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Numerical simulation of large spot laser + MIG arc brazing–fusion welding of Al alloy to galvanized steel

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ABSTRACT

A finite element model was developed to investigate the thermal process of large spot laser + MIG arc brazing–fusion welding. The laser was treated as a Gaussian plane heat source, the MIG arc was performed as a modified double ellipse Gaussian plane heat source, in which the arc distortion was taken into consideration and the overheated droplet was treated as a uniform body heat source. The calculated weld bead geometry and heat-affected width of zinc coating had good agreement with experimental results. The temperature field, especially for the brazed interface, showed non-uniform and asymmetric distribution. The thermal cycles at brazed interface had obvious bimodal characteristic at arc center and laser spot center and the high-temperature zone at the brazed interface was widened duo to the introduction of laser beam compared with conventional MIG brazing–fusion welding. A fundamental processing window was determined based on the founded model to satisfy a certain energy condition, in which the Al alloy was fully penetrated and steel plate was not melted.

1. Introduction

The aim of lightning in automobile industry raises requirement of Al alloy to steel joining, which can achieve higher fuel efficiency and corresponding lower exhaust emission. A brazing–fusion welding process has been proposed to achieve high-quality Al to steel joining, in which appropriate heat input is used to melt Al alloy but to maintain the steel in solid state. The molten Al alloy and filler metal spread on top surface of steel plate to form the brazed joint, which combines the characteristics of brazing and fusion welding.

The brazing–fusion welding process of Al alloy to steel can be realized by various methods. Jácome et al. (2009) achieved high-strength brazing–fusion butt joint of Al to steel through cold metal transfer (CMT) welding. Dong et al. (2012) conducted the brazing–fusion welding of Al to galvanized steel by tungsten inert gas (TIG) welding and further studied the influence of different filler wires. Laser brazing–fusion welding was used for lap joining of Al to galvanized steel by Dharmendra et al. (2011). Gao et al. (2014) used laser + MIG hybrid welding to join Al to stainless steel and obtained joint with strength exceeding 130 MPa.

In conventional laser + MIG hybrid welding, the laser beam with high energy density was used as main heat source to form deep penetration. However, this process underestimated other positive effects of laser such as arc stabilization and weld appearance improvement which may be more important for brazing–fusion welding and it had much higher energy cost duo to the low power efficiency of laser beam. Recently, Qin et al. (2014) proposed a novel large spot laser + MIG arc brazing–fusion welding process. The leading laser performed in the defocusing state aiming at stabilizing arc and preheating steel, while the trailing MIG arc was used as the main heat source. This technique can improve process stability, weld appearance quality and welding efficiency compared with MIG welding and had much lower energy cost compared with conventional laser + MIG hybrid welding.

In large spot laser + MIG arc brazing–fusion welding, the thermal process was changed duo to the introduction of laser beam, which had significant effects on the macrostructural and microstructural characteristics of welded joint. Especially, the microstructure and distribution of IMCs were influenced by the thermal cycles at the brazed interface, which determined the resultant mechanical properties. Numerical simulation method can investigate the large spot laser + MIG arc brazing–fusion welding thermal process quantificationally, which make deep understanding of this welding process, predict the welding energy condition and control weld quality.

Previous numerical simulation of Al to steel joining mainly focused on the laser brazing. Park and Na (1998) developed a 2D finite element model for the thermal analysis of stud-to-plate laser brazing process of AISI 304 stainless steel and AI 5052 aluminum using commercial software ABAQUS and temperature fields in the braze joint were obtained. Mathieu et al. (2006) also used numerical

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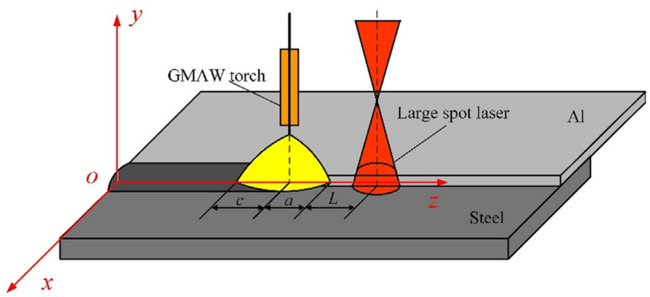

Fig. 1. Schematic of laser + MIG arc welding experimental system.

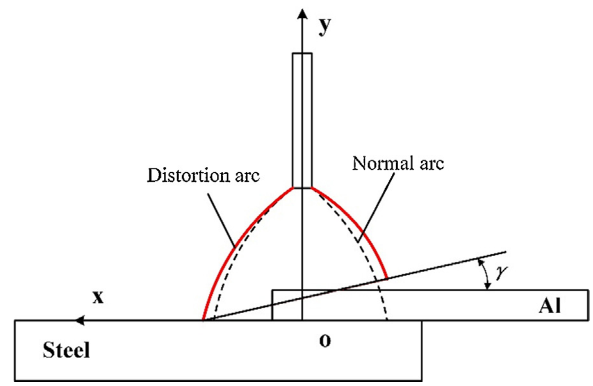

Fig. 2. Schematic of arc distortion.

simulation method to investigate the laser brazing thermal process of 6016 Al alloy to low carbon steel and compared with surface temperature measured by thermography. They founded that the thermal process had significant influence on the formation of IMCs layer. Peyre et al. (2007) studied the temperature history of laser brazing–fusion welding of 6016 Al alloy to low carbon steel through finite element method and the element diffusion in the joint was calculated to predict the intermetallic thicknesses based on the temperature data, which had good agreement with experimental results. However, the simulation work about laser-arc hybrid brazing–fusion welding process of Al to steel is lacked.

In this paper, sound 5A02 Al alloy to galvanized steel brazing–fusion weld was obtained by large spot laser + MIG arc brazing–fusion welding. A finite element model was developed to investigate the thermal process and temperature distribution on the brazed interface using commercial software ANSYS. The combination of welding current, laser power and welding speed was also analyzed, which provided foundation for parameter optimization to fulfill the energy condition in large spot laser + MIG arc brazing–fusion welding of Al to steel.

2. Experimental procedure

The 5A02-T4 Al alloy plate with dimension of 200 mm × 50 mm × 1 mm and SGCC galvanized steel plate with dimension of 200 mm × 50 mm × 2 mm were used in experiments. Al based ER4043 filler wire with 1.2 mm in diameter was used as filler metal. Their nominal chemical compositions are shown in Table 1. A digital MIG welding power source (Fronius TPS 5000) with matched wire feeding system operating in the one-droplet-one-pulse mode and a lamp-pumped Nd:YAG solid laser oscillator (Haas HL 2006D) were used to establish the experimental system.

Lap welding was conducted by placing Al plate over steel plate with an overlap length of 10 mm. The laser spot was aligned with the edge of Al base metal and the filler wire had 1 mm offset to Al plate, as shown in Fig. 1. The laser spot and arc positions were determined by preliminary experiments to obtain sound weld appearance. The shielding gas was pure argon gas with 16 L/min flux.

3. Formulation

3.1. Heat source model

The laser spot was in defocusing state and the laser power was generally less than 1000 W. Hence, the laser performed in heat conduction welding mode without keyhole phenomenon and obvious weld pool surface deformation. The laser heat input was treated as Gaussian plane heat source. Considering different laser absorptivity for Al and steel base metal, the laser heat source was written as:

$$q_l(x,z)=\frac{3\alpha_1 P}{\pi R_1^2}\exp\left(-3\frac{x^2+z^2}{R_1^2}\right)\quad (x\le 0) \tag{1}$$

$$q_l(x,z)=\frac{3\alpha_2 P}{\pi R_2^2}\exp\left(-3\frac{x^2+z^2}{R_2^2}\right)\quad (x\ge 0) \tag{2}$$

The laser radiuses at Al and steel plate were calculated as $R=0.0116(\Delta y)^2+R_0$. All the nomenclatures used in simulation are shown in Table 2.

The zinc coating was evaporated by the laser beam and MIG arc, which decreased the thermal efficiency. In this study, it was assumed that the zinc coating with width w was completely evaporated by only MIG arc and the power loss caused by zinc evaporation was calculated as:

$$Q_{Zn}=\rho_{Zn} w d_{Zn} v L_{Zn} \tag{3}$$

Hence, the arc power absorbed by the workpiece which was also named effective MIG arc power was expressed as:

$$Q=\eta UI-\rho_{Zn} w d_{Zn} v L_{Zn} \tag{4}$$

The total effective MIG welding energy was divided into two heat sources in modeling. Part of effective arc power was treated as a double-elliptic planar heat source. The droplet heat combining with the rest part of effective arc power was treated as a time-averaged uniform body heat source.

In large spot laser + MIG arc brazing–fusion welding, however, the molten Al had better wettability on the top surface of solid steel plate compared with MIG brazing–fusion welding duo to the preheating of laser beam, which made the MIG arc distort to the steel plate. In addition, the introduction effect of laser beam to arc also enhanced this distortion. Hence, the double-elliptic heat source should be modified.

It was assumed that the arc was distorted to form an angle γ to the welding plane, as shown in Fig. 2. In this study, the distortion angle was calculated as $\gamma=\arctan(h/w)$. The heat flux in the front half-ellipse was written as:

$$q_a(x,z)=q_{mf}\exp(-Ax^2-Bz^2)\quad (z-vt\ge 0) \tag{5}$$

The total heat input in the front section was determined as:

$$Q_f=2\int_0^{\infty}\int_0^{\infty} q_{mf}\exp(-Ax^2-Bz^2)dxdz \tag{6}$$

Then the maximum heat flux in the front half-ellipse was obtained:

$$q_{mf}=Q_f\frac{2\sqrt{AB}}{\pi} \tag{7}$$