Effect of droplet transition on the dynamic behavior of the keyhole during 6061 aluminum alloy laser-MIG hybrid welding

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Abstract
The simulation method in laser-MIG hybrid welding, which involves two heat sources and multiple welding parameters, is beneficial to reveal the complex physical phenomena and dynamic behavior of molten pool keyhole during the welding process. In this investigation, laser-MIG hybrid welding for 6-mm-thick 6061 aluminum alloy was performed under different heat input by the high-power disc laser, MIG welding system, and KUKA robot. The high-speed camera system was used to observe the droplet transition phenomenon in the welding process. Besides, a thermal-fluid coupling model was established to simulate the temperature field and flow field, which was changed by the droplet transfer during laser-MIG hybrid welding. The experimental and simulated results showed that the droplet transition behavior affected the formation of the keyhole. The keyhole was the smallest when the droplet contacted the molten pool. In addition, the droplet transition brought external momentum and energy to the molten pool, which was conducive to the increase of the flow rate of the molten pool.

Keywords Droplet · Keyhole · Thermal-fluid coupling simulation · Laser-MIG hybrid welding

1 Introduction

Contemporary aerospace is based on the goal of improving the carrying capacity through weight reduction [1, 2]. Aluminum alloys have been widely used in the aerospace field owing to their small density, high specific strength, and corrosion resistance [3–5]. At present, there are numerous problems in the traditional arc welding, such as low welding efficiency, large heat input, and large deformation after welding, which seriously limits its application [6]. Although aluminum alloy has high reflectivity to laser, a keyhole is still generated at a high energy density, i.e., greater than 10⁶ W/cm², which greatly improves the laser absorption rate of aluminum alloy [7, 8]. Laser welding for aluminum alloy is gradually used in aerospace, vehicle, rail transportation, and other fields due to its advantages of obvious weight loss, slight deformation, and high welding efficiency [9, 10]. However, in laser welding, weaknesses of poor bridging ability and strict requirement of the joint gap exist [11]. As an applicative and emerging deep penetration connection technology, laser-arc hybrid welding technology, which was developed in the 1990s, has been widely applied in civil passenger aircraft, automobiles, construction machinery, rail transportation, and equipment manufacturing fields [12, 13]. In the laser-arc hybrid welding process, the dual heat source synergy and interaction effect between laser and arcs produce narrow and deep welds, thereby greatly improving production efficiency [14]. Laser-arc hybrid welding with the characteristics of high welding energy, strong gap bridging ability, and high joint quality [15] makes up for the deficiencies in the single processing heat source and, meanwhile, effectively combines the advantages of the two welding methods [16].

Many researches have been carried out to observe the morphology of the molten pool during the laser-MIG hybrid welding process by high-speed cameras. Faraji et al. [17] used laser-MIG hybrid welding to fabricate 3-mm-thick 2198 aluminum alloys, and the mechanical property of the welded joint was compared and analyzed. It was found that comparing with a single laser heat source, the keyhole with the deep penetration was easy to obtain even at higher welding speed. Moreover, the microhardness and microstructure of high laser power with low arc power were better. Zhang et al. [18] filmed the transformation mode of molten droplets and the shape
characteristics of welding pool in the process of double-sided MIG welding and laser-MIG hybrid welding by a high-speed camera. It is found that the laser-MIG hybrid welding joint exhibited better mechanical properties, thermal properties, and electric properties. Liu et al. [19] observed the droplet transfer and the keyhole in the molten pool during laser-arc hybrid welding by a high-speed camera. It revealed that the laser had a compressive effect on the arc pressure with the surface of the molten pool. Zhang et al. [20] performed laser-MAG hybrid welding of large thickness steel and investigated the influence of the ratio of laser power to arc power on the weld morphology. Zhang et al. [21] used a high-speed camera to observe the effect of laser power modulation on the behavior of molten pool and keyhole during the laser-MIG hybrid welding process. It was observed that the generation of weld defects, such as spatter and porosity, was suppressed, and the transverse shrinkage of welding seam was decreased by optimizing the modulation parameters. What is more, the image of the molten droplet and arc morphology were observed with the help of a high-speed camera system. It was revealed that as the ratio of laser to arc energy increases, the aspect ratio of the weld exhibits a linear increase.

In recent years, the research method of simulation was used to explain complex physical phenomena, which promoted the research on the mechanism level. Lu et al. [22] proposed a three-dimensional transient model coupled with fluid flow, bubble motion, and solidification to study the process of keyhole-induced porosity. The simulation results showed that the number of porosity was mainly determined by the frequency of keyhole collapse. As the laser power increased, as well as the welding speed and spot diameter decreased, the keyhole tended to collapse more easily. Guo et al. [23] performed laser-GMAW hybrid welding of 6-mm aluminum alloy, and simulated the formation of keyhole-induced pores with the help of two-dimensional flow field calculations. It was found that under the action of the arc force, relatively stable counterclockwise vortices appeared in the middle and rear of the composite molten pool, which tended to prevent the bubbles from moving to the low temperature area at the rear of the molten pool, thus helping the bubbles to float upward.

However, the research on the droplet transfer behavior in the laser-MIG hybrid welding process is still insufficient. It is not enough to study the effect of droplet transition on the temperature field distribution of the molten pool. In this paper, with the help of a high-speed camera and the establishment of a thermal-fluid coupling model, droplet transition behavior is studied.

### 2 Experimental details

#### 2.1 Experimental material and setup

The base metal used in this paper is 6061-T6 aluminum alloy; its chemical composition is shown in Table 1. The size of the aluminum alloy plate is 150 mm × 30 mm × 6 mm, with a Y-shaped groove, as shown in Fig. 2(a). The selected filler wire is ER4047 with a diameter of 1.2 mm whose main chemical composition is shown in Table 1. The laser-MIG hybrid welding experiment equipment adopted is TruDisk-12003 disc laser with a maximum laser output of 12,000 W, KR60HA robot, TPS 5000 Fronius welding machine, and self-designed installation fixture. Besides, a CP70 high-speed camera is used to take pictures of the molten pool morphology and droplet transition during the welding process. The experimental equipment is shown in Fig. 1.

#### 2.2 Experimental process

During the laser-MIG hybrid welding of the 6061 aluminum alloy, the aluminum alloy plate is connected to the negative electrode effectively, considering the dense oxide film on the surface of the aluminum alloy. The cathode crushing effect in arc welding is instrumental to remove the oxide film and facilitate the droplet transition. The schematic diagram of laser-MIG hybrid welding is shown in Fig. 2. In order to prevent the damage of the laser head by the vertical laser irradiation, the angle between the laser beam and the workpiece is 86.5°. At the same time, the angle between the MIG welding torch and the aluminum alloy plate is 45° considering the interference of the experimental equipment. The relative distance between the laser beam and arc, which is called wire-spot distance, is designed to 3 mm. Argon with purity of 99% is used as the welding shielding gas and its flow rate is 15 L/min. The welding parameters adopted in this experiment are as shown in Table 2.

### 3 Mathematical modeling

#### 3.1 Governing equations

The flow of the molten pool and the behavior of metal vapor during the laser-MIG hybrid welding process are both complex physical phenomena [24]. It follows the law of conservation of mass, energy, and momentum, which governs the

| Composition | Si | Fe | Cu | Mn | Mg | Zn | Ti | Cr | Al |
|-------------|----|----|----|----|----|----|----|----|----|
| 6061        | 0.56 | 0.70 | 0.30 | 0.89 | 0.93 | 0.25 | 0.15 | 0.04 | Balance |
| ER4047      | 12  | 0.8 | 0.03 | 0.15 | 0.1 | 0.2 | -   | -   | Balance |

Table 1 Chemical composition of 6061 aluminum alloy and ER4047 (wt.%)
thermodynamics and kinetics of the molten pool owing to the fluid characteristics at the welding process [25]. The formulas of the three laws are as follows.

**Continuity equation**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  
(1)

especially for incompressible fluids, \(\frac{\partial \rho}{\partial t} = 0\).

**Energy equation**

\[
\rho \left( \frac{\partial H}{\partial t} + (u - u_0) \frac{\partial H}{\partial x} + v \frac{\partial H}{\partial y} + w \frac{\partial H}{\partial z} \right) = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + q_{\text{net}}
\]

(2)

where \(H\) is the mixing enthalpy, \(T\) is the temperature, \(\lambda\) is the heat conductive coefficient, and \(q_{\text{net}}\) is the heat input during the laser-MIG hybrid welding process.

**Heat balance equation**

\[
q_{\text{net}} = q_A + q_L + q_D - q_E - q_R - q_C
\]

(3)

where \(q_A\) is the heat input from the electric arc; \(q_L\) is the heat input from the laser; \(q_D\) is the heat input from droplet; \(q_E\) is the evaporation heat loss from the molten metal; \(q_R\) is the heat loss by radiation; and \(q_C\) is the heat loss by convective heat exchange with the environment. The unit of these parameters is \(\text{J/m}^2\text{s}\).

**Momentum equation**
\[
\frac{\partial}{\partial t} (\rho \vec{u}) + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \eta \nabla[(\nabla \vec{u} + \nabla \vec{u}^T) - \frac{2}{3} \nabla \vec{u}^T] + \vec{S}_m
\]

where \( \vec{u} = (u, v, w) \), \( \vec{S}_m \) is the source term for momentum conservation.

### 3.2 Driving forces

The vapor recoil pressure (\( P_R \)) of the gas is an important reason for the keyhole, which is mainly driven by the plasma generated at the bottom of the keyhole, and the liquid metal is expelled to both sides of the molten pool [26, 27]. The equation of recoil pressure is expressed as follows:

\[
P_R = P_0 \cdot \exp\left(\frac{T - T_b}{RTT_b}\right)
\]

where \( P_0 \) is the ambient air pressure, \( L_v \) is latent heat of vaporization, \( T_b \) is the boiling temperature, and \( R \) is the gas constant value.

The surface tension is one of the driving forces to increase the width of the molten pool. The temperature coefficient of the surface tension with the aluminum alloy liquid metal is negative [28]. The molten metal on the surface of the molten pool flows around the keyhole, resulting in a wide and shallow cross section of the molten pool.

The Marangoni force has great effect on the width of molten pool. Especially, when the temperature gradient coefficient of surface tension is negative, the surface tension of the liquid metal increases as the temperature decreases. Thus, the surface tension is low at the center of the molten pool, and it is high near the molten pool edge, which contributes to an outward flow; thus, it forms consequently a wider and shallower molten pool. The equation of the Marangoni force is expressed as follows:

\[
\tau = \frac{dy}{dT} \frac{dT}{dy}
\]

where \( \tau \) is the Marangoni stress, \( dy/dT \) is the temperature coefficient of surface tension, and \( dT/dy \) is the temperature gradient.

The buoyancy force is caused by the density variations. The variation of density in the molten pool induces the fluid rising in the hotter and less-dense region. At the same time, the fluid sinks in the cooler and denser region. The force is expressed by the following equation:

\[
F_b = \rho g \beta (T - T_{ref})
\]

where \( \rho \) is the density of liquid metal, \( \beta \) is the thermal expansion coefficient, and \( T_{ref} \) is the arbitrarily selected reference temperature.

Electromagnetic force is named as Lorentz force, which effects on the heat and mass transfer in the molten pool and contributes to smaller width and deeper penetration. The equation is expressed as:

\[
F_m = \vec{J} \times \vec{B}
\]

where \( \vec{J} \) is the current density and \( \vec{B} \) is the magnetic field.

The laser-MIG hybrid welding process involves the joint action of many forces, among which the arc pressure contributes to smaller width and larger penetration. On the contrary, the plasma flow force leads to larger width and shallower penetration. Marangoni convection and surface tension effectively increase the upper and lower width of the molten pool. The scheme diagram of driving force in the cross section and longitudinal section of the molten pool during laser-MIG hybrid welding is as shown in Fig. 3.

### 3.3 Condition of computational domain

Considering the gas–liquid two-phase flow under the laser-MIG hybrid welding process, two domains of air and aluminum alloy are established, where the thickness of the air is 3 mm and the thickness of the aluminum alloy is 6 mm, as shown in Fig. 4. The top of the air domain is selected as the inflow, the velocity is set to 0.1 m/s, and the other three sides of the air domain as the outflow are set as an atmosphere. The remaining faces are set as walls. The thermo-physical properties of the 6061 aluminum alloy and plasma are as shown in Table 3 and Table 4, respectively.

### 3.4 Heat source

Considering the laser and MIG heat sources during the welding process, a hybrid heat source model of a Gaussian rotating body heat source combination and a double ellipsoid heat source are selected for simulation, as shown in Fig. 5. The heating range of the MIG heat source is wider and the width of the weld seam is larger; thus, the double ellipsoid heat source model better reflects the shape of the molten pool [29]. The laser heat source acts on the surface of the workpiece and produces a keyhole effect, which plays a leading role in the welding process [30].

Since the weld under the laser heat source is nail-shaped in cross section, in order to better fit the simulation effect, the Gaussian rotating body heat source is selected as the laser heat source model, which mainly includes Gaussian surface heat source and Gaussian body heat source. The distribution functions of heat flux density are described as:

\[
q_s(x, y) = \frac{bQ}{\pi r_s^3} \exp \left( -b \left( \frac{x^2 + y^2}{r_s^2} \right) \right)
\]
Fig. 3 The schematic diagram of driving force during laser-MIG hybrid welding. (a) In cross section. (b) In longitudinal section

Fig. 4 a–c The schematic diagram of computational domain

| Table 3 Thermo-physical properties of 6061 aluminum alloy for simulation |
|-----------------------------------------------|-------|----------------|----------------|
| Physical property                           | Symbol | Value           | Unit           |
| Mass density                                 | $\rho$ | 2630 kg/m$^3$   |                |
| Thermal expansion coefficient                | $\beta$ | $3.02 \times 10^{-5}$ | 1/K            |
| Heat conductivity                            | $\lambda$ | 204 W/(m·K)   |                |
| Solid temperature                            | $T_w$ | 858.13 K       |                |
| Liquid temperature                           | $T_l$ | 923.15 K       |                |
| Evaporation temperature                      | $T_b$ | 2790 K         |                |
| Latent heat of fusion                        | $L_p$ | $5.03 \times 10^5$ J/kg |                |
| Latent heat of evaporation                   | $L_v$ | $1.07 \times 10^7$ J/kg |                |
| Special heat capacity of solid               | $C_p$ | 900 J/(kg·K)   |                |
| Special heat capacity of liquid              | $C_l$ | 1200 J/(kg·K)  |                |
| Surface tension                              | $\sigma$ | 0.99 N/m |                |
| Temperature coefficient of surface tension   | $A_\sigma$ | $-1.3 \times 10^{-4}$ N/(m·K) | |
| Dynamic viscosity                            | $\eta$ | 0.0045 Pa·s    |                |
| Surface emissivity                           | $\epsilon$ | 0.1 /       |                |
| Ambient temperature                          | $T_{ref}$ | 300 K         |                |
| Magnetic permeability                        | $\mu$ | $1.26 \times 10^{-6}$ H/m |  |
1) 3

where \( q_s \) and \( q_v \) are the heat flux distributions of Gaussian surface heat source and bulk heat source, respectively, \( b \) is the heat flux concentration coefficient, \( Q_s \) and \( Q_v \) represent the power of surface heat source and bulk heat source, \( r_s \) and \( R_0 \) are the effective radius of action of the surface heat source and bulk heat source, respectively, and \( H(t) \) is the effective depth of action at which the body heat source changes over time. And the relationship between \( Q_s \) and \( Q_v \) is expressed as:

\[
Q_V + Q_S = \frac{P}{\eta_L}
\]

where \( P \) is the laser power and \( \eta_L \) is the thermal efficiency of the laser.

The double ellipsoid heat source model is described as:

\[
q_f(x,y,z) = \frac{6\sqrt{3}f_f\eta_L U}{a_f b c \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{a_f^2} - \frac{3(y - v_0 t)^2}{b^2} - \frac{3z^2}{c^2}\right), y \geq 0
\]

(12)

\[
q_r(x,y,z) = \frac{6\sqrt{3}f_r\eta_L U}{a_r b c \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{a_r^2} - \frac{3(y - v_0 t)^2}{b^2} - \frac{3z^2}{c^2}\right), y < 0
\]

(13)

3.6 Droplet transition model

The mass, energy, and momentum are brought by the droplet transition behavior, which impact the temperature field and flow field of the molten pool as well as the dynamic evolution behavior of the keyhole. In this model, the boundary at the entrance in the geometric model is set as the position where the droplet grows up gradually. As the droplet grows up completely, it falls into the molten pool by free fall. Based on the results observed by the high-speed camera, the droplet transition period of 0.06 s was set, and the wire moving speed was set the same as the laser heat source moving speed. The geometric model and boundary conditions of the

\[
f_f + f_r = 2
\]

(14)

In the formula, \( q_f \) and \( q_r \) are the heat source densities of the two ellipsoids in the double ellipsoid heat source model; \( f_f \) and \( f_r \) are the heat distribution coefficients of the two ellipsoids, \( I, U \), and \( v_0 \) are the arc current, voltage, and welding speed; and \( a_f, a_r, b, \) and \( c \) are heat source model parameters. \( \eta_A \) is the arc thermal efficiency.

3.5 Experiment validation

The wire-spot distance remains nearly constant in this study, which is 3 mm. According to the heat-fluid coupling solution process of the laser-MIG hybrid welding process, the numerical simulation calculation is carried out. After the relevant parameters of the model are corrected, the results of heat source verification result for 1# is shown in Fig. 6. Comparing the weld cross section with the weld simulation results, it is seen that the macroscopic appearances of 1# is basically symmetrical, so the modified hybrid heat source model can be used for the subsequent simulation calculation of the temperature field and flow field of laser-MIG hybrid welding.

### Table 4 Thermo-physical properties of plasma for simulation

| Physical property     | Symbol | Value   | Unit   |
|----------------------|--------|---------|--------|
| Mass density         | \( \rho_g \) | 0.06    | kg·m\(^{-3}\) |
| Special heat capacity| \( C_g \) | 49      | J·kg\(^{-1}\)·K\(^{-1}\) |
| Convection heat transfer coefficient | \( h_g \) | 3.74   | W·m\(^{-2}\)·K\(^{-1}\) |
| Dynamic viscosity   | \( \eta_g \) | 0.0045 | Pa·s   |

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droplet transition are shown in Fig. 7. During the forming and falling of the droplet, it is affected by gravity, surface tension, arc force, and other forces. The arc force includes electromagnetic contraction force, plasma flow force, and spot pressure. Therefore, the droplet is not a regular circle in the falling process; a necking is formed on the top of the droplet. Whether the droplet can break away from the end of the welding wire and enter into the molten pool smoothly depends on whether the resultant force of the droplet is downward.

4 Results and analysis

4.1 High-speed camera results

In order to facilitate the analysis of the droplet transfer behavior in the laser-MIG hybrid welding process, the high-speed camera results of 1# parameter ($P = 4.0$ kW, $I = 90$ A, $v = 1.2$ m/min) were taken, and a picture was extracted every 2 ms for observation and analysis, as shown in Fig. 8. At $t_0$, the droplet just started to contact the molten pool. Due to inertia, the center of gravity of the molten droplet shifted along the side opposite to the welding direction. The contact surface gradually increased under the action of the surface tension of the molten pool and gravity; the molten droplet was completely separated from the end of the welding wire at $t_0 + 6$ ms. With the falling of the molten droplet, the molten droplet gradually merged into the molten pool. At $t_0 + 10$ ms, the molten droplet completely merged into the molten pool. The front of the molten pool formed a keyhole under the action of the laser. Owing to the impact and momentum brought by the droplet drop, a depression appeared in the front of the liquid molten pool at $t_0 + 12$ ms, and the diameter of the keyhole was also significantly reduced.

It is seen that the droplet transition behavior has an important influence on the stability of the molten pool and the volatility of the keyhole. The external momentum and energy brought by the droplet transition promote the flow of the molten pool, which is beneficial for the beneficial elements of the molten droplet. The elements are fully mixed with the molten pool and promote the escape of bubbles. In the process of droplet transition, the back wall of the keyhole is squeezed due to the impact force of the droplet on the molten pool. The opening of the keyhole is suppressed; meanwhile, the laser energy is affected to the bottom of the keyhole, which results in a smaller keyhole.

4.2 Effect of droplet transition on thermal-fluid coupling field distribution

In order to study the effect of droplet transition on the temperature field and flow field of the molten pool, under 2# parameter ($P = 4.0$ kW, $I = 100$ A, $v = 1.2$ m/min), the droplet between 64.8 and 68.8 ms is selected. The results of the transition simulation were analyzed, and the method of adding and not adding the droplet transition was used to analyze the influence of the droplet transition behavior on the morphology of the keyhole. The simulation results of the temperature field are shown in Fig. 9 and Fig. 10, respectively.

The droplet transition process causes pressure on the back wall of the keyhole, so the angle of the keyhole back wall changes, as shown in Fig. 9. At $t = 64.8$ ms, the molten droplet was contracted and hung above the molten pool under the action of electromagnetic force, the back of the molten pool was slightly dented by the action of the arc force. At $t = 65.6$ ms, the droplet contacted the back of the molten pool, the momentum by the falling droplet caused an impact on the molten pool, and the back wall of the keyhole was squeezed by the liquid at the back of the molten pool.
Fig. 8 a–i High-speed camera photos in the droplet transition process

Fig. 9 Distribution of temperature field in molten pool during droplet transition. (a) $t=64.8$ ms. (b) $t=65.5$ ms. (c) $t=66.4$ ms. (d) $t=67.2$ ms. (e) $t=68.0$ ms. (f) $t=68.8$ ms
At $t=67.2$ ms, the back wall of the keyhole bulged due to the squeezing effect of the droplets falling into the molten pool, and the direction pointed to the inside of the keyhole. At $t=68.0$ ms, owing to the squeezing of the molten metal in the rear molten pool and the filling of the molten pool, the angle of the lower part of the back wall of the keyhole was changed, which facilitated the laser irradiation into the keyhole and brought a greater depth of the keyhole. At $t=68.8$ ms, the back wall of the keyhole continued to be affected by the fusion of the molten droplets to the back of the molten pool, and the lower part of the back wall of the keyhole had a boss pointing to the inside, which was not conducive to the laser irradiation to the bottom of the keyhole, thus affecting the absorption of laser energy in molten pool.

Compared with added droplet transfer, the surface morphology of the back of the molten pool without droplet is smoother, as shown in Fig. 10. It is found that the depth of the keyhole is the same, but the back wall of the keyhole changes greatly. At $t=68.0$ ms, there is a slight depression in the lower part of the rear wall of the keyhole. It is mainly because there is no increase in the volume of the back of the molten pool due to the transfer without adding droplets, resulting in a slight depression in the lower part of the keyhole back wall.

Because the molten droplet brings external momentum to the molten pool, the flow field distribution of the molten pool also changes. The simulation results of the flow field are shown in Fig. 11 and Fig. 12, respectively.

It is seen from Fig. 11 that the flow velocity inside the molten pool is very small, and the flow velocity on the surface of the molten pool and the wall of the keyhole is relatively large. The flow velocity on the surface of the molten pool varies from 0.7 to 1.1 m/s, the flow velocity at the bottom of the keyhole varies greatly, about 0.4 to 1.4 m/s. At $t=64.8$ ms, the molten droplet had not yet fallen into the molten pool. At this time, the fluid in the front of the molten pool flowed upward along the front wall of the keyhole, and the fluid at the rear of the molten pool flowed down in a clockwise direction in front of the molten pool. It flowed upward along the back wall of the keyhole extended backward under the action of Marangoni circulation on the surface of the molten pool. A clockwise vortex appeared in the fluid below the back of the molten pool. At $t=65.6$ ms, the transition of the droplet brought an impact on the back of the molten pool, so the flow direction of the fluid in the bottom area of the keyhole was from the back to the front of molten pool.

Meanwhile, the droplet completely fell into the molten pool, the impact force brought by the droplet was relatively large, and the maximum velocity reached 2.05 m/s.

For the flow field distribution of the molten pool without added droplet transition, the flow field distribution is basically the same as that of the added droplet transition, but its peak velocity at different times is less than the added droplet transition, mainly because the droplet transition brings about external momentum [19]. The change of the shape of the keyhole by the droplet transition is mainly achieved by promoting the downward flow of the fluid at the back of the molten pool to fill the depression below the back wall of the keyhole, thus squeezing the back wall of the keyhole. When a convex shape appeared on the back wall of the keyhole, which affects the heating effect of the laser on the molten pool, the back wall of the keyhole will adjust the angle under
the thermal capillary force to maintain the absorption of the laser by the molten pool.

4.3 Effect of droplet on keyhole-induced pore

Figure 13 shows that the trajectory of the bubble formed during the droplet transition under 3# parameter ($P = 4.5$ kW, $I = 120$ A, $v = 1.2$ m/min). It is seen that the droplet transition has an important influence on the stability of the keyhole, and it is easy to bring external bubbles when falling into the molten pool. Before the molten droplet fell into the molten pool, the maximum speed of the free fall reached 2.262 m/s, which brought external momentum and energy to the molten pool. At $t = 66.4$ ms, the molten droplet fell into the molten pool forming a gap, and the movement direction of the surrounding fluid was a counterclockwise vortex, the vortex velocity varies from 0.39 to 0.78 m/s. At $t = 67.2$ ms, an irregular bubble formed on the surface at the back of the molten pool. The flow direction of the fluid was still a counterclockwise vortex, and the moving speed is reduced. At $t = 67.6$ ms, the liquid bridge above the bubble was broken, and the bubble escaped from the molten pool. The flow direction of the fluid around the bubble was clockwise circulation, and the maximum surface velocity caused by the liquid bridge fracture reached 2.805 m/s. It can be seen that the droplet transition brings smaller bubbles to the surface of the molten pool.
the molten pool, and escapes the surface of the molten pool under the action of the surrounding circulation. The circulation velocity is slightly higher than that of the surrounding fluid, and the bubbles are easy to escape.

The forces acting on the bubbles in the molten pool are buoyancy force $F_b$, gravity $G$, the fluid driving force $F_d$, and viscous force $F_v$, as shown in Fig. 14(a). Because most of the bubbles are very small with the diameter of tens of microns, $F_d$ is the main force. The bubbles move in the molten pool under the driving force of the molten pool fluid [31]. Figure 14(b) shows that the smaller bubbles move downward along the solidification interface under the action of fluid flow in the middle of the molten pool, and upward along the back wall of keyhole under the action of Marangoni circulation at the back of the molten pool. Finally, the smaller bubbles escape from the molten pool. The large bubbles formed in the molten pool, which are mainly affected by $F_b$. When the laser beam continues to move forward, under the combined action of thermal buoyancy and fluid, the closed large bubble moves upward along the rear wall of the keyhole, and escapes from the molten pool after reaching the surface of molten pool. If it fails to escape in time, it will stay in the upper of the molten pool and form pores. As a result, larger pores are more likely to appear in the upper part of the molten pool, and there are more pores due to the floating of bubbles.

5 Conclusions

In this investigation, a high-speed camera was used to observe the droplet transition of laser-MIG hybrid welding for aluminum alloy. The thermal-fluid coupling model was established to study the effect of droplet transfer on the shape of the molten pool. Based on the experimental and simulation results, the conclusions are drawn as follows:
(1) The process of the droplet falling into the molten pool hinders the formation of the keyhole, and the keyhole opening is the smallest when the droplets are in contact with the molten pool.

(2) The mass, energy, and momentum are brought by the droplet transition behavior, which change the temperature field and flow field of the molten pool. In addition, the maximum velocity of molten pool is bigger than that without droplet.

(3) The changes of the keyhole morphology are mainly behaved as the squeezing of the back wall of the keyhole. Additionally, the appearance of a boss on the keyhole wall affects the absorption of laser energy by the molten pool, thus affecting the depth of keyhole.

(4) The droplet transition is easy to bring bubbles, which are drawn into the molten pool by the counterclockwise vortex formed on the upper surface of the molten pool. After that, under the combined action of the thermal buoyancy and the clockwise vortex formed on the upper surface of the molten pool, the bubbles easily escape the molten pool.

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Availability of data and material All data generated or analyzed during this study are included in this published article.

Code availability Not applicable.

Declarations

Ethics approval The content in this article does not violate the ethics.

Consent to participate All authors in this article have informed consent to participate in this study.

Consent for publication All authors and their institutions agree to publish this article in The International Journal of Advanced Manufacturing Technology.

Conflict of interest The authors declare no competing interests.

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