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Abstract

Considering the effects of droplets and keyhole on the weld pool, a three-dimensional transient numerical analysis model for fluid flow in the weld pool during laser + gas metal arc welding (GMAW) hybrid heat source welding was established based on FLUENT software. The arc heat input was described using a double ellipsoid heat source, while the laser heat input was treated as a hyperbolic rotating body heat source with adjustable peak heat flux, whose heat source distribution parameters were determined through a simplified keyhole shape and size model. The droplet transfer process was modeled as the inflow of high-temperature liquid metal into the weld pool from a specific region at the top of the pool, and the droplet transfer frequency was characterized by establishing a periodic function of liquid metal flow velocity with respect to time. The keyhole was regarded as a deformation of the weld pool surface caused by laser-induced vapor recoil force to simplify the computational process, focusing on the primary influence of keyhole existence on the weld pool fluid flow pattern. The established model was used to simulate and calculate the keyhole morphology, weld pool fluid flow, and temperature field in laser + GMAW hybrid welding under different welding conditions, analyze the flow field characteristics of hybrid welding, and investigate the influence law of laser power on the dynamic behavior of the hybrid welding weld pool. The results show that under a welding speed of 1 m/min, humping defects occurred in GMAW welding (laser power of 0 W); when the laser power was 500 W, the humping defects disappeared, but no keyhole was generated in the weld pool, and the fluid flow pattern was similar to that of GMAW welding; however, when the laser power increased to 2000 W, a keyhole appeared in the weld pool, making the fluid flow pattern more complex. The calculated weld cross-section shape and dimensions were compared with experimental results, and the two showed good agreement, thereby demonstrating the accuracy and applicability of the model.

Full Text

Numerical Analysis of Fluid Flow in Laser+GMAW Hybrid Welding

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Abstract

Laser + gas metal arc welding (GMAW) hybrid welding combines the advantages of both laser welding and GMAW, enabling high-quality, high-efficiency, and relatively low-cost welding of thin and thick plates, thus holding great promise for industrial manufacturing applications. However, compared with single heat source welding, hybrid welding involves more process parameters and more complex physical processes, making process optimization difficult. When parameters are mismatched, welding defects can still occur in high-speed welding, affecting the reliability of hybrid welding. Therefore, in-depth study of the physical mechanisms in hybrid welding is necessary to suppress defects and improve process stability. Fluid flow in the weld pool critically influences weld formation in hybrid welding, and modeling this flow helps to fully understand the process mechanisms. To date, however, few studies have examined the velocity field in hybrid welding due to its complexity.

In this work, considering the effects of droplets and the keyhole on the weld pool, a three-dimensional transient model was developed to numerically analyze fluid flow in the weld pool during laser+GMAW hybrid welding using FLUENT software. Arc heat input was modeled using a double-ellipsoid heat source, while laser heat input was treated as a hyperbolic curve-rotated heat source with adjustable peak power density, with its distribution parameters determined based on a simplified model for keyhole geometry and size. Droplet transfer was described as the process of high-temperature liquid metal flowing into the weld pool from a specific domain above it. Using the developed model, keyhole behavior, fluid flow, and temperature distribution in laser+GMAW hybrid welding under different welding conditions were calculated. The characteristics of the velocity field in hybrid welding were analyzed, and the effect of laser power on weld pool dynamic behavior was discussed.

The results show that at a welding speed of 1 m/min, weld bead humping occurs in GMAW alone (laser power 0 W). When laser power is increased to 500 W, the humping defect disappears, but no keyhole forms in the hybrid weld pool and the fluid flow pattern remains similar to that in GMAW. When laser power is further increased to 2000 W, a keyhole forms, making the fluid flow in the weld pool more complex. The predicted weld geometries and dimensions for various laser powers show good agreement with experimental measurements, thereby demonstrating the accuracy and applicability of the established model.

Keywords: hybrid welding, weld pool, fluid flow, keyhole, numerical simulation

Laser+GMAW hybrid welding integrates the dual advantages of laser welding and GMAW, enabling high-speed, high-quality, and relatively low-cost welding of both thin and thick plates, with tremendous application prospects in industrial manufacturing. However, compared with single heat source welding processes, hybrid welding involves numerous process parameters that are difficult to optimize. Improper parameter matching can still lead to welding defects in high-speed welding, resulting in relatively poor process reliability and hindering further widespread application. Weld pool fluid flow patterns are closely related to defects such as humping, undercutting, and porosity, and have a critical influence on weld formation. Therefore, numerical analysis of fluid flow in laser+GMAW hybrid welding is essential for comprehensively understanding defect formation mechanisms and optimizing process parameters to improve welding reliability, holding significant academic and engineering value.

In hybrid welding, strong coupling exists among the laser-induced keyhole, droplets, and weld pool, making the fluid flow patterns more complex than in single heat source welding. Consequently, previous numerical simulation studies on laser+GMAW hybrid welding mechanisms have primarily focused on thermal fields and stress fields, with very limited research on weld pool fluid flow. Moreover, existing fluid flow studies have concentrated on specific physical phenomena under single welding conditions. Cho and Farson modeled fluid flow and weld formation in laser+GMAW hybrid welding using a double-ellipsoid heat source and FLOW-3D software, but their study was only applicable to hybrid welding without keyhole formation. Cho et al. developed a three-dimensional numerical model for laser+GMAW hybrid welding by combining a Gaussian planar heat source with a keyhole heat source to analyze fluid flow patterns under a single condition, but this model did not consider laser-arc interaction and lacked experimental validation. Zhou and Tsai analyzed droplet diffusion into the keyhole during stationary hybrid welding using a two-dimensional numerical model, while Wang Renping similarly simulated droplet transfer, arc, and weld pool using a 2D model. However, neither study addressed weld formation, and their models were unsuitable for moving heat source welding or three-dimensional fluid flow analysis, limiting their broader application. Gao Zhiguo numerically calculated fluid flow in aluminum alloy hybrid welding, but the short calculation time (less than 0.2 s) prevented comprehensive characterization of hybrid welding fluid flow features and their effects on weld formation.

This work establishes an applicable three-dimensional transient numerical model for weld pool fluid flow in laser+GMAW hybrid welding based on FLUENT software. The model simulates fluid flow patterns, analyzes their characteristics, and investigates the influence of laser power on fluid flow and weld formation, thereby providing technical support and theoretical foundation for in-depth understanding of the internal mechanisms and engineering applications of laser+GMAW hybrid welding.

Experimental Setup

The base material was 304 stainless steel plate with a thickness of 6 mm. The filler wire was 304 stainless steel with a diameter of 1.2 mm. [Figure 1: see original paper] shows a schematic of the laser+GMAW hybrid welding process. During hybrid welding, the laser beam was positioned ahead and perpendicular to the workpiece surface, while the arc trailed at a 27° angle to the laser, with a 3 mm distance between them. The welding current was 170 A, arc voltage was 20 V, welding speeds were 1 and 2 m/min, and laser powers were 0 (pure GMAW), 500 W, and 2000 W. The defocus amount was -1 mm, laser focal spot diameter was 0.2 mm, and the shielding gas was Ar+10%CO₂ (by volume).

2.1 Heat Source Models

2.1.1 Arc Heat Input—Double-Ellipsoid Heat Source Model During welding, the weld pool surface (around the keyhole region) deforms under arc pressure and laser-induced vapor recoil pressure. Due to the relatively high welding speed in hybrid welding, a double-ellipsoid heat source model was adopted to describe the arc heat input distribution. In calculations, the heat source center was located on the workpiece surface, with heat flux density distribution function $q_f(x, y, z)$ as follows:

$$q_f(x, y, z) = \frac{6\sqrt{3}f_f\eta_A IU}{a_f b_h c_h \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{a_f^2} - \frac{3y^2}{b_h^2} - \frac{3z^2}{c_h^2}\right)$$

where x, y, z are coordinates; a_f, a_r, b_h, c_h are heat source distribution parameters; f_f and f_r are heat distribution coefficients for the front and rear portions of the heat source; η_A is arc heat efficiency; I is welding current; U is arc voltage; v is welding speed; and t is time.

2.1.2 Laser Heat Input—Keyhole-Based Conical Heat Source Model

To improve computational efficiency and focus on fluid flow analysis, a hyperbolic curve-rotated heat source model with adjustable peak heat flux was employed to describe the laser heat distribution. The heat flux density distribution function $q_L(r, z)$ is expressed as:

$$q_L(r, z) = \frac{3\eta_L P_L}{\pi(r_e^2 + r_e r_i + r_i^2)} \cdot \frac{r_0(z)^2}{[r_0(z)^2 + (c-1)(z-z_i)^2]^2} \cdot \exp\left(-\frac{3r^2}{r_0(z)^2}\right)$$

where r, z are coordinates, $r = \sqrt{x^2 + y^2}$, η_L is laser heat efficiency, P_L is laser power, $r_0(z)$ is the heat source action radius, r_e and r_i are the upper and lower surface radii of the heat source, z_e and z_i are the z -coordinates of the upper and lower surfaces, c is the ratio coefficient of heat flux peaks at the

upper and lower surfaces, and a and b are calculation parameters. The specific formulas for parameters A and B are given in reference [14].

This model comprehensively considers the variation of laser heat input region and peak heat flux along the workpiece thickness direction. The action radius decreases hyperbolically along the thickness, while the peak heat flux density along the central axis also varies hyperbolically. When the ratio coefficient $c > 1$, the heat flux peak increases hyperbolically along the thickness; otherwise, it decreases. During calculation, a numerical analysis model for keyhole shape based on a line heat source was used to determine keyhole dimensions, which then defined the upper/lower surface radii and height of the heat source model. The specific calculation procedure is detailed in reference [15]. The influence of multiple laser reflections inside the keyhole and Fresnel absorption by the keyhole wall on laser energy distribution was indirectly considered by appropriately adjusting the ratio coefficient c of heat flux peaks at the upper and lower surfaces.

2.2 Droplet Transfer Model

To reduce computational cost while accounting for droplet effects on fluid flow, keyhole dynamics, and heat distribution, a simplified droplet transfer model was developed based on FLUENT. In calculations, droplet transfer was treated as liquid metal flowing into the weld pool from a specific region above it at a certain velocity. This region's area equaled the filler wire cross-section, assuming the droplet diameter matched the wire diameter.

As shown in [Figure 2: see original paper], the upper boundary of the computational domain was set as a velocity inlet for liquid filler metal. An initial inflow velocity (along the negative z -direction) was specified in the wire action region (with area equal to the wire cross-section), while velocities elsewhere were zero, indicating no liquid metal inflow in other regions. Similar to the heat source model, the wire action region moved along the welding direction during calculation.

The liquid metal was only subjected to gravity during inflow. The effects of electromagnetic force and plasma flow force on droplet transfer velocity were indirectly considered by appropriately increasing the initial inflow velocity. Additionally, a periodic time function was applied to the inflow velocity to simulate droplet transfer frequency, assuming zero liquid metal velocity for half of each droplet transfer period. The initial liquid metal velocity was set to 1 m/min, higher than that in reference [21]. Droplet transfer frequency was determined based on wire feed speed, and liquid metal temperature was assumed to be 2400 K [21].

2.3 Governing Equations and Boundary Conditions

Fluid flow in laser+GMAW hybrid welding is extremely complex, requiring simplifications. The following assumptions were made: (1) Except for thermal

conductivity, specific heat, and dynamic viscosity, other material properties are temperature-independent; (2) Weld pool fluid is incompressible Newtonian fluid with laminar flow; (3) Pressure inside the keyhole equals atmospheric pressure. Weld pool fluid flows under the action of arc pressure, surface tension, electromagnetic force, gravity, buoyancy, Marangoni force, and laser-induced vapor recoil pressure. The governing equations describing heat transfer and fluid flow in the droplet-weld pool-keyhole system include energy, momentum, and mass conservation equations, with specific expressions given in reference [26]. The enthalpy-porosity method [27] was used to simulate solidification and melting.

The keyhole strongly stirs the weld pool fluid during hybrid welding, making it essential to consider keyhole dynamic behavior in numerical simulations. The keyhole was treated as a deformation of the weld pool surface caused by the combined effects of laser-induced vapor recoil pressure, arc pressure, and surface tension, ignoring the thermal and force fields of plasma inside the keyhole. During calculation, the following stress boundary condition existed on the weld pool free surface:

$$P = P_A + P_R + P_S$$

where P is the pressure acting on the weld pool free surface, P_A is arc pressure, P_R is vapor recoil pressure, and P_S is surface tension.

Arc pressure adopts a double-elliptic distribution pattern [16]:

$$P_A = \frac{\mu_0 I^2}{8\pi^2} \cdot \frac{C}{(a_{j1} + a_{j2})b_j} \cdot \exp\left(-\frac{x^2}{2a_{j1}^2} - \frac{y^2}{2b_j^2}\right)$$

where μ_0 is magnetic permeability, C is a calculation coefficient, and a_{j1} , a_{j2} , b_{j1} , b_{j2} are arc pressure distribution parameters.

Laser-induced vapor recoil pressure is the primary driving force for keyhole formation and can be expressed as [23]:

$$P_R = A_0 \exp\left(-\frac{B_0}{T_w}\right) \sqrt{\frac{m_a}{2\pi k_b T_w}} \cdot \frac{U_0 L_b}{N_a}$$

where A_0 and U_0 are calculation coefficients, B_0 is an evaporation constant, T_w is weld pool surface temperature, m_a is atomic mass, L_b is latent heat of vaporization, N_a is Avogadro's constant, and k_b is Boltzmann's constant.

Surface tension is expressed as:

$$P_S = \gamma \kappa$$

where γ is surface tension coefficient and r is free surface curvature radius, with calculation formulas given in reference [26]. Since arc pressure, vapor recoil pressure, and surface tension are surface forces, they were converted to volume forces and applied as source terms in the momentum equation at the gas-liquid interface [21,24]. Initial conditions and other energy and momentum boundary conditions are given in reference [21], while electromagnetic force, buoyancy, and other forces were treated as in reference [7].

2.4 Weld Pool Free Surface

The VOF method was used to track the weld pool free surface. The governing equation for the fluid volume fraction F is:

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0$$

where u , v , w are fluid velocities in the x , y , z directions.

2.5 Solution Method

The fluid dynamics software FLUENT was used to simulate hybrid welding fluid flow. Due to symmetry, half of the workpiece was taken as the computational domain with dimensions of $50 \text{ mm} \times 20 \text{ mm} \times 9 \text{ mm}$, with 3 mm of air above it ([Figure 2: see original paper]). The geometric model was created using GAMBIT software and meshed. For the air region, all boundaries except the symmetry plane were set as pressure outlets, with the upper boundary as a velocity inlet. For the metal region, all boundaries except the symmetry plane were set as walls. User-defined functions were employed to define boundary conditions (including initial velocity of high-temperature liquid metal entering the weld pool), material properties, and source terms for energy and momentum. To balance computational accuracy and efficiency, variable time steps ranging from 10^{-4} to 10^{-6} s were used, and the PISO (Pressure-Implicit with Splitting of Operators) algorithm was employed to calculate the flow field.

3 Numerical Calculation of Hybrid Welding Fluid Flow

Using the above model, fluid flow in laser+GMAW hybrid welding under different welding conditions was simulated with FLUENT. Material properties and computational parameters are given in references [23,26]. Model distribution parameters were determined using the above methods. For pure GMAW (laser power 0 W, with the torch still at an angle to the workpiece surface), the parameters were: $a_f = 4 \text{ mm}$, $a_r = 6 \text{ mm}$, $b_h = 4 \text{ mm}$, $c_h = 2 \text{ mm}$, $a_{j1} = 3 \text{ mm}$, $a_{j2} = 4 \text{ mm}$, $b_j = 3 \text{ mm}$. Parameters for other process conditions were similarly determined.

[Figure 3: see original paper] shows the calculated fluid flow in the longitudinal section of the GMAW weld pool. Due to the high welding speed, fluid in the

front of the weld pool rapidly flows backward under arc pressure, reaching a maximum velocity of 2.5 m/s, while a large depression forms in the arc-affected region at the front. The liquid metal layer at the front wall of the depression is very thin, with metal flowing at high speed toward the depression bottom. At $t = 0.3$ s, the liquid weld pool volume is small and short. Under arc pressure, liquid metal at the bottom of the depression flows backward, generating a clockwise vortex near the heat source in the middle of the weld pool, while a counterclockwise vortex forms at the rear due to surface tension and hydrostatic pressure ([Figure 3a: see original paper]). As the arc heat source moves, liquid metal gradually accumulates at the rear, forming a thin transition region between the accumulation zone and the front depression. Liquid metal in this region flows rapidly toward the rear, overcoming hydrostatic pressure to create a counterclockwise vortex ([Figure 3b: see original paper]). Since the transition region contains less heat, it solidifies quickly. This region also has poor thermocapillary stability and tends to contract transversely [8], hindering flow from the front to the rear and backflow from the accumulation zone to the front, resulting in new metal accumulation at the front ([Figure 3c: see original paper]). At $t = 2$ s, because the transition region temperature is low, less liquid metal flows from front to rear. Under hydrostatic pressure, liquid metal at the rear flows both backward and forward, while a counterclockwise vortex reappears at the front ([Figure 3d: see original paper]). After the transition region solidifies, a humping defect forms in the weld bead. Since weld pool fluid flow is affected by multiple factors, the flow pattern fluctuates; the patterns shown represent specific moments. [Figure 4: see original paper] compares calculated and experimental results for the GMAW weld bead top surface, showing good agreement and validating model accuracy. It should be noted that the fluid flow pattern shown in [Figure 3: see original paper] is the key factor causing humping defects under the studied conditions, though the relationship between peak flow velocity and humping is not obvious due to influences from welding speed, current, and other parameters. Humping formation is also affected by surface tension stability along the weld direction and material properties [8].

[Figure 5: see original paper] shows calculated temperature and flow fields in the GMAW weld pool cross-section at $x = 21$ mm. At $t = 0.5$ s, the workpiece metal melts under arc heat and deforms under arc pressure, with liquid metal flowing to the pool bottom. At $t = 0.6$ s, the surface depression is filled by liquid metal. On the symmetry axis ($y = 0$), liquid metal flows downward from the pool surface, related to electromagnetic force effects, while fluid slightly away from the axis flows toward the pool boundary under surface tension. As the heat source continues moving, arc pressure and electromagnetic force effects at this location gradually decrease. At $t = 1.2$ s, metal buildup forms, creating a clockwise vortex under surface tension and buoyancy ([Figure 5c: see original paper]). As time progresses, flow velocity decreases, the pool begins to solidify, and weld reinforcement forms ([Figure 5d: see original paper]).

[Figure 6: see original paper] and [Figure 7: see original paper] show calculated temperature and flow fields for hybrid welding at 500 W laser power. With rela-

tively low laser power density, vapor recoil pressure effects are insignificant, no keyhole forms in the hybrid weld pool, and only a large deformation occurs in the arc-affected region at the front, similar to GMAW. The basic flow patterns in both longitudinal and cross-sections are also similar to GMAW. However, unlike pure GMAW, no obvious metal accumulation occurs and humping defects disappear at 500 W. This may be because the added laser energy increases total heat input, enlarging the liquid weld pool volume and extending cooling time, providing sufficient time for backflow of liquid metal at the pool rear. Additionally, increased heat flux density raises liquid metal temperature, reduces dynamic viscosity, and enhances fluidity, improving weld formation. Furthermore, preheating by the leading laser improves wettability of liquid metal on the workpiece surface, promoting lateral spreading and suppressing humping defects. Thus, even at low power, the laser effectively suppresses humping but has minimal effect on the basic fluid flow pattern, only altering heat distribution characteristics.

[Figure 8: see original paper] shows temperature and flow fields for hybrid welding at 2000 W laser power. With higher laser power, laser-induced vapor recoil pressure increases significantly, and a keyhole forms in the weld pool. The added laser energy not only eliminates humping defects but also substantially increases weld penetration, indicating that at high laser power, laser heat input critically affects hybrid welding penetration.

Under this condition, keyhole depth at $t = 0.3$ s and $t = 1.0$ s is greater than at $t = 0.6$ s, showing that the keyhole oscillates rather than remaining stable during hybrid welding. This occurs because the large liquid weld pool volume and droplet transfer, combined with arc pressure, droplet impact force, and electromagnetic force, make it difficult to balance forces on the keyhole wall, especially the rear wall, resulting in unstable keyhole depth. However, the oscillation range remains basically stable. Additionally, due to the high welding speed, the keyhole is not symmetric about the laser center axis but tilts noticeably backward ([Figure 8a: see original paper] and [Figure 8b: see original paper]), exhibiting the main characteristic of a bent keyhole in high-speed welding [28]. For a bent keyhole, using an axisymmetric volumetric heat source helps stabilize most of the energy on the keyhole front wall, making its force stability relatively greater, which matches the actual physical process in high-speed laser deep penetration welding [28,29]. The model thus captures the main features of keyhole dynamic behavior and its influence on hybrid welding fluid flow.

Further analysis shows that during hybrid welding, arc pressure creates a certain depression near the keyhole opening, while vapor recoil pressure causes high fluid velocities near the keyhole wall. For the keyhole front wall, under relatively stable vapor recoil pressure, nearby liquid metal velocity is significantly higher than elsewhere, reaching over 5 m/s, always flowing downward from the keyhole opening to the bottom, then backward to the pool rear, and upward under buoyancy. The upward-flowing metal partially flows toward the pool tail and partially back to the front, forming a clockwise vortex in the middle of the weld

pool. For the keyhole rear wall, in addition to vapor recoil pressure, droplet impact force, arc pressure, and fluid dynamic and static pressures have relatively large effects, making its shape less stable and nearby fluid flow more complex and dependent on keyhole morphology. When the keyhole is deep, vapor recoil pressure on the lower rear wall overcomes surface tension, causing downward flow that merges with backward-flowing metal at the pool bottom, while upper metal flows upward under arc pressure, then backward along the pool surface. However, this metal flows back toward the pool bottom at some distance from the keyhole under the influence of pool impact force, electromagnetic force, and backflowing metal from the rear, then flows backward again ([Figure 8a: see original paper] and [Figure 8c: see original paper]). When the keyhole is shallow, only upward flow exists along the rear wall ([Figure 8b: see original paper]), related to expulsion by downward-flowing front wall metal and arc pressure effects.

Thus, at 2000 W laser power, the presence of the keyhole makes the longitudinal fluid flow pattern significantly different from both GMAW and low-power laser hybrid welding. Under these conditions, a relatively stable clockwise flow exists in the weld pool, which helps transport more arc heat to the pool bottom, increasing penetration and promoting uniform distribution of alloying elements from the filler metal.

The stirring action of the keyhole also alters weld pool cross-section morphology and fluid flow. [Figure 9: see original paper] shows calculated cross-sectional flow fields for hybrid welding at 2000 W. At $t = 0.44$ s, workpiece metal begins to melt under arc current, creating surface deformation under arc pressure. At $t = 0.5$ s, a deep keyhole forms under vapor recoil pressure, with fluid flowing top-down, giving the cross-section characteristics of laser deep penetration welding. As the heat source moves, the keyhole at this location is filled by liquid metal and disappears, while the upper pool width increases due to current heat flux. At $t = 0.8$ s, reinforcement forms and fluid velocity decreases significantly. The upper pool width is large while the lower portion is narrow, giving the cross-section characteristics of both GMAW and laser deep penetration welding. At this stage, fluid at the symmetry axis flows top-down under electromagnetic force and pool impact force. At $t = 1.2$ s, with reduced arc pressure and electromagnetic force effects, fluid at the symmetry axis flows bottom-up under buoyancy, forming a clockwise vortex in the upper pool under surface tension.

It should be noted that laser suppression of humping defects is affected by welding speed. [Figure 10: see original paper] shows calculated longitudinal sections for hybrid welding at 500 W laser power and 2 m/min welding speed. With significantly increased speed, hybrid weld penetration decreases markedly, while laser thermal effects on the weld pool relatively weaken, and humping defects reappear.

[Figure 11: see original paper] and [Figure 12: see original paper] compare experimental and calculated results for weld top surfaces and cross-sections at laser powers of 500 W and 2000 W. Weld reinforcement was determined

based on filler metal buildup, with specific calculation methods for cross-section reinforcement and dimensions given in reference [16]. The results show good agreement, with only minor errors in fusion line shape, thereby validating the model's accuracy and applicability.

Conclusions

1. Considering the coupling effects of droplets, weld pool, and keyhole in laser+GMAW hybrid welding, an applicable three-dimensional transient numerical model for keyhole, weld pool fluid flow, and temperature field was established based on FLUENT software.
2. The model simulated fluid flow and temperature fields in stainless steel laser+GMAW hybrid welding under different conditions. Calculated weld cross-section shapes and dimensions agreed well with experimental results, demonstrating that the model captures the main features of hybrid welding fluid flow.
3. For pure GMAW (laser power 0 W) at 1 m/min welding speed, metal accumulation occurred in the weld pool, resulting in humping defects.
4. For laser+GMAW hybrid welding at 500 W laser power and 1 m/min speed, no keyhole formed and the basic fluid flow pattern was similar to GMAW, but humping defects disappeared. However, when welding speed increased to 2 m/min, humping reappeared.
5. At 2000 W laser power and 1 m/min speed, a keyhole formed in the hybrid weld pool with unstable, oscillating depth. Metal flow near the keyhole front wall was consistently high-velocity and downward from the keyhole opening. Flow patterns near the keyhole rear wall depended on keyhole dynamics. The keyhole strongly stirred the weld pool fluid, maintaining a clockwise vortex in the middle of the pool that helped transport arc heat to the pool bottom and uniformly distribute alloying elements from the filler metal.

References

- [1] Defalco J. *Weld J*, 2007; 86(10): 47
- [2] Graf T, Staufner H. *Weld J*, 2003; 82(1): 42
- [3] Staufner H. *Weld J*, 2007; 86(10): 36
- [4] Bagger C, Olsen F O. *J Laser Appl*, 2005; 17: 2
- [5] Mahrle A, Beyer E. *J Laser Appl*, 2006; 18: 169
- [6] Gao M, Zeng X Y, Hu Q W, Yan J. *Trans China Weld Inst*, 2008; 29(6): 85
- [7] Wu C S. *Thermal Process and Weld Pool Behavior*. Beijing: China Machine Press, 2007: 5
- [8] Cho M H, Farson D F. *Weld J*, 2007; 86(9): 253
- [9] Le Guen E, Fabbro R, Carin M, Coste F, Le Masson P. *Opt Laser Technol*, 2011; 43: 1155

- [10] Bendaoud I, Mattei S, Cicala E, Tomashchuk I, Andrzejewski H. Opt Laser Technol, 2014; 56: 334
- [11] Atabaki M M, Nikodinovski P, Chenier P, Liu W, Kovacevic R. Opt Laser Technol, 2014; 59: 68
- [12] Xu G X, Wu C S, Qin G L, Wang X Y. Acta Metall Sin, 2012; 48: 1033
- [13] Xu G X, Wu C S, Qin G L, Ou H L. China Weld, 2011; 20(1): 22
- [14] Xu G X, Wu C S, Qin G L, Wang X Y, Lin S Y. J Eng Manuf, 2011; 225: 528
- [15] Xu G X, Wu C S, Qin G L, Wang X Y, Lin S Y. Int J Adv Manuf Technol, 2011; 57: 245
- [16] Xu G X, Wu C S, Qin G L, Wang X Y, Lin S Y. Acta Metall Sin, 2009; 45: 107
- [17] Zhang Z Z, Xu G X, Wu C S. Acta Metall Sin, 2011; 47: 1045
- [18] Kong F R, Ma J J, Kovacevic R. J Mater Process Technol, 2011; 211: 1102
- [19] Xu G X, Wu C S, Qin G L, Wang X Y. Acta Metall Sin (Engl Lett), 2013; 26: 352
- [20] Zhang T, Wu C S, Qin G L, Wang X Y, Lin S Y. Comput Mater Sci, 2010; 47: 848
- [21] Cho J H, Na S J. Weld J, 2009; 88(2): 35
- [22] Cho I W, Na S J, Cho M H, Lee J S. Comput Mater Sci, 2010; 49: 172
- [23] Zhou J, Tsai H L. Int J Heat Mass Trans, 2008; 51: 4353
- [24] Wang R P. PhD Dissertation, Beijing University of Technology, 2011
- [25] Gao Z G. PhD Dissertation, Shanghai Jiaotong University, 2009
- [26] Zhang T, Wu C S, Feng Y H. Numerical Heat Transfer, 2011; 60A: 685
- [27] Voller V R, Prakash C. Int J Heat Mass Transfer, 1987; 30: 1709
- [28] Jin X Z, Peter B, Thomas G. J Phys, 2006; 39D: 4703
- [29] Semak V V, Matsunawa A. J Phys, 1997; 809D: 30

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