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Modelling of fluid flow phenomenon in laser+GMAW hybrid welding of aluminum alloy considering three phase coupling and arc plasma shear stress

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ABSTRACT

The present study aims to develop a unified three dimensional numerical model for fiber laser+GMAW hybrid welding, which is used to study the fluid flow phenomena in hybrid welding of aluminum alloy and the influence of laser power on weld pool dynamic behavior. This model takes into account the coupling of gas, liquid and metal phases. Laser heat input is described using a cone heat source model with changing peak power density, its height being determined based on the keyhole size. Arc heat input is modeled as a double ellipsoid heat source. The arc plasma flow and droplet transfer are simulated through the two simplified models. The temperature and velocity fields for different laser powers are calculated. The computed results are in general agreement with the experimental data. Both the peak and average values of fluid flow velocity during hybrid welding are much higher than those of GMAW. At a low level of laser power, both the arc force and droplet impingement force play a relatively large role on fluid flow in the hybrid welding. Keyhole depth always oscillates within a range. With an increase in laser power, the weld pool behavior becomes more complex. An anti-clockwise vortex is generated and the stability of keyhole depth is improved. Besides, the effects of laser power on different driving forces of fluid flow in weld pool are also discussed.

1. Introduction

Aluminum alloy welded structure has been widely used in the industries for the sake of the environmental protection [1]. However, due to its special thermo-physical properties, welding defects, such as pore, hot crack and so on, are still easily generated by laser welding [2] or traditional arc welding [1,3], thus leading to a poor stability of welding quality. As a new type of welding technology, laser+GMAW hybrid welding combines the advantages of each process and overcomes their limitations by coupling laser welding and GMAW, which has been reported to have the potentials of large weld penetration depth, high welding speed, good gap-bridging ability and improved weld quality with reduced susceptibility to welding defect [4–6]. Therefore, laser+GMAW hybrid welding is receiving a growing attention in welding of aluminum alloy. However, hybrid welding involves a large number of process parameters and very complicated physical process and is difficult to be optimized [7]. During welding, transport phenomena concerning thermal field and fluid flow is closely related to the welding defect, which has a crucial effect on weld formation. To improve the reliability of hybrid welding quality, it needs a better understanding of transport phenomenon in hybrid welding.

Currently, extensive efforts have been made to investigate the weld formation mechanism of laser+MIG/MAG hybrid welding. But they still heavily depend on experimental observations and mainly focused on the hybrid welding of steel [8–20]. Ascari et al. [19] experimentally studied the influence of different process parameters on porosity formation in laser-GMA welding of AA6092 aluminum alloy and found that the current had significant effect on pore percentage and size. Katayama et al. [6] observed the basic fluid flow pattern in hybrid welding of aluminum alloy through tracking W particle using a real-time X-ray imaging system. According to their results, the liquid metal at the weld pool surface flowed backward with high velocity and was redirected forwards at the rear part of weld pool, which then encountered the intense flow of backward flow along the keyhole bottom, leading to a more complex flow pattern than that in single laser welding. Through the similar method, Le Guen et al. [20] analyzed the flow mode and motion velocity of liquid metal at the surface of hybrid weld

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pool of steel and also discovered that there was a strong backward surface flow near the symmetric axis at the front part of the weld pool, which was deflected towards the edge of molten pool at the rear part, producing a vortex-like structure. Meanwhile, their observation results confirmed that the flow velocity of molten metal in hybrid welding was higher than that in GMAW but this difference gradually decreased with increasing wire feeding rate (or welding current). Although these experimental results can improved the qualitative understanding of hybrid welding process, they cannot show the physical mechanisms responsible for fluid flow phenomena in hybrid welding.

To deeply understand the physical process of laser+GMAW hybrid welding, some modeling studies were also performed, concerning thermal field [7,21,22], stress [23,24] as well as fluid flow [25–29]. However, due to the complexity of molten pool hydrodynamics in hybrid welding, there is still lack of available study results involving this aspect, especially for aluminum alloy. Zhou and Tsai [26] proposed a numerical model to calculate the transport phenomena in CO_2 laser+MIG hybrid welding for S345 stainless steel. This model considered the Fresnel absorption and Inverse Bremsstrahlung (IB) absorption of laser intensity as well as the main pressures acting on the liquid metal pool, including the evaporation-induced recoil pressure, surface tension, arc pressure and so on. The volume of fluid (VOF) method was used to track weld pool free surface. However, their study primarily focused on the distribution of filler metal and weld pool behavior in the case that the filler droplet could fall into the laser-induced keyhole, which seldom occurs in the realistic welding condition due to small size of keyhole and the effect of metal vapor ejected out of the keyhole. Besides, this model was only limited to two dimensional and no comparison with experimental results was done. Cho, et al. [27] developed a three dimensional model to analyze the fluid flow in laser+GMAW hybrid welding of steel. For their model, real-time ray tracing technology was utilized to take into account the influence of Fresnel absorption and multiple reflections of laser in the keyhole and could calculate the temperature field, fluid flow and dynamic keyhole. According to the analysis of Cho, et al. [7], the liquid metal flowed toward the front part of weld pool along the weld pool surface, leading to a relatively stable clockwise vortex in the middle part of weld pool, which is not consistent with the observations of Katanawa et al. [6]. Moreover, this model is extremely time-consuming, thus limiting its application. Zhang et al. [28] also calculated the velocity field in hybrid welding of steel, but their model depicted the keyhole using a simplified preset model, which cannot reflect the feature of keyhole dynamic behavior as well as its influence on molten metal flow. Cho et al. [29] numerically studied the fluid flow pattern in laser+GMAW hybrid welding of steel through a three dimensional model based on Flow-3D. However, in their research, no keyhole occurred. Therefore, their model only benefits the case of shallow penetration depth. In addition, for arc welding, some earlier researches [30,31] have concluded that, besides the arc pressure, the shear stress by arc plasma flow can also affect the motion of liquid metal near weld pool surface and the resulting whole fluid flow pattern within weld pool, but the current models for hybrid welding do not take into account this effect, which is responsible for their limitations to some degree.

According to the above review, it is found that, due to limitation of the existing models, the exact physical mechanism of fluid flow in laser+GMAW hybrid welding is not clear and there even exist debates in the some important simulated results. Thus, the objective of this study is to propose a unified three dimensional transient numerical model to investigate the fluid flow phenomenon in fiber laser+GMAW hybrid welding of 6061 aluminum alloy with considering the three phase coupling of gas, liquid and solid as well as arc plasma shear stress. This model can simulate the hybrid welding process more reasonably and has high computational efficiency, which can be used to analyze the temperature field, fluid flow, weld formation and the influence of different welding parameters on them, benefiting the selection of welding parameters and the increased stability of hybrid welding quality. Although this model is established for bead on plate welding, it can also be applied to the complex joint through minor modification. Meanwhile, in this paper, using developed model, the temperature profiles and fluid flows in hybrid welding of aluminum alloy under different welding conditions are calculated, which are also compared with those of GMAW. According to the simulated results, the mechanisms of fluid flow phenomenon in hybrid welding of aluminum alloy are studied, which contributes to the improved understanding of weld formation mechanism in hybrid welding of aluminum alloy and the process optimization.

2. Experimental

Fiber laser+GMAW hybrid bead-on-plate welding were performed on 6061 aluminum alloy plate with a thickness of 6 mm under different welding conditions. Filler material is 5356 aluminum alloy wire with a diameter of 1.2 mm. Copper backing plate is used underneath the workpiece. During hybrid welding, a fiber laser beam with a maximum power of 6.0 kW is applied, which has 1.07 μm wavelength, 0.3 mm focal spot diameter and 300 mm focal length. As show in Fig. 1, laser is in front of the arc and is perpendicular to the workpeice top surface. Focal position in welding is set at -1 mm. The axis of the GMAW torch is tilted 27° with respect to laser beam centerline. The standoff distance between laser and arc is 2 mm on the top surface of workpiece. Shielding gas is 100%Ar with a flowing rate of 3.33×10^{-4} $m^3 \cdot s^{-1}$. Welding speed is kept at a constant of $0.02\ m \cdot s^{-1}$. Other parameters are listed in Table 1.

3. Modelling

3.1. Governing equations

In calculation, both the molten metal and gas are assumed be incompressible, Newtonian and laminar flow. Moreover, gas, liquid

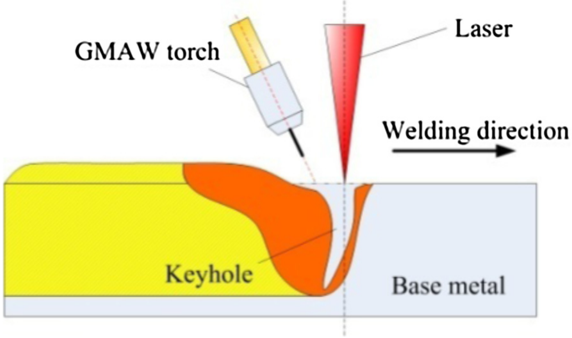

Fig. 1. Schematic of laser+GMAW hybrid welding.

Table 1
Process parameters in laser+MIG hybrid welding.

Case No.	Welding current [A]	Arc voltage [V]	Laser power [kW]
1	120	18	0
2	120	18	2.0
3	120	18	3.5
4	120	18	5.0