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An improved simulation of temperature field in VPPA–GMAW of Al–Cu–Mg alloy

Zhenbang Sun, Yongquan Han*, Maohua Du, Jiahui Tong, Haitao Hong

School of Materials Science and Engineering, Inner Mongolia University of Technology, Hohhot, 010051, PR China

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ABSTRACT

The thermal properties with consideration of the phase transitions were established to simulate the temperature field of the paraxial variable polarity plasma arc (VPPA)–gas metal arc welding (GMAW) hybrid welding. A variable combined heat source model was developed to describe the heat transfer process of hybrid welding. The effects of different energy ratios of hybrid welding on the weld pool geometries and penetration depth were investigated. An appropriate increase in the VPPA welding power could improve the depth-to-width ratio of weld beads, to achieve deep-penetration welding. Experiments were performed to measure weld geometries, and the weld pool was captured in situ by a high-speed camera to verify the developed finite element model. The calculated results were in good agreement with the experimental results. The adapted matching of the VPPA and GMAW powers was determined by the numerical simulation to optimize the hybrid welding process, resulting in high-quality butt welds.

1. Introduction

Nunes et al. (1984) introduced the variable polarity plasma arc (VPPA) welding process to fabricate aluminum external tanks for space shuttles at NASA's Marshall Space Flight Center. As a high-energy-density welding process developed for aluminum alloys, VPPA has an unsymmetrical square alternating-current waveform and operates in keyhole mode during welding. VPPA independently alternates polarity, amplitude, and duty ratio to satisfy the cathode cleaning action and obtain high-quality weld joints.

In recent years, with the advance of new welding processes for higher productivity capacity, researchers have pursued the development of a high-efficiency and high-quality hybrid welding process. The VPPA process has been modified for deep-penetration welding of thick-plate aluminum alloys by using gas metal arc welding (GMAW) as an additional heat source, which evolved from the plasma-GMAW process first proposed by Essers and Liefkens (1972) at Philips Research Laboratories. According to the spatial position of the two heat sources, the plasma-GMAW is divided into coaxial and paraxial processes. The coaxial plasma-GMAW process has been widely researched. Ton (1975) demonstrated by optical spectroscopy analysis that the temperature of the plasma arc was twice as high as that of the GMAW arc, and that part of the GMAW current flows associated into the plasma arc. Bai et al. (2010a, b) investigated the droplet transfer and analyzed the influence of welding parameters on aluminum weld porosity. Hertel et al. (2014) discussed a numerical procedure to describe the properties of the plasma-GMAW joint as a function of the process parameters. Resende et al. (2011) claimed that the coaxial plasma-GMAW process had a wider contact area with the workpiece, and, as a result, a larger heated area, a reducing weld penetration, and greater bead width. Essers and Walter (1981) observed that the arc around the tip of the welding wire tended to rotate at high currents, which caused the droplet transfer to the weld pool to be less focused. These phenomena are not conducive to deep penetration. Therefore, the coaxial plasma-GMAW is limited for thick-plate aluminum alloy welded structures.

The paraxial VPPA–GMAW hybrid welding process integrates the advantages of the VPPA welding process—high energy density, high-velocity plasma jet, and large penetration depths (Chen et al., 2018; Han et al., 2012; Wu et al., 2006a, b)—with those of the GMAW process—high welding efficiency and varied technological parameters (Zeng et al., 2017; Cho et al., 2013). The paraxial welding torch uses a smaller constricting nozzle, to acquire a concentrated plasma arc and avoid interactions between the VPPA and GMAW arcs. VPPA can also reduce the loss of the plasma electrode and clean oxidation film. Hong et al. (2016a, b) investigated the arc coupling mechanism and droplet transfer characteristic of VPPA–GMAW by multiple experiments, which indicated that the process was appropriate for welding thick-plate aluminum alloys. However, most of the welding parameters were

* Corresponding author.
E-mail address: hanyongquan-imut@outlook.com (Y. Han).

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determined empirically, requiring numerous experiments for verification. Murphy (2015) emphasized that numerical simulation can be used to obtain a complete understanding of mechanisms, allowing advanced optimization of the welding parameters. There is still a lack of fundamental research to guide or understand the VPPA–GMAW process. Moreover, most numerical-simulation studies on welding do not consider the effect of the phase transitions of metals on the thermal properties during welding. For some heat-treated metal alloys, phase transitions occur during the rapid heating and cooling of the welding process. The thermal properties are affected during the welding process because of the phase transitions. Accurate thermal-property parameters of materials are the basis for calculating the temperature field. To calculate the temperature field of welding more accurately, it is necessary to investigate the effects of phase transitions on thermal diffusivity, specific heat capacity, and thermal conductivity.

In this research, the thermal properties of Al–Cu–Mg alloys were analyzed in depth and used for the finite-element analysis of VPPA–GMAW. Furthermore, a variable combined heat source model was established to investigate the temperature field for different VPPA–GMAW welding conditions for Al–Cu–Mg alloy plates. Experiments were conducted to validate the results of the numerical simulations. The VPPA–GMAW process was optimized by the numerical simulation to obtain high-quality butt welds.

2. Materials and experimental methods

Al–Cu–Mg alloy plates (T4) with thicknesses of 6 mm were used in the experiments as the base metal. The chemical compositions of this alloy are shown in Table 1. The melting point of the alloy is 638 °C. The precipitation during the artificial aging of Al–Cu–Mg alloys proceeds in the sequence illustrated by Wolverton (2001) and Lu et al. (2007): solid solution → Guinier–Preston (GP) zone → (S″) → S′ → S.

As shown in Fig. 1, thermal diffusivity (α) was measured by a laser flash technique (Netzsch, LFA427, Germany), from 30 °C to 500 °C at a heating rate of 10 °C/min. The samples with a diameter of 12.7 mm and a thickness of 2.5 mm were prepared from the alloy plates. Cylinder-shaped samples with a diameter of 4.7 mm and a height of 11 mm were taken from the alloy plates for the specific heat capacity measurements. The specific heat capacity (C_p) was measured using a differential scanning calorimeter (DSC) (Setaram, France) with synthetic sapphire (Al_2O_3) as the reference material, from 30 °C to 500 °C at a heating rate of 10 °C/min. The classical three-step method with continuous heating mode was followed to measure the specific heat capacity. The two tests were carried out under a protective Ar atmosphere to prevent samples from oxidizing.

The bulk density of the sample was found to be 2.77 ± 0.01 g/cm^3 at room temperature. The density above room temperature was corrected by the measurement of the thermal expansion coefficient. The thermal conductivity, which is closely connected to the thermal diffusivity, was calculated for a given material composition using Eq. (2) (Tritt, 2004).

$$\lambda = \alpha C_p \rho \tag{1}$$

where λ is the thermal conductivity (W/m·K), α is the thermal diffusivity (m^2/s), C_p is the specific heat capacity (J/kg·K), and ρ is the density (g/cm^3).

The VPPA–GMAW hybrid welding system consisted of a VPPA power source (Fronius MagicWave3000), GMAW power source (Fronius TPS4000), SUPER-MIG welding torch, and Kuka robot. The SUPER-MIG torch includes a plasma torch perpendicular to the working plane and a GMAW torch at an angle of 16° to the plasma torch. The distance between the GMAW and plasma torches was kept at 18 mm. A thoriated tungsten electrode with a diameter of 3.2 mm was used, and the angle of the electrode tip was 60°. The distance between the VPPA nozzle and workpieces was kept at 8 mm. The distance between the GMAW nozzle and workpieces was kept at 18 mm. The plasma gas and GMAW shielding gas were surrounded by the overall shielding gas. High-purity argon (99.99%) was used in the three gases with gas flow rates of 3.5, 23, and 40 L/min, respectively. ER2319 with a diameter of 1.6 mm was used as the welding wire. The set values of the welding parameters used in the experiments are summarized in Table 2. The time ratio of direct current electrode negative (DCEN) to direct current electrode positive (DCEP) durations was 17 to 3 ms. The welding speed was controlled to be 500 mm·min^{-1}. A high-speed camera (Redlake Y4) was used to capture in situ images of the weld pools. A laser source was used as a backlight, with a narrow-band optical filter to weaken the effect of the arc.

Table 1
Chemical compositions of Al–Cu–Mg alloys (percent by weight).

Cu	Mg	Mn	Fe	Si	Ti	Zn	Al
3.8 ~ 4.9	1.2 ~ 1.8	0.3 ~ 0.9	0.5	0.5	0.15	0.12	Remainder

3. Thermal properties

The secondary phase distribution in the joint is non-uniform because of the phase transitions of Al–Cu–Mg alloys during the rapid heating and cooling of the welding process, as shown in Fig. 2. The phase transitions of Al–Cu–Mg alloys during the VPPA–GMAW process will influence their thermal properties. To better calculate the temperature field in the VPPA–GMAW process, several significant thermal property parameters, including specific heat capacity, thermal diffusivity, and thermal conductivity, were investigated.

The thermal properties of Al–Cu–Mg alloys, in the range between room temperature and 500 °C, are presented in Fig. 3. The thermal diffusivity, shown against temperature in Fig. 3(a), can be explained by three trends, according to the slope of the thermal diffusivity at certain temperatures. The value of thermal diffusivity slightly increased with increasing temperature between 30 °C and 150 °C. This was caused by a reduction in the number of solute atoms dissolved in the aluminum matrix, as reported by Choi et al. (2015). The thermal diffusivity, as a heat flow channel, is influenced more sensitively by the concentration of solute atoms in solid solution and the precipitation of various phases. Heat flows through solid metals by two methods of transportation: lattice vibrational waves, also known as phonons, and free electrons. Solute atoms act as scattering centers and disturb the movement of free electrons; as the temperature increases, the electrons are more easily scattered by high-frequency lattice vibration, which induces a decrease in thermal diffusivity. At 200 °C, the thermal diffusivity increased to 60 mm^2/s. Between 200 °C and 400 °C, the thermal diffusivity trend differed obviously, which corresponded to the formation of secondary phases. As the temperature of solid metals increases, the lattice vibrations have a higher frequency, which disturbs the movement of electrons. Therefore, the thermal diffusivity decreases (Tritt, 2004; Choi et al., 2016). This highlights the temperature dependence of the thermal diffusivity of Al–Cu–Mg alloys in these ranges.

Fig. 3(b) shows the continuous specific heat capacity of Al–Cu–Mg alloys between room temperature and 500 °C. In Fig. 3(b), the continuous specific heat capacity shows abnormal behaviors near the transformation temperature, through the occurrence of four peaks. The change of specific heat capacity is caused by the latent heat of phase transitions of Al–Cu–Mg alloys. The endothermic reaction during the phase transitions increases the specific heat capacity, whereas the exothermic reaction decreases the specific heat capacity. The continuous specific heat capacity was analyzed based on the findings of Smith et al. (2000); Bassani et al. (2007), and Lu et al. (2007). An exothermic peak (A) at about 110 °C is attributed to the formation of GP zones, which is a characteristic of Al–Cu–Mg alloys. The peak (A) is not visible, as the GP zones had already formed during the aging treatments. The endothermic peak (B) corresponds to the dissolution of the