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Melt flow and thermal transfer during magnetically supported laser beam welding of thick aluminum alloy plates

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ABSTRACT

A multi-field coupled numerical model was proposed to calculate the weld pool dynamics during the full-penetration laser beam welding of 12 mm thick aluminum alloy plates under the function of a longitudinal magnetic field. The model dealt with the melt flow, heat transfer, solid-liquid transition and magnetic diffusion phenomena in welding process. The Lorentz force directing from the keyhole to the liquid-solid interface was induced in magnetic field supported cases. The Marangoni convection near the weld pool surfaces was obviously weakened due to the electromagnetic braking effect, which was featured with decreased velocity and compressed vortex. The heat transfer condition was largely changed, resulting in declined weld pool dimensions. When the magnetic flux density applied was larger than 0.5 T, the convective heat exchange at the middle height of weld pool became notable again due to the reversed melt flow direction. The liquid-solid lines with lower curvature were achieved. The reinforcement of Hartmann effect became limited. The model and the simulated weld pool morphologies were verified in experiment.

1. Introduction

Laser beam welding (LBW) for aluminum (Al) alloy plates used to be unattainable due to the high reflectivity of metal, Fresnel absorption and limited energy input, even though the power density of laser had far exceeded most of conventional welding heat sources. The invention of high power laser (initially, the CO_2/YAG laser, and recently, the fiber/disc coupling laser with an output up to 10 kW level) and the improvement on beam quality made it possible to overcome the problems. Not only the thin sheets, but also the thick parts could be fully penetrated and jointed by single-pass treatment of the laser beam. Researchers have become interested in the possibility of using the high-power laser to weld the heavy-walled Al structures and tried to identified the superior performances of which in welding efficiency, flexibility and quality. The resulting low welding distortion, refined grain size and relative high mechanical strength made LBW a quite promising technology in the construction of Al-structure automobile, high-speed train, vessel and aerospace shuttle.

However, there were still a lot of difficulties for laser welding thick Al parts in practice. The unstable surface formation (humping pattern, undercut and spatter) and large bead width occurred during the welding, resulting in decline of joint mechanical properties. The main influencing factors were high heat conductivity, low viscosity of molten Al and large temperature gradient between the keyhole edge and the melting-solidification front (around 10^5 K/m), which could cause the intensive thermocapillary (Marangoni) convection in the weld pool. Wang et al. (2007) numerically showed that the dynamic pressure gradient near the weld pool surface mainly drove the molten metal flow during the deep-penetration laser welding. Pang et al. (2015) revealed the weld pool dynamics during laser welding by considering the surface tension gradient (Marangoni shear stress) in his 3D transient keyhole model. As observed by Katayama et al. (2009) and Nakamura et al. (2015), the peak velocity of the melt flow usually occurred at weld pool surface, giving rise to melt ejection, spatter and humping bead phenomena during the welding process. Furthermore, Ye and Chen (2002) reported that the violent Marangoni convection caused the goblet-shape in transverse section (TS) and thereby the prominent residual stress concentration.

To control the laser induced flow pattern in weld pool, several approaches have been put forward including optimizing the processing parameters and adjusting the welding heat source. Kim and Park (2011) optimized the welding conditions for wire filling laser welding of AA5183 by considering the control factors of laser power, welding speed and wire feed rate, respectively. Zhang et al. (2014) examined the

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influence of laser focal position, welding speed and type of shielding gas on seam formation during deep penetration laser welding of 12 mm thick SS304 plates. Chen et al (2016a) found that compared with the single-beam mode, laser welding in the dual-beam mode resulted in better weldappearance and larger effective joining width during the dissimilar metal joining of Q235 steel and 5052 Al alloy. Allen et al. (2006) made a comparative investigation on weld penetration and porosity rate of 12.7 mm 7xxx Al alloy by using laser and hybrid laser-MIG welding respectively. These approaches showed some improvement on melt flow and welding quality. However, they suffered from poor flexibility and low cost effectiveness.

The first attempt on molten pool dynamics control during LBW using a typical magnetic field (MF) system could be traced back to ten years ago when Kern et al. (2000) firstly indicated that an externally applied static MF could make a difference on the stationary laminar flow and eliminate the humping bead in LBW of Al alloy at a high velocity. The work was based on the magnetic fluid dynamics theory in which the external MF could act on the flowing fluids provided the materials were electrically conductive. The principle of the action could be divided into two aspects. Firstly, the relative motion between the fluid and external magnetic filed induced electric currents within the weld pool. Secondly, the currents in combination with the disturbed MF produced Lorentz force, which had effect on fluid flow (Hartmann effect).

In the past two decades, the magnetic supported technology has been proved as a potential alternative for controlling the melt flow behavior, thereby improving the weld formation qualities during the LBW of thick Al alloy plates. It displayed distinct advantages including non-contact, high flexibility and high efficiency. Bachmann et al. (2013) numerically and experimentally studied the magnetically supported laser beam welding (MSLBW) at a welding speed of 0.5 m/min and a laser power of 16 kW. The results included suppressed Marangoni, reduced bead upper width and smoother bead surface, indicating there were significant Hartmann effects within the weld pool. Bachmann et al. (2016) also pointed out a positive correlation between the Hartmann effect and the molten pool volume, which further clarified the applicability of MSLBW in thick-plate welding cases. Avilov et al. (2012) successfully introduced an alternating MF at intermediate frequency below the substrates to cope with the melt sagging in laser welding of 20–30 mm AlMg3 alloy. It was then declared by Bachmann et al. (2012) that an upward electromagnetic (EM) pressure can be exerted on the molten pool using a horizontally applied AC field, based on simulation results.

By exerting the induced Lorentz force on melt flow, the MF further influenced the microstructure morphologies and solute elements distribution in solidified beams which largely determined the joints strength. Thomy and Vollertsen (2005) adopted a coaxial low frequency oscillation field to solve the blocked silicon diffusion in laser welding. A more uniform distribution of silicon over the weld beam was achieved in his work, which was beneficial to reducing the hot cracking tendency. Tang and Gatzen (2010) comparatively studied the different stirring effects on elementary dilution by varying flux densities and excitation frequencies. Chen et al. (2017) reported that the static field caused grain enlargement and chemical heterogeneity inside the weld beam of 5A06 alloy due to the modified crystallization condition. Additionally, Yuan et al. (2013) advocated that the electromotive force (EMF) at the solid-liquid (S/L) interface could retard elements diffusion process for dissimilar metals joining or diffusion bonding. Chen et al. (2016b) further revealed the decrease of precipitation thickness of intermetallic compounds using a permanent MF with a flux density around 240 mT.

Due to the complexity of melt flow in laser welding as well as the variety of operating parameters of MF, it was difficult to completely elucidate the resulting weld pool motor behavior and summarize the reasonable magnet-assist solutions to solve the issues in high-power laser welding of Al alloy. A comprehensive numerical assessment on thermodynamics and magnetohydrodynamics (MHD) of the weld pool with MF support could deliver an insight in predicting the bead formation quality effectively and benefit procedure screening. Further research was needed to explore the heat transfer condition within the MF controlled weld pool since it closely related to the weld bead geometry. Furthermore, it helped to further illustrate the Hartmann effect and its functionary mechanism.

This paper targeted developing a magnetically supported laser welding system, in both simulation and experimental levels, to reveal the molten metal flow and heat transfer mechanisms during the full-penetration welding of thick Al parts in butt configuration. The MF used was steady and was aligned in longitudinal direction, vertical to workpiece surface. The thermal transfer, melt convection and magnetic diffusion phenomena in the weld pool were numerically solved using a multi-physical coupled computational fluid dynamics (CFD) model. A simplified keyhole model was adopted to improve the computing efficiency for the workpiece at large thickness. The temperature field, melt flow velocity distribution as well as the MHD information including the induced current, Lorentz force and Hartmann number within the weld pool was predicted and comparatively analyzed based on varying magnetic flux densities. In addition, the experiments on MSLBW of Al alloy were conducted to examine the reproducibility of the simulation results.

2. Mathematical modeling

2.1. Basic assumptions

Due to the complexity of the thermal dynamic phenomena inside the keyhole and molten pool during laser welding, using a complete and absolutely accurate model for MSLBW simulation (e.g., considering the beam multiple reflections and absorptions and plasma eruption) was nearly impossible and inefficient, especially for thick plates. As discussed by Gatzen and Tang (2010), the liquid-solid (L/S) transformation, molten metal convection and thermo-physical properties of material should take precedence over the other physical aspects in terms of a thermal-fluid dominated weld pool. Therefore, several basic assumptions were made and listed as follows.

- Only the melting and solidification process of the weld pool were considered. The influence of vapor phase on melt flow was neglected.
- The liquid phase inside the weld pool was incompressible. A Newtonian, laminar flow pattern was adopted to deal with the melt convection.
- The keyhole was assumed in steady state, based on the assumption that the recoil pressure on the keyhole wall was ideally balanced by the surface tension. The temporal oscillation of the keyhole and the sagging of weld bath were neglected.
- The molten pool flow was mainly driven by Marangoni shear stress and heat buoyancy.
- The thermal electric currents (TECs) due to the Seeback effect occurring at the S/L interface of weld pool was out of consideration.

2.2. Governing equations

To simulate the molten metal flow within the weld pool of MSLBW, we needed to solve the conservation equations coupled with the magnetic diffusion equation. They were written or deduced as follows.

- Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{u}) = 0 \tag{1}$$

where ρ was the mass density and $\mathbf{u}$ = (u, v, w) was the velocity field of the melt flow. For incompressible fluid, the rate of mass density change