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Numerical study of heat transfer and solute distribution in hybrid laser-MIG welding

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ABSTRACT

In the quest for the transport mechanism in the molten pool during hybrid laser-MIG welding of aluminum alloy, an improved three-dimensional numerical model is developed. A modified model for laser heat source is utilized to investigate the energy absorption mechanism in keyhole. Some driving forces are considered to simulate the fluid flow, such as electromagnetic force, surface tension and buoyancy. The effects of arc pressure and droplet impact are taken into account to track the free surface. Several dimensionless numbers are utilized to analyze the relative importance of driving forces. The temperature field, liquid velocity field and magnesium and zinc distribution are numerically and experimentally studied. Results shows that the laser beam create a great impression on the heat transfer, fluid flow, solute distribution and weld bead geometry. In MIG welding, there is an insufficient mixing zone at the front of the pool, while the solute distribution in hybrid laser-MIG welding is observed more uniform. Magnesium and zinc are found concentrated in lower and upper part of the molten pool, respectively. The mathematical model is well validated by the experimental observations, and the calculated element distribution agrees well with the experimental measurements. Furthermore, the improved model provides an effective method for parametric optimization to improve the properties of hybrid laser-MIG welding joints.

1. Introduction

The hybrid laser-MIG (metal inert gas) welding, which combined the laser beam welding and gas metal arc welding, was widely used in manufacturing industry [1,2]. The hybrid welding enhanced the advantages of individual process, and resulted in stronger robustness for industrial application with characteristics of high speed, deep penetration, less deformation and ability to bridge larger gap [3]. The hybrid laser-MIG welding is a complex physical process, including keyhole, additional metal, thermal behavior, fluid flow, mass transfer, solute redistribution, vapor and spatter *etc* [4–6]. To understand underlying mechanism and obtain expected mechanical properties, the choice of appropriate welding parameters were essential [7]. It was well known that temperature and composition had determining effect on final microstructure and weldment performance [8–10]. Therefore, investigation of heat and mass transfer mechanism was very helpful to optimize processing parameters and achieve desired weld seam quality.

In recent years, several numerical simulations for laser-arc welding were developed. Zhou et al. [11] studied the transport phenomena for hybrid laser-MIG keyhole welding through a developed two-dimensional computation model. In the model, to handle solid phase, liquid phase and mushy zone, the continuum formulation was used during the processes of melting and solidification. They considered the influence of energy transportation, fluid flow, and interaction between weld pool and droplets in their calculation. A computational model to investigate the dynamic development process of the weld pool for stationary hybrid laser-MIG welding was established by Gao et al. [12]. They calculated the shape of weld pool and transient velocity distribution of liquid metal, and the calculated weld bead geometry agreed well with experimental measured geometry. Piekarska et al. [6] developed a model to calculate the temperature and liquid velocity field of the melt pool. In their model, different heat source modules for laser and arc, buoyancy and liquid flow were considered, and the results were verified by experiments. Bendaoud et al. [13] simulated UR2507Cu duplex steel with high thickness and Y-shaped chamfer geometry. In their model, a numerical exploratory method was used to determine the parameters for heat source in order to minimize the difference between

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Nomenclature

t	Time
x_i	Distance along i directions
u_j	Liquid velocity along j direction
P	Pressure
V	Scanning speed
f_l	Liquid fraction
C_p	Specific heat
ΔH	Latent heat content
F	Volume force
F_{Lx}	Electromagnetic force along x direction
F_{Ly}	Electromagnetic force along y direction
F_{Lz}	Electromagnetic force along z direction
h	Sensible heat enthalpy
k	Thermal conductivity
C	Concentration
C_l	Concentration in liquid phase
C_s	Concentration in solid phase
C_{ref}	Reference Concentration
D	Diffusion coefficient of element
Q_{laser}	Body heat source of laser
Q_{arc}	Body heat source of arc
Q_d	Sensible heat from droplets
q_{laser}	Surface heat source of laser
r	Radius
H	Thickness of workpiece
L	Characteristic length
g	Acceleration due to gravity
I	Welding current
h_c	Heat transfer coefficient
t_{bx}	Tangential unit vector parallel to the x-z plane
t_{by}	Tangential unit vector parallel to the y-z plane
n_b	Outward normal vector
f	Frequency of droplet transfer
ρ_w	Density of welding wire
C_w	Specific heat capacity of welding wire
d_w	Wire diameter
U_w	Wire feed speed
T	Temperature
T_w	Droplet temperature
T_l	Liquidus temperature
T_{ref}	Reference temperature
T_a	Ambient temperature

Greek symbols

ρ	Density
μ	Viscosity
μ_m	magnetic permeability
β	Coefficient of volume expansion
γ	Surface tension
$\frac{d\gamma}{dT}$	Temperature coefficient of surface tension
σ	Stefan-boltzmann constant
σ_j	Radius of the arc pressure
ε	Surface emissivity

the experimental and numerical results. A finite element model was developed by Meng et al. [14] in order to understand the thermal behavior of large spot laser-MIG welding. In their calculation, the laser, the MIG torch and the droplet were treated as Gaussian plane, modified double ellipse, and uniform body heat source, separately. The temperature distribution, especially the brazing interface, and weld bead geometry were all numerically studied.

Although some progress was made on fluid flow and heat transfer of the melt pool, few researchers tried to address mass transfer for hybrid laser-MIG welding. Won-Ik Cho et al. [15]established a numerical model to simulate the alloying element distribution in CO_2 laser-GMA hybrid welding. They found that the alloying element distributions might be affected by fluid flow. Despite the mass transfer in molten pool greatly affected the mechanical properties of the weld [5,10,16–18], the existing work on mass transfer and alloying element distribution was far from enough. The heat transfer and solute distribution in molten pool for hybrid laser-MIG welding was not fully understood. It was extremely essential to develop and improve the related numerical model to explore the heat and mass transfer mechanism systematically.

In this work, a 3D numerical model was established to analyze the thermal behavior and solute distribution in hybrid laser-MIG welding of aluminum alloy. A combined heat source for laser was adopted in this work, and the MIG torch was utilized as a surface heat source with distribution of Gaussian. The couple effect of laser beam and MIG torch was considered in the model. The driving forces, including electromagnetic force, surface tension and buoyancy, were taken into consideration. In addition, the droplet impact and arc pressure were taken into account to track the free surface. The redistribution of magnesium and zinc element in the molten pool was analyzed and compared. A detailed insight into the thermal behavior, fluid flow and solute distribution was provided in the work. Furthermore, the simulated geometry of weld pool and composition profile were compared with those from experimental results.

2. Experimental procedure

The A7N01 aluminum alloy and ER5356 of 1.2 mm in diameter were selected as base metal and welding wire respectively, and the composition of materials were presented in Table 1. A Nd:YAG laser combined with a MIG torch were utilized to implement hybrid laser-MIG welding. A 1 kW Nd:YAG laser manufacturing system with 1070 nm wavelength was used as laser power source, and a pulsed MIG weld machine, with the maximum current of 350 A, was used as the source of arc power. The preparation of metallographic specimen was in the order of electric discharge cutting, mechanical milling and grinding, and then standard mechanical polishing. The dimension of samples was 60 mm × 10 mm × 6 mm. To investigate the element distribution, the weld seam was observed by scanning electron microscopy (JSM-5800), equipped with energy dispersive spectrometer (LinkISIS S-530).

3. Mathematical model

In the work, a 3D model was developed to analyze the heat transfer and solute distribution in hybrid laser-MIG welding. Fig. 1 shows the

Table 1
Material compositions of A7N01 aluminum and ER5356 welding wire [8].

Materials	Mg	Zn	Fe	Mn	Si	Cr	Ti	Cu	Al
A7N01	1.0–2.0	4.0–5.0	0.35	0.2–0.7	<0.30	<0.30	<0.20	<0.20	Bal.
ER5356	4.5–5.5	<0.1	<0.4	0.05–0.2	<0.25	0.05–0.2	0.06–0.2	<0.10	Bal.