this paper, an easier method which is only based on a narrowband filter and high speed camera is used. This technique is easier to use because of the elimination of the back-lighting laser.

2. Experimental setup and procedure

Experiments were carried out on an automated GMAW platform. A simple schematic of the experimental setup with data flow is shown in Fig. 3. During trials, an Olympus i-SPEED high speed camera was used to image and record the metal transfer process for later analysis. The camera direction was perpendicular to the welding direction. The torch was moved while the work-piece was in a fixed position such that camera was stationary in relation to the work-piece. The high speed camera used a sampling speed of 3000 frame per second (fps). In addition to an aperture of 11 and a shutter of 1, a narrowband filter (central wavelength 940 nm, bandwidth 20 nm) was used to reduce the arc brightness in order to image the metal transfer.

All welds were made with a standard water cooled welding gun Miller Roughneck C 4015, using 1.2 mm (0.045 inch) diameter Quantum ARC 6 carbon steel wire (AWS A5.18, ER70S-6). The chemical composition of the wire is given in Table 1. The pure Ar as shielding gas was used.

Table 1.
Chemical composition of wire

C	Mn	Si	P	S	Cu
0.06-0.15	1.40-1.85	0.8-1.15	<0.025	<0.025	<0.05

The torch was moved at the travel speed 25 cm/min (10 inch/min) to make bead-on-plate welds. Direct current levels between 178 and 246 A were examined, all at an operating voltage of 32 V. The current and, therefore, the metal transfer mode were changed by changing the wire feed rates in the range from 3,81 m/min to 6.1 m/min (150 to 240 inch/min). The conventional three-phase welding machine Hobart EXCEL – ARC 8065 CC/CV was used. The wire feeder was a Miller R-115.

During welding the arc voltage, welding current and wire feed speed were continuously measured. The closed-loop Hall effect current sensor Model CLN-500 was used to measure the welding current. This sensor provides electrical isolation between the current carrying conductor and the output of the sensor. The voltage was measured by a resistance bridge directly in the output of power supply. Signals from the welding circuit were recorded on the PC through the data acquisition card NI DAQ 6036E.

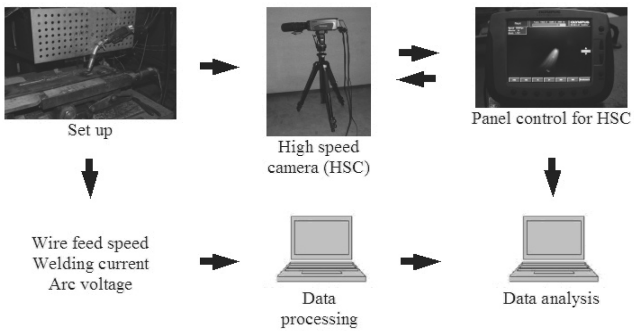

Fig. 3. Experimental setup with flow of data

3. Results and discussion

The recorded images of metal transfer from the high speed camera are analyzed by i-SPEED viewer and Irfanviewer software. An image sequence of droplet track in GMAW for wire feed speed 150 inch/min – welding current 175 A and arc voltage 32 V, is shown in Fig. 4 and for 240 inch/min in Fig. 5. Sampling speed is 3000 frames per second. The arrow marks the same droplet be tracked.

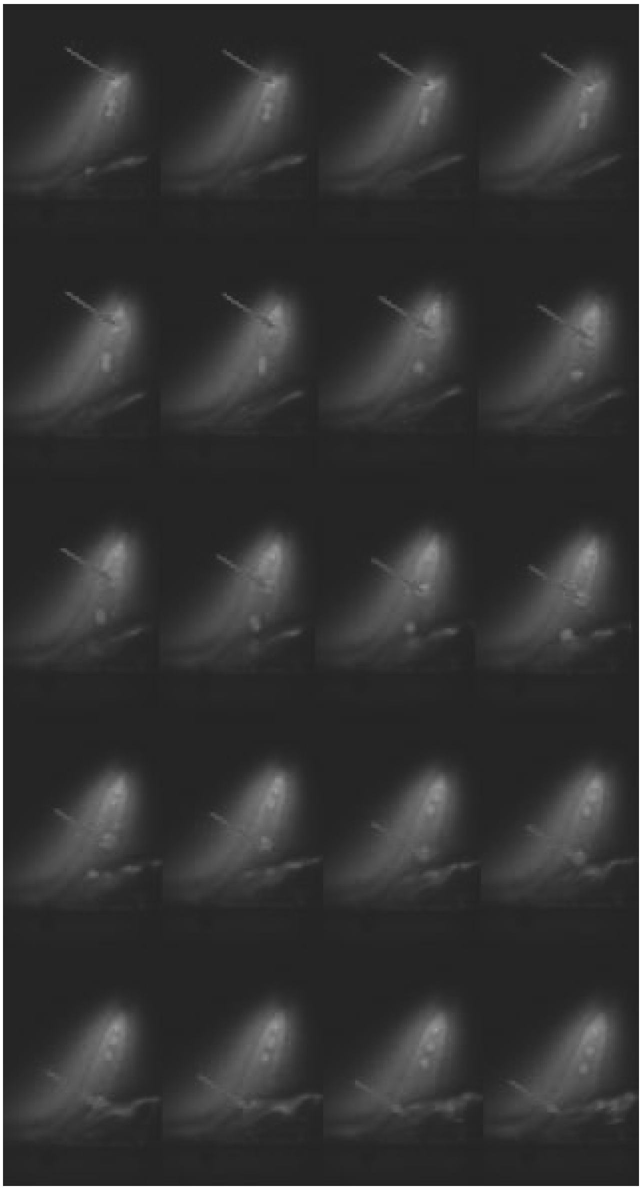

Fig. 4. Image sequence of droplet track in GMAW. Wire speed 150 inch/min (3.81 m/min) – welding current 175 A, arc voltage 32 V, 100 % Ar. Sampling speed is 3000 frames per second. The arrow marks the same droplet

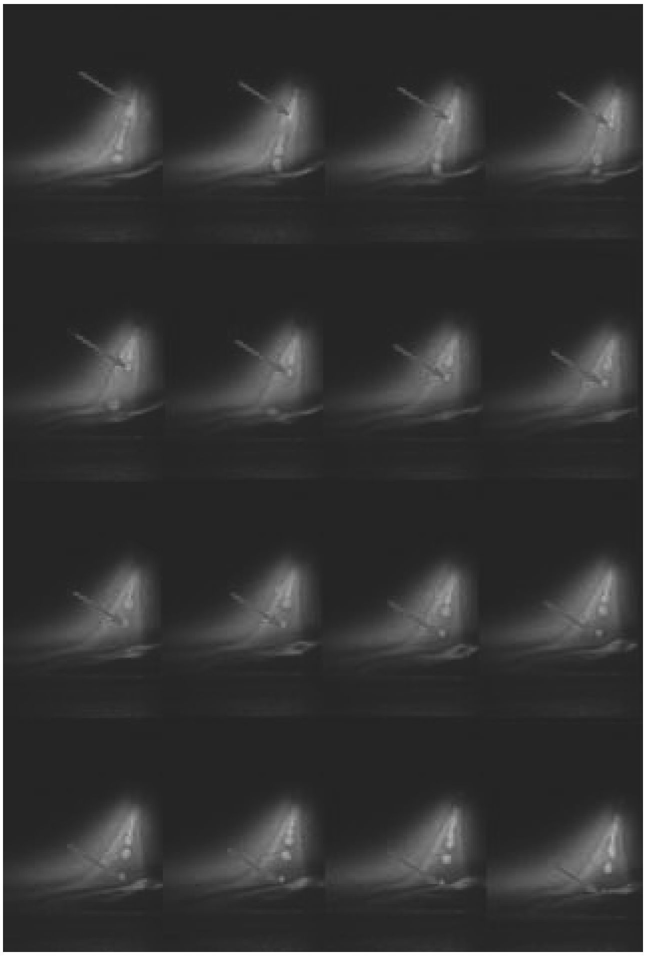

Fig. 5. Image sequence of droplet track in GMAW. Wire speed 240 inch/min (6.1 m/min) – welding current 246 A, arc voltage 32 V, 100 % Ar. Sampling speed is 3000 frames per second. The arrow marks the same droplet

3.1. Droplet diameter and number of droplet per second

One of the main goals of this investigation was to calculate the diameter of the droplet and he droplet transfer rate (the number of droplets detached per second). To this end, it was necessary to measure droplet diameter in two directions (horizontal d_h and vertical d_v diameter), as shown in Figure 6. The diameter D of the droplet is calculated as $D=(d_h + d_v)/2$ when the droplet to be analyzed reaches a particular location in the image. The average diameter was calculated for each set of welding parameters using seven image sequences. The lowest and highest diameters were not used in the calculation. If the difference between horizontal and vertical diameter was higher than 20%, next sequence was used. The standard error of droplet diameter was calculated according to formula 1:

$$S_D = \sqrt{S_d^2 + S_i^2} \quad (1)$$

where:
S_D – standard error of droplet diameter,
S_d – standard deviation ,
S_i – measurement resolution.

The measurement resolution was an S_i = 0.1 mm. The results of calculation are given in Table 2. To calculate the transfer rate the following assumptions were made:

- the difference between horizontal and vertical diameter is less than 20%, and the droplet can be assumed to be spherical,
- the welding process is stable and transfer rate is constant vs. time,
- spatters are negligible.

In a unit time, the total volume of the transferred droplets is equal to the molten metal:

$$n\frac{4}{3}\pi\left(\frac{D}{2}\right)^3 = \frac{1}{4}\pi d^2 v_{el} \quad (2)$$

where:
n – number of droplets per second,
D – average diameter of droplet [m],
V_{el} – wire feed [m/s].
The number of droplet can be calculated as:

$$n = \frac{3}{8}\cdot\frac{d^2}{D^3}\cdot v_{el} \quad (3)$$

The results of the transfer rate calculation are given in Table 2 for wire feed rate in the range from 150 inch/min to 240 inch/min. The results were rounded to integers.

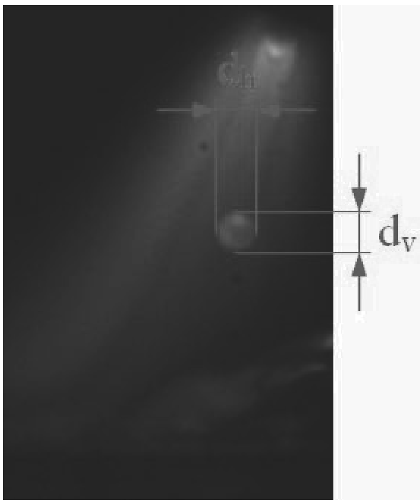

Fig. 6. Methodology for calculating the diameter of a single droplet in GMAW. d_h – horizontal diameter, d_v – vertical diameter

Table 2.
Relationship between wire feed speed, droplet diameter and transfer rate

No	Wire feed [inch/min] /(m/min)	Welding current and standard deviation $I \pm S_{dI}$ [A]	Mean value of d_v/d_h [%]	Standard deviation S_d [mm]	Real value with standard error $D \pm S_D$ [mm]	Transfer rate (number of droplets per second based on formula 3)
1.	150 / 3.81	178±27	90.11	0.23	1.29±0.25	16
2.	160 / 4.06	180±24	105.93	0.07	1.08±0.12	30
3.	170 / 4.32	194±35	96.41	0.10	1.05±0.13	34
4.	180 / 4.57	206±19	101.86	0.12	0.99±0.16	42
5.	190 / 4.83	211±33	110.08	0.12	0.90±0.16	60
6.	200 / 5.08	216±12	105.07	0.06	0.82±0.12	83
7.	210 / 5.33	225±7	93.36	0.07	0.68±0.12	153
8.	220 / 5.59	229±5	100.41	0.08	0.65±0.13	183
9.	230 / 5.84	232±4	101.23	0.12	0.52±0.15	374
10.	240 / 6.10	246±7	96.54	0.12	0.51±0.15	414

3.2. Droplet velocity

To determine the droplet velocity the static force balance theory [13] was used. There are four major forces acting on the pendant droplet: the surface tension which retains the droplet and three detaching forces (gravity, viscous drag and electromagnetic force). To derive a simple formula to calculate the droplet velocity at detachment, we only consider the effect of the electromagnetic force, F_m, on the droplet velocity (Other two detaching forces can be considered to balance out with the surface tension.). Treating the droplet as a simple body, the kinetic energy imparted to the droplet is:

$$\frac{1}{2} m v^2 = \int F_m ds \tag{4}$$

where:
m – mass of the droplet,
v – the droplet velocity,
s – the distance the droplet travels before detachment.
The electromagnetic force is given by:

$$F_m = \frac{\mu_0 I^2}{4\pi} f(s) \tag{5}$$

where:
I – welding current,
μ_0 – the magnetic permeability of the free space,
$f(s)$ – a geometric shape factor depending on the droplet radius and neck diameter during droplet growth and detachment.

By substituting F_m in (4), the droplet velocity can be calculated from:

$$v = \frac{I}{D} \frac{3\mu_0^{1/2}}{\rho \pi^2} \Psi \tag{6}$$

where:
D – the droplet diameter,
ρ – the density of the droplet,
Ψ – geometrical shape factor, determines the electromagnetic work done on the drop during growth and detachment process at a given current.

The following physical properties were used:

- mass density: 7860 kg m^{-3}
- permeability: $4\pi \cdot 10^{-7}$ $H \cdot m^{-1}$

To estimate the tracking equation of a single droplet a 3^{th} degree of polynomial regression was used:

$$y(t) = A + B_1 \cdot t + B_2 \cdot t^2 + B_3 \cdot t^3 \tag{7}$$

where:
t – time [ms] ,
y – distance along the arc axis from detachment [mm],
A, B_i – coefficients.

After fitting the coefficients in the formula 7 we obtained for wire speed 150 inch/min

$$y_{150}(t) = 0.0229 + 0.12404 \cdot t + 0.07585 \cdot t^2 - 0.00451 \cdot t^3 \tag{8}$$

and for 240 inch/min

$$y_{240}(t) = 0.102 + 0.38482 \cdot t + 0.02997 \cdot t^2 - 0.00049 \cdot t^3 \tag{9}$$

Comparison between measurements (from high speed video) and mathematical description is shown in Figure 7 for wire speed 150 and 240 inch/min. As can be seen, the change in wire feed speed did cause changes in the model coefficients. Different coefficients in formula 8 and 9 regarding value, and the similarity of the fitting curves in Fig. 7 indicate that is it possible to model the movement of droplet transfer in the whole range (150 to 240 inch/min). As shown in Fig. 7 the mathematical formula 8 and 9 have a good agreement with the experimental data in the whole range.

To estimate the velocity v_{150} and v_{240} for wire feed speed 150 inch/min and 240 inch/min, the derivative of movement equation 8 and 9 can be calculated. To achieve droplet velocity in mm/s unit the formula 8 and 9 was multiplication by 1000 times.

For wire feed speed 240 inch/min

$$v_{150} = \frac{dy_{150}}{dt} \tag{10}$$

then,

$$v_{150} = 124.04 + 151.7 \cdot t - 13.53 \cdot t^2 \tag{11}$$

For wire feed speed 240 inch/min

$$v_{240} = \frac{dy_{240}}{dt} \tag{12}$$

then,

$$v_{240} = 384.82 + 59.94 \cdot t - 1.47 \cdot t^2 \tag{13}$$

The droplet velocity vs. time shown in Figure 8 for the two wire feed speeds.

As can be seen in Fig. 8 the droplet velocity for v_{150} has relative extremum of function 549.2 mm/s at t=5.6 ms. As shown in Fig. 8 the maximum velocity 770.2 mm/s the droplet achieve for t=8.0 ms for wire feed speed 240 inch/min.

Based on formula 6 the geometrical shape factor can be calculated for wire speed 150 inch/min using the average droplet velocity:

$$\Psi_{150} = \frac{\bar{v}_{150} \cdot D_{150} \cdot \rho \cdot \pi^2}{3 \cdot I_{150} \cdot \mu_0^{1/2}} = \frac{\rho \cdot \pi^2}{3 \cdot \mu_0^{1/2}} \cdot \frac{\bar{v}_{150} \cdot D_{150}}{I_{150}} \pm \Delta\Psi \tag{14}$$

where:

$\bar{v}_{150}$ - average droplet velocity calculated from the following formula:

$$\bar{v}_{150} = \frac{1}{T} \int_0^T v_{150}(t) dt \tag{15}$$

where:

T is the time the droplet reaches the weld pool,

$\Delta\Psi$ – the standard error of geometrical shape factor calculated acc. to the following formula:

$$\Delta\Psi = \sqrt{\left(\frac{Se_D}{D}\right)^2 + \left(\frac{Sd_I}{I}\right)^2} \tag{16}$$

where:

S_D – Standard error of diameter of droplet from Table 2,

S_{dI} – standard deviation of welding current from Table 2.

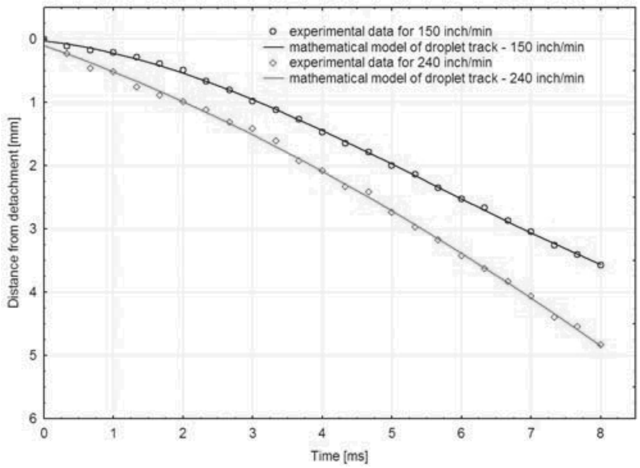

Fig. 7. Influence of wire speed rate (welding current) on droplet flight trajectory

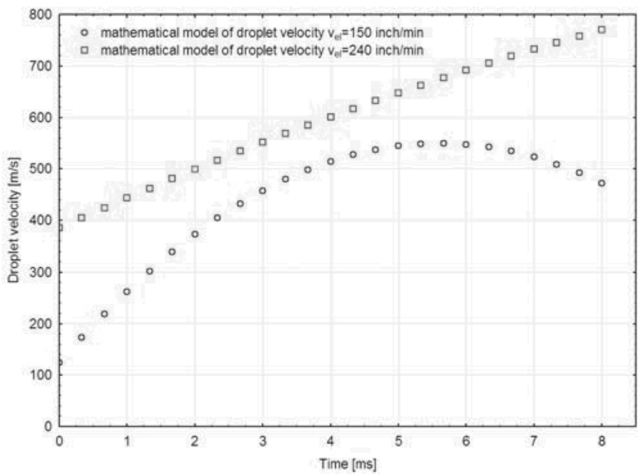

Fig. 8. Influence of wire speed rate (welding current) on droplet velocity

The average droplet transfer velocity for wire feed speed 150 inch/min is:

$$\bar{v}_{150} = 436.17 \text{ mm/s}$$

The geometrical shape factor for wire feed speed 150 inch/can be written as:

$$\psi_{150} = 72.860 \pm 0.057 \quad (17)$$

The results for 240 inch/min are:

$$\bar{v}_{240} = 592.54 \text{mm/s}$$

$$\Psi_{240} = \frac{\rho \cdot \pi^2}{3 \cdot \mu_0^{1/2}} \cdot \frac{\hat{v}_{240} \cdot D_{240}}{I_{240}} = 28.315 \pm 0.035 \quad (18)$$

We can notice a difference between geometrical shape factor for wire feed speed 150 inch/min and 240 inch/min. The minimum difference between Ψ_{150} and Ψ_{240} is :

$$\Psi_{150} - \Psi_{240} = 44.453 \quad (19)$$

This results suggest that geometric shape factor depending on the droplet radius, and also indicate that the electromagnetic force plays an important role in the metal transfer process.

4. Conclusions

In this paper, measurements of metal transfer are presented in the GMAW process in the range of welding wire speed from 150 inch/min to 240 inch/min. The measurement system is based on a high speed camera and it can measure the metal transfer at 3000 frames per second.

Effect of welding current on the metal transfer are evaluated using dimensional and kinetic analysis and the results lead to the following conclusions:

- measurement of the droplet diameter size has shown that average diameter of droplet in the range of wire feed rate from 150 to 240 inch/min changes in the range from 1.29±0.25 mm to 0.51±0.15 mm for pure argon shield gas,
- transfer rate is in the range from 16 to 414 droplets per second
- to fit the droplet flight trajectory a 3rd degree polynomial was used; similarity coefficients suggest that is possible to create only one single mathematical formula for a wide range of welding parameters,
- to calculate the changes in droplet velocity, the derivative of movement equation was calculated. The results indicate the velocity behave quite differently under different wire feed speeds,
- based on references and experimental data the geometrical shape factor of droplet was calculated. The results indicate the geometrical shape factor changes with the welding parameters and the changes are very significant.

The gained experience would allow the authors to determine the further directions on metal transfer research and use the simple method proposed in this study to on-line monitor the welding process in automated GMAW.

Acknowledgements

The authors would like to thank The Fulbright Commission for financing this research, which was done within the framework of the research project Young Advanced Research Grant – University of Kentucky Centre for Manufacturing, Welding Research and Development Laboratory and the Applied Machine Vision Laboratory 2007-2008. This research is also supported in part by the National Science Foundation under grant CMMI-0726123.

References

[1] R.W. Messler, Principles of Welding, Processes, Physics, Chemistry, and Meallurgy, Chapter 3, John Wiley & Sons, New York, 1999.
[2] K. Luksa, Z. Rymarski, Collection of arc welding process data, Proceedings of the 12th International Scientific Conference "Achievements in Mechanical and Materials Engineering"AMME'2003, Gliwice–Zakopane, 2003, 377-380.
[3] F.L. Zhu, H.L. Tsai, S.P. Marin, P.C. Wang, A comprehensive model on the transport phenomena during gas metal arc welding process, Progress in Computational Fluid Dynamiccs 4 (2004) 99-117.
[4] S.K. Choi, Y.S. Kim, C.D. Yoo, Dimensional analysis of metal transfer in GMA welding, Journal of Physics D: Applied Physics 32 (1999) 326-334.
[5] G. Fu, F. Tian, H. Wang, Studies on softening of heat-affected zone of pulsed-current GMA welded Al–Zn–Mg alloy, Journal of Materials Processing Technology 180 (2006) 216-220.
[6] G. Wang, G. Huang, Y.M. Zhang, Numerical analysis of metal transfer in gas metal arc welding under modified pulsed current conditions, Metallurgical and Materials Transactions B 35 (2004) 857-866.
[7] P.K. Palani, N. Murugan, Selection of parameters of pulsed current gas metal arc welding, Journal of Materials Processing Technology 172 (2006) 1-10.
[8] P.K. Ghosh, L. Dorn, M. Hübner, V.K. Goyal, Arc characteristics and behaviour of metal transfer in pulsed current GMA welding of aluminium alloy, Journal of Materials Processing Technology 194 (2007) 163-175.
[9] S.K. Choi, C.D. Yoo, Y.S. Kim, The dynamic analysis of metal transfer in pulsed current gas metal arc welding, Journal of Physics D: Applied Physics 31 (1998) 207-215.

[10] K. Li, Y.M. Zhang, Metal Transfer in Double-Electrode Gas Metal Arc Welding, Journal of Manufacturing Science and Engineering-Transactions of the ASME, (in print).
[11] Q. Lin, X. Li, S.W. Simpson, Metal transfer measurements in gas metal arc welding, Journal of Physics D: Applied Physics 34 (2001) 347-353.
[12] F. Wang, W.K. Hou, S.J. Hu, Modelling and analysis of metal transfer in gas metal arc welding, Journal of Physics D: Applied Physics 36 (2003) 1143-1152.
[13] K. Luksa, Diagnosing of short circuit gas metal arc welding process, Proceedings of the 3rd Scientific Conference "Materials, Mechanical and Manufacturing Engineering" M3E'2005, Gliwice–Wisła, 2005, 977-984.
[14] D. Iordachescu, L. Quintino, Steps toward a New Classification of Metal Transfer in Gas Metal Arc Welding, Journal of Materials Processing Technology (in print).
[15] P.J. Modenesi, R.I. Reis, A model for melting rate phenomena in GMA welding, Journal of Materials Processing Technology 189 (2007) 199-205.
[16] G. Campana, A. Fortunato, A. Ascari, G. Tani, L. Tomesani, The influence of arc transfer mode in hybrid laser-MIG welding, Journal of Materials Processing Technology 191 (2007) 111-113.
[17] C.D. Allemand, R. Schoeder, D.E. Ries, T.W. Eager, A method of filming metal transfer in welding arcs, Welding Journal 64 (1985) 45-47.