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Research paper

Special features of double pulsed gas metal arc welding

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ABSTRACT

Since the pulsation of heat input provides a flexible and effective way to control temporal variation of weld pool geometry, cooling rate and solidification parameters, double pulsed (DP) gas metal arc welding (GMAW) serves as an unique tool for controlling the structure and properties of welds. A comprehensive model of DP-GMAW, when adequately tested with experimental data, provides a powerful tool for achieving predictable, high-quality welds. Here we develop a three-dimensional, transient, numerical model of DP-GMAW and test it against carefully planned experiments. The variation of current amplitude enables tailoring of weld attributes such as geometry, cooling rates, solidification parameters and microstructure and its role in the welding of an aluminum alloy is examined both experimentally and theoretically. Since the grain size in the fusion zone is significantly affected by its cooling rate, experimental measurements of grain size for various current amplitudes are correlated with the corresponding computed cooling rates at a constant heat input. Results indicate that cooling rates can be increased and grain size can be refined at a constant heat input while using DP-GMAW. The current amplitude of DP-GMAW can be used to adjust the average cooling rate without changing the heat input. The effects of current amplitude on the fusion zone geometry, cooling rates, solidification parameters, and grain size are investigated for improved understanding of DP-GMAW.

1. Introduction

Gas metal arc welding (GMAW) is the most widely used welding process because of its ability to bridge gaps in large butt joints and tailor weld metal composition and properties by appropriate selection of filler metal at low cost. An important variable in GMAW is the heat input that represents the amount of energy deposited per unit length. Reduction of heat input results in smaller molten pool, narrower size of the heat affected zone and improved weld quality. In GMAW, lower heat input is often achieved by current pulsing to reduce the average current. In automotive and sheet metal industries where welding of thin sheets is important, pulsed current GMAW, otherwise known as single pulsed (SP) GMAW provide superior control of metal droplet transfer from the melting filler wire to the liquid weld pool. The droplet transfer mode achieved in SP-GMAW is spray transfer with one molten metal drop transferred from the melting electrode into the weld pool in each current pulse. This mode of metal transfer provides excellent surface finish and significantly reduced spatter. Since a high pulsing frequency of up to several hundred pulses per second is used, the pool shape and size and the cooling rate of the fusion zone does not change with time after the initial start of welding. The fusion zone size and cooling rate depend on the welding current and the heat input. In other words, in SP-GMAW, control of cooling rate, which influences the microstructure and properties of welds is achieved by selecting the heat input, just like the practice in other fusion welding processes.

A variant of pulsed GMAW, known as double pulsed (DP) GMAW has changed the interrelation between cooling rate and heat input, because it enables adjustment of various weld attributes at a constant heat input by changing the pulsing parameters. Fig. 1 illustrates schematically the typical current waveform of DP-GMAW. As shown in the figure, pulsing in DP-GMAW involves repeated application of two sequential phases of somewhat different pulsing characteristics. Both the first and second phases contain several current pulses at high frequencies, and Liu et al. (2013a) have discussed that these current pulses are used to achieve the metal transfer in spray transfer mode. However, the base current and number of current pulses during the first phase are higher than those during the second phase. Consequently, the average current of the first phase (I_F) is higher than that in the second phase (I_S). An important variable in DP-GMAW is the current amplitude (A) which is defined as half of the difference between I_F and I_S. DP-GMAW has been used for the welding of aluminum alloys because of its ability to provide reduced porosity in the weld metal as reported by Mathivanan et al. (2014), better gap bridging ability as demonstrated by Yamamoto et al. (1992), and better ability to control the mode of droplet transfer,

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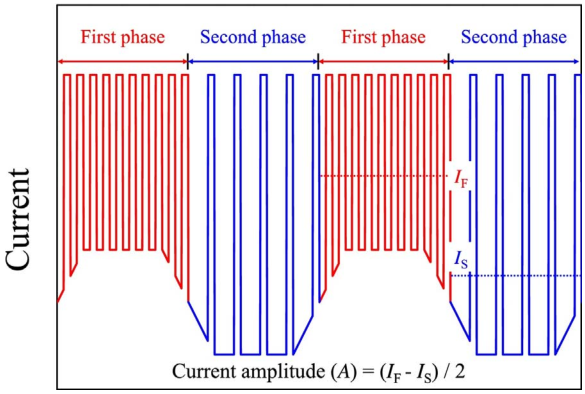

Fig. 1. Schematic diagram of current waveform of DP-GMAW. Current amplitude (A) is defined as half of the difference between the average current of the first phase (I_F) and the average current of the second phase (I_S).

all of which affect weld quality.

Sen et al. (2015) established that heat input was time-dependent and related to the temporal variation of arc current during DP-GMAW. Liu et al., (2013b) observed that the geometry of the weld pool varied with time in DP-GMAW due to the variation of current waveform and heat input. Wang et al., (2016b) found that DP-GMAW typically produced a wavy weld penetration and the temporal variation of weld pool depth depended on pulsing parameters. Other weld attributes such as the cooling rate and solidification parameters also vary with time. Yamamoto et al. (1993) found that mean grain size could be reduced by using of DP-GMAW. Wang et al., (2017b) observed that double pulsed gas tungsten arc welding (GTAW) produced finer dendrite than that produced by conventional pulsed GTAW. Wang et al., (2016a) are ported that the scale of the dendrite could be changed through changing the current period of DP-GMAW while keeping the mean welding current and heat input constant.

Although the advantages of DP-GMAW has been well documented in the literature, the mechanisms for these observations are not well understood. Here we develop a phenomenological model based on the scientific principles to better understand the origins of the improvements achievable by DP-GMAW. The equations of conservation of mass, momentum, and energy are solved with appropriate boundary conditions to examine the role of important variables in DP-GMAW for various welding conditions. Periodic variations of fusion zone geometry, liquid metal flow fields, temperature distributions, cooling rates and solidification parameters are examined. Experiments are conducted to verify the calculations. Remelting and resolidification of the previously solidified metal near the trailing edge of the weld pool are studied. Grain refinement of 1060 aluminum welds is characterized experimentally, and its mechanism is examined by using the estimated mean cooling rate.

2. Materials and methods

2.1. Materials and process parameters

Aluminum alloy AA1060 was welded using ER1070 filler metal. Table 1 shows the chemical compositions of the base metal and the filler wire given by Liu et al., (2013c). The base metal plates were 200 mm long, 80 mm wide and 4 mm in thickness and the filler wires had a diameter of 1.2 mm. Bead-on-plate welding was carried out using a digital welding power source. The shielding gas was 99.99% argon with gas flow rate of 15 l/min, and the electrode extension was 15 mm. Specimens were cut along the central longitudinal and transverse sections of welds after welding. The samples were ground and polished to 0.06 μm using colloidal silica and subsequently were electrolytically etched using the standard Barker's reagent (2.5 ml HBF_4 + 100 ml H_2O) with 120 s. The metallographic images were taken using a polarized microscope.

Table 1
Chemical compositions of AA1060 and ER1070 (wt%).

Material	Fe	Si	Cu	V	Zn	Mg	Mn	Ti	Al
AA1060 (base metal)	0.35	0.25	0.05	0.05	0.05	0.03	0.03	0.03	Balance
ER1070 (filler wire)	0.25	0.20	0.04	0.05	0.04	0.03	0.03	0.03	Balance

Table 2
Welding process parameters.

Process parameters	No. 1	No. 2	No. 3	No. 4
Mode of welding current	SP-GMAW	DP-GMAW	DP-GMAW	DP-GMAW
Current amplitude (A)	0	30	40	50
Mean voltage (V)	22.3	22.3	22.3	22.3
Mean current (A)	100	100	100	100
Welding speed (mm s^{-1})	8	8	8	8
Current period (s)	–	0.4	0.4	0.4
First phase mean current (A)	–	130	140	150
Second phase mean current (A)	–	70	60	50
First phase time (s)	–	0.2	0.2	0.2
Second phase time (s)	–	0.2	0.2	0.2

The welding process parameters are presented in Table 2. Cases 1 and 3 are used to compare SP-GMAW and DP-GMAW. Cases 2, 3 and 4 are used to study the effect of current amplitude on fusion zone sizes and solidification parameters of DP-GMAW. The actual welding current waveforms of cases 2, 3 and 4 are shown in Fig. 2. As shown in the figure, greater current amplitude results in an increase in the average current of the first phase (I_F) and decrease in the average current of the second phase (I_S). Note that all the cases have the same heat input and welding speed.

2.2. Numerical methods

2.2.1. Heat transfer and fluid flow model

The heat transfer and fluid flow in the weld pool are calculated by solving the equations of conservation of mass, momentum, and energy in three dimensions as summarized by Wei et al. (2015) and Wei et al., (2017). The model considers the effect of Marangoni stress, electromagnetic force and buoyancy on liquid metal convection within the weld pool, as discussed by David and DebRoy (1992). The governing equations and boundary conditions have been shown by Wei et al. (2016) and Mishra et al. (2008), and they are not repeated here. The liquid metal droplets from the tip of the filler wire were transported into the melt pool with one droplet per current pulse. Kim et al. (2003) proposed a volumetric heat source to account for the energy transferred by the overheated droplets, and the volumetric heat source was incorporated in the model. The thermophysical properties used in the calculation of temperature and velocity fields are presented in Table 3.

The pulsing current of SP-GMAW in the model is implemented as constant mean current of 100 A. Such a simplification offers enhanced computational efficiency without affecting the accuracy of the calculations. The current pulsing frequency of SP-GMAW was 80 Hz, Wang et al. (2014) experimentally and Liu et al. (2015) numerically found that the weld penetration depth remained constant with time due to short application times for the high and low current pulses under such high frequency. The mean currents during the first and the second pulse phases of the DP-GMAW are implemented in a similar way to that of the SP-GMAW. Roy et al. (2006) proposed a method for unsteady-state welding, the model stored spatial distribution of temperature and velocity at the ending time of the first phase, which were loaded at the starting time of the second phase, and vice versa. The temperature field,