Effect of Weld Pool Flow and Keyhole Formation on Weld Penetration in Laser-MIG Hybrid Welding within a Sensitive Laser Power Range

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Abstract: The weld penetration variation in laser-MIG hybrid welding under sensitive laser power range was investigated by welding experiments and CFD (computational fluid dynamics) simulation. During this investigation, joints of AH36 sheets were welded with varying laser powers by the laser-MIG hybrid welding process. In addition, the CFD model was established based on experimental parameters and measurement results. Moreover, surface tension, electromagnetic force, buoyancy, recoil pressure, evaporative condensation, evaporative heat exchange, melt drop transfer, and other factors were considered. The influence of various factors on molten pool depth and keyhole depth were studied, including temperature, velocity, and flow direction of liquid metal. The results show that the weld-forming effect is better at the laser power is 7.5 kW in the range of sensitive laser power. After the keyhole is formed, its depth gradually entered the stage of linear increase, oscillation increase, and oscillation balance. Increasing the laser power can effectively shorten the time of the two growth stages and allow the keyhole to enter the balance stage earlier. During the oscillation balance state of the keyhole, the molten metal under the keyhole flowed to the molten pool root in the reverse direction of welding; it can also promote weld penetration.

Keywords: laser-MIG hybrid welding; sensitive laser power range; keyhole; molten metal

1. Introduction

With the development of modern industrialization, metal materials are used in various areas. The application environment is more and more complex, and the performance requirements are stringent, especially for AH36 steel. The AH36 steel is widely used in the field of shipbuilding due to its high strength, high toughness, and high corrosion resistance [1,2]. AH36 steel has good weldability and can be welded using traditional methods [3].

It is difficult to maintain high welding efficiency when using traditional arc welding methods to weld a medium-thickness AH36 steel plate [4]. In addition, welding medium-thick plates often requires a prefabricated bevel, which will undoubtedly increase the welding cost. Laser welding heat input is small; the keyhole can effectively transfer heat to the depth of the weld. Therefore, it can effectively solve the problems of AH36 steel arc welding, such as large deformation, large residual stress, and high crack sensitivity. This feature makes laser welding more and more widely used [5,6]. Webster et al. [7] used laser welding of thick steel plates and found that the welding speed was very fast,
the plate deformation was small, the melt pool depth was large, and the thick steel plate could be welded through in a single pass. Kumar et al. [8] used pulsed laser welding of stainless-steel heterogeneous joints; they found that inputting a low energy pulse facilitated the production of fine grains and good mechanical properties. Cao et al. [9] used laser welding of 316 L and EH36 heterogeneous joints; they found reducing the welding speed was effective in reducing the degree of tissue segregation in the joints. The laser-arc hybrid welding process couples the two heat sources with each other, fully integrating the advantages of laser and arc welding. During welding, the arc stability is good, and the laser keyhole is stable. Laser-arc hybrid welding can produce high-quality products with high efficiency and has been widely used to weld thick plates of 15 mm or more [10–13].

Liu et al. [14] studied the melting drop transition form of laser-MIG hybrid welding; they found the arc energy determines the melting drop transfer mode, and the laser energy has an important effect on the melt drop transition. Yifu et al. [15] researched the laser-arc hybrid welding process for thick plates; they found that arc can effectively reduce the requirements for laser power and optimize energy input. In laser-MIG hybrid welding, metal forms a hybrid molten pool by absorbing laser and arc energy. Under arc irradiation with low energy density, the molten pool is mainly affected by the Marangoni effect caused by surface tension [16,17], so the resulting molten pool is large in width and small in depth. Under the action of a high-energy-density laser, the molten pool is mainly affected by the steam recoil pressure. In addition, the generated keyhole is more likely to transfer the energy to the melt pool’s bottom and increase the penetration depth. The laser-arc hybrid weld forms a typical “nail” shape with the coupling of heat sources.

Furthermore, the melt flow affects the forming quality of the weld. The study of melt flow is important to analyze the morphology and mechanical properties of welded joints. A three-dimensional transient mathematical model using CFD can help to study the melt flow inside the melt pool. Li et al. [18] established a simple 3D heat transfer model, taking into account the influence of phase transition, and found the relationship between heat transfer, mass transfer, and temperature gradient in the molten pool. Faraj et al. [19] established a 3D heat transfer and fluid flow model, using a laser-arc hybrid heat source and considering the influence of electromagnetic force, recoil pressure, and surface tension. They also researched the influence of welding speed, current, laser power, and other parameters on melt flow and weld morphology of AA6082 aluminum alloy. It was found that the keyhole behavior plays a leading role in the penetration depth. Wu et al. [20] established a mathematical model to study laser-arc hybrid welding of stainless steel. They found that the welding process parameters can be optimized by simulating keyhole variations in the melt pool. Chen et al. [21] researched the effect of droplet transition on melt flow in laser-MIG hybrid welding; a 3D mathematical model of droplet transition was established, which further considered the effects of surface tension, electromagnetic force, and buoyancy on melt flow. It was found that the penetration of the welded joint is larger and the width is smaller when the droplet impact is considered. Ya et al. [22] established a 3D mathematical model for laser-arc composite welding of high strength steel to simulate the deformation and residual stress of a steel plate after welding. The model considers the convection and radiation effects of the material, but ignores the conduction of heat of the fixture. Kubiak et al. [23] established a mathematical model for different power distributions of arc and laser, which simulated the temperature field and velocity field of molten material in the welding pool by considering the effects of phase transition, buoyancy, and convective heat transfer.

As we know, most of the studies on the influence mechanism of process parameters on laser-MIG composite welding are focused on experiments, while the simulation studies on welded joints are mainly focused on the microstructure and mechanical properties [24–26]. In laser-MIG hybrid welding, there are few simulations on the relationship between molten flow, pore behavior, and molten pool depth. Compared with laser welding and arc welding, laser-MIG hybrid welding requires more complex process parameters to be adjusted, so it is necessary to study the welding process through simulation to reduce the experimental workload. In this paper, the relationship between melt flow and keyhole behavior in
the sensitive laser power range is studied, and the influence of the keyhole with regular fluctuation on the depth of the molten pool after entering the high-frequency oscillation stage is studied. Laser-MIG hybrid welding technology was used to weld AH36 steel in this experiment. The cross-sectional profile of the welded joint was photographed using a light microscope, and the weld dimensions were statistically analyzed. In order to better study, the Fluent finite element software was used to establish a 3D transient mathematical model based on three conservation equations. This model adopts the Semak V recoil pressure model and comprehensively considers the influence of surface tension, electromagnetic force, buoyancy, recoil pressure, evaporation condensation, evaporation heat transfer, droplet transfer, convection heat transfer, radiation heat transfer, and other factors. In terms of heat source, the combination of a Gaussian cylindrical heat source and a double ellipsoid heat source with linear attenuation along the direction of depth was selected to successfully obtain the “nail” morphology of the laser-arc composite welding joint, adjust the mathematical model according to the actual welding process and weld size parameters, and realize the verification of simulation and actual results. The melt pool under the action of dual heat source coupling was simulated under the sensitive laser power range, and the temperature field, velocity field, keyhole, and depth of melt changes were analyzed and verified with experimental results. This experiment studied the relationship between melt flow, keyhole behavior, and weld depth in the sensitive laser power range, providing a theoretical basis for the optimization of the laser-MIG hybrid welding process.

2. Experiments

The laser-MIG hybrid welding experimental equipment mainly includes a TruDisk16002 laser, power supply, arc welding robot, and workbench. The welding equipment is shown in Figure 1.

![Figure 1. Laser-MIG hybrid welding equipment.](image)

The laser can reach a maximum power of 16 kW, and the generated laser can be delivered to the laser processing head via an optical fiber. The laser processing head is in front of the arc welding gun. The laser beam is incident at an angle of 90°. The arc welding gun is at 45° to the workpiece. The laser-arc spacing is 2 mm, and the welding shielding gas is pure argon. The welding wire is JM-56 with a diameter of 1.2 mm, and the workpiece is made of AH36 steel with a size of 300 × 150 × 5 mm. The chemical composition of AH36 steel and JM-56 wire is shown in Table 1, and the welding parameters are shown in Table 2. After welding, the width of the weld was first measured statistically, and then a sample with a size of 10 × 10 × 5 mm was taken using the wire cutting technique. The samples were mechanically polished and chemically etched, and the microstructure of the welded
joint was photographed by optical microscope and electron microscope with 5% nitric acid ethanol solution as etchant.

Table 1. AH36 steel and JM-56 wire chemical composition (wt.%).

|         | Fe   | C    | Si  | Mn  | Mo  | Cr  | V  | P   | S   | Cu  | Ni  | Nb |
|---------|------|------|-----|-----|-----|-----|----|-----|-----|-----|-----|----|
| AH36    | 98.021 | 0.16 | 0.4 | 1.4 | -   | 0   | 0  | 0.014 | 0.003 | 0   | 0   | 0.002 |
| JM-56   | 97.399 | 0.077 | 0.87 | 1.45 | 0.002 | 0.031 | 0.004 | 0.012 | 0.013 | 0.125 | 0.017 |

Table 2. Welding experimental parameters.

| Parameters                  | Values | Unit |
|-----------------------------|--------|------|
| Laser power                 | 7      | kW   |
| Laser power                 | 7.5    | kW   |
| Laser power                 | 8      | kW   |
| Current                     | 200    | A    |
| Welding speed               | 41.7   | mm/s |
| Feed rate                   | 166.7  | mm/s |
| Defocus distance            | 0      | mm   |
| Interval                    | 0      | mm   |
| Shielding gas flow rate     | 333.3  | mL/s |
| Laser diameter              | 0.2    | mm   |

3. Mathematical Model

3.1. Assumptions

During this experiment, a 3D transient mathematical model was established by the computational fluid dynamics software Fluent based on the characteristics of continuous laser-MIG hybrid welding. The heat and mass transfer between the heat source and the material, as well as the effects of surface tension, recoil pressure, buoyancy, electromagnetic forces, evaporative condensation, evaporative heat transfer, and gravity of the molten droplets, were mainly considered in the model. Post-processing analysis was performed using CFD-post.

Because of the complex flow behavior of the laser-arc hybrid welding pool, the surface of the molten pool fluctuated dramatically in the actual welding process. It was difficult to consider all the conditions in numerical simulation. Therefore, to simplify the model, we made the following assumptions:

1. The effect of protective gas on melt flow is neglected.
2. The initial temperature of the material is 300 K.
3. Specific heat capacity, thermal conductivity, viscosity as a function of temperature, and other material thermophysical properties are constants.
4. The liquid phase of the melt pool cannot be compressed, and the flow pattern is laminar flow.
5. The absorption rate of the welded workpiece to the arc and laser energy is constant.
6. Thermal buoyancy is assumed using the Boussinesq approximation.

3.2. Mesh Division and Boundary Conditions

The size of AH36 steel in the experiment is 300 × 150 × 5 mm. To simplify the model and speed up the calculation, the asymmetric model was used and part of it was taken for simulation. A model of size 15 × 7 × 7 mm was created, and the model is shown in Figure 2. The model is set up with an air layer of 2 mm thickness. A dense mesh was used in the near-weld area, and a loose mesh was used in other areas. The minimum mesh size is 0.125 mm, and the total number of meshes is 270,000.
Figure 2. Model grid for simulation.

Boundary conditions are important factors affecting the simulation results, and the boundary conditions should be consistent with the actual welding situation. The melt drop volume, melt drop initial temperature, and melt drop initial velocity was set in the inlet position of the model. According to the measurement results of the high-speed camera during the experiment, the melt droplet body radius $r_a$, the average heat absorption time of the melt droplet $t_a$, and the initial velocity $v_a$ were obtained.

The molten droplet is simplified to a sphere and the volume formula is:

$$V_0 = \frac{4}{3} \pi r_a^3$$  \hspace{1cm} (1)

The initial temperature of the molten droplet $T_0$ is:

$$T_0 = \frac{3\eta UI l a}{4\pi C \rho r_a^3} + T_1$$  \hspace{1cm} (2)

where $C$ is the specific heat capacity of the wire material, $\eta$ is the arc energy absorption efficiency of the wire, $U$ is the voltage, $l$ is current, $\rho$ is the density of the wire in the molten state, and $T_1$ is the room temperature.

3.3. Heat Source Model

To more closely match the formation of laser-arc hybrid welding “nail” shape, a combination of heat sources was used. The welding pool is deep and the diameter is small in laser welding, while the welding pool is shallow and the diameter is large in arc welding. Given this, the combined heat source was selected as a Gaussian columnar heat source model with linear decay along the depth direction and a double ellipsoidal heat source model.

The expression for the Gaussian columnar heat source model with linear decay along the depth direction is as follows:

$$Q_0 = \frac{3P \eta_1}{\pi R^2} \cdot D(z) \cdot \exp\left(-\frac{3}{R^2} r^2\right) \cdot u(z)$$  \hspace{1cm} (3)

where $Q_0$ is the heat source, $P$ is the laser power, $\eta_1$ is laser absorption efficiency of the workpiece, $D(z)$ is the decay function of the peak heat flow, which indicates the peak heat flow decay rate in the depth direction, $R$ is the effective action radius of the laser heat source, $r$ is the distance from a point within the effective radius of action of the heat source to the heat source, and $u(z)$ is the unit step function.
Based on the data obtained after cutting and processing the welded parts, the expression of the laser heat source model is simplified:

$$Q_0 = \frac{9P\eta_1}{\pi R^2 H} \cdot \exp\left(-\frac{6a^2}{R^2 \log\left(\frac{H}{h}\right)}\right)$$  \hspace{1cm} (4)

where $H$ is the depth of action of the laser heat source, and $h$ is the depth of a point.

The power density expression for the first 1/4 ellipsoid of the double ellipsoid heat source model is:

$$Q_1 = \frac{6\sqrt{3}\eta_2 f_1 U1I}{\pi^2 a_1 bc} e^{-3(x-vt)^2} \frac{1}{a_1^2} e^{-3y^2} \frac{1}{b_1^2} e^{-3z^2} \frac{1}{c_1^2}$$  \hspace{1cm} (5)

The power density expression for the last 1/4 ellipsoid of the double ellipsoid heat source model is:

$$Q_2 = \frac{6\sqrt{3}\eta_2 f_2 U1I}{\pi^2 a_2 bc} e^{-3(x-vt)^2} \frac{1}{a_2^2} e^{-3y^2} \frac{1}{b_2^2} e^{-3z^2} \frac{1}{c_2^2}$$  \hspace{1cm} (6)

where $f_1 + f_2 = 2$  \hspace{1cm} (7)

where $Q_1$ and $Q_2$ are the heat source, $\eta_2$ is the arc energy absorption efficiency of the workpiece, $a_1$ and $a_2$ are the radii of the first and second half of the melt pool, $b$ and $c$ are the effective action width and effective action depth of arc heat source, respectively, and $f_1$ and $f_2$ are the energy fractions of the anterior and posterior ellipsoids.

### 3.4. Driving Force

According to the joint action of laser and arc, the distribution of driving forces inside the hybrid molten pool is exceptionally complex. During the laser-arc welding process, the melt pool is mainly affected by droplet impact, buoyancy, surface tension, recoil pressure, electromagnetic force, etc. Due to the existence of temperature intervals from the liquid phase line to the gas phase line of the metal material, the temperature of the liquid metal at different locations within the molten pool during the welding process varies, forming a temperature gradient. The density of the molten metal at different temperatures differs, resulting in the formation of thermal buoyancy:

$$F_{a1} = \rho_0 \beta g \Delta T$$  \hspace{1cm} (8)

where $F_{a1}$ is thermal buoyancy, $\Delta T$ is the temperature difference, $\beta$ is the coefficient of thermal expansion of the material, and $\rho_0$ indicates the density at the measured point.

Surface tension acts at the gas-liquid interface and is mainly influenced by temperature. The surface tension formula is:

$$\gamma = \gamma_1 + \kappa_1 (T - T_m)$$  \hspace{1cm} (9)

where $\gamma$ is surface tension, $\gamma_1$ is the surface tension of the solid metal, $\kappa_1$ is the surface tension coefficient, and $T_m$ is the melting point.

The metal is rapidly vaporized by the high energy density laser irradiation to form a metal vapor, which is rapidly detached from the metal surface. The reaction force of the metal vapor on the metal surface is the recoil pressure:

$$P^1 = 0.54\delta_1 \exp\left(\frac{(T - T_g)H_a}{TT_g R_0}\right)$$  \hspace{1cm} (10)

where $P^1$ is the recoil pressure, $\delta_1$ is the standard atmospheric pressure, $H_a$ and $T_g$ are the latent heat of vaporization and gasification temperature of AH36 steel, respectively, and $R_0$ is the ideal gas constant.
3.5. Thermophysical Properties of Materials

The thermophysical properties of a material are functions of temperature. To simplify the calculation, the thermophysical property parameters of the material except for specific heat capacity, thermal conductivity, and viscosity were taken as constant values in different states. The thermal physical properties of AH36 steel are shown in Table 3 and Figure 3.

### Table 3. Material properties of AH36 steel.

| Property                  | Symbol | Unit       | Value  |
|---------------------------|--------|------------|--------|
| Solid density             | ρs     | kg·m⁻³     | 7300   |
| Liquid density            | ρl     | kg·m⁻³     | 6960   |
| Solid temperature         | Ts     | K          | 1670   |
| Liquid temperature        | Tl     | K          | 1780   |
| Vaporization temperature  | Tg     | K          | 3100   |
| Heat conductivity         | λ      | W/(m·K)    | 44     |
| Heat capacity             | Cp     | J/(kg·K)   | 630    |
| Dynamic viscosity         | η      | kg/(m·s)   | 0.0064 |
| Latent heat of fusion     | Hf     |            | 2.26 × 10⁵ |
| Ambient temperature       | Tref   | K          | 300    |

![Figure 3. Thermophysical properties of AH36 steel: (a) density, (b) heat capacity, (c) thermal conductivity, (d) viscosity.](image)

4. Results and Discussion

Figure 4 shows the weld pool morphology and melt flow of welded joints under different laser-arc spacing. It can be seen that when other welding parameters are the same (laser power is 7.5 kW) and the laser-arc spacing is in the range of 1–3 mm, the laser-arc spacing is increased, and the composite pool length is increased, too. When the laser-arc spacing is 1 mm, the maximum velocity below the keyhole is 2.2 m/s. When the laser-arc spacing is 2 mm, the maximum velocity below the keyhole is 1.4 m/s. When the laser-arc...
spacing is 3 mm, the maximum velocity below the keyhole is 1.4 m/s. Thus, the smaller the laser-arc spacing, the greater the downward melt flow rate.

![Figure 4. Morphology and flow rate of molten pool with different laser–arc spacing: (a) 1 mm, (b) 2 mm, (c) 3 mm.](image)

According to Figure 4, when the laser-arc spacing is 1 mm, the melt flow rate between the two heat sources is about 1.8 m/s. Therefore, the laser weld pool and the arc weld pool can be joined together earlier to form a composite weld pool. However, the laser has a great influence on the arc and reduces the stability of the droplet transfer. In addition, the arc interferes with the keyhole and decreased keyhole stability. When the laser-arc spacing is 3 mm, the melt flow rate between the two heat sources is about 0.5 m/s. Because the distance between the arc and the laser is too far to couple well together, they almost form two molten pools. However, when the laser-arc spacing is 2 mm, the melt flow rate between the two heat sources is about 1 m/s. The composite molten pool can be connected together quickly, the droplet transition is stable, and the keyhole is stable.

The laser beam was in front of the welding torch in the laser-MIG compound welding experiment. First, the laser melted the metal surface in the welding direction, and the molten droplets were transferred directly to the molten metal. During the welding process, the arc remained stable, and the spatter, which was caused by the molten drop transition, was reduced. Figure 5 shows the weld morphology of AH36 steel under different laser powers. It can be seen that when the laser power is 7 kW, the weld bottom is narrow, the fusion line is discontinuous, the weld depth is insufficient, and the formability is poor. When the laser power is 7.5 kW, the welded joint has better effect. When the laser power is 8 kW, there is an obvious edge-biting phenomenon at the top of the weld, the bottom of the weld reinforcement is too high, and there is an obvious collapse phenomenon. The results show that the welding joint bottom forming is best when the laser power is 7.5 kW under three laser powers.

![Figure 5. The shape of weld seam with different laser powers.](image)
To ensure the accuracy of the simulation results, the simulated and experimental results with different laser powers were compared. Figure 6a–c shows the simulated weld cross-sectional profiles with experimental results for laser powers of 7 kW, 7.5 kW, and 8 kW, respectively. \( W_{A1}, W_{A2}, W_{A3}, W_{a1}, W_{a2}, \) and \( W_{a3} \) denote the widths of the upper surface of the melt pool. \( W_{B1}, W_{B2}, W_{B3}, W_{b1}, W_{b2}, \) and \( W_{b3} \) denote the widths of the necking zone of the melt pool. \( W_{D1}, W_{D2}, W_{D3}, W_{d1}, W_{d2}, \) and \( W_{d3} \) denote the widths of the lower surface of the melt pool. The simulation and experimental results are both typical “nail” shapes, and the appearance tends to be consistent.

![Figure 6. Comparison of simulated cross-sectional profile and experimental cross-sectional profile: (a) laser power 7 kW, (b) laser power 7.5 kW, (c) laser power 8 kW.](image1)

The experimental results of AH36 steel hybrid welding were compared with the simulation results to further verify the reliability of the simulation results. As shown in Figure 7, the magnitudes of the simulated and experimental melt pool widths for the three laser powers are similar, and the variation trend is consistent. The simulation results are slightly larger than the experimental results, which agrees with Li et al. [27]. With increasing laser power, the surface of the melt pool and the width of the necking zone increased at first, reaching a maximum value at 7.5 kW laser power. When the laser power was increased to 8 kW, the width of the upper surface of the melt pool and the necking zone shrank slightly. The width of the molten pool’s bottom continued to grow as the laser power increased from 7 kW to 8 kW. As the laser power increased, the energy in the molten pool increased and the weld width increased. The workpiece collapsed as the laser power increased to 8 kW, some of the energy was transferred to the melt pool’s bottom, the upper part of the melt pool’s energy decreased, and the bottom collapse energy increased. The results in Figure 5 further demonstrate the reliability of the simulation results.

![Figure 7. Simulation and experimental results of molten pool width.](image2)
Figure 8a shows the total power share of the input laser power. Increasing the laser power increases its total power share. Figure 8b shows the total area share of the laser zone area. The laser area share of the lower part of the weld is smaller than the laser power share, indicating that some of the laser energy acts on the upper part of the weld to preheat the molten pool below the arc and increase the arc area. Under the same conditions of other process parameters, the laser area share gradually increased when the laser power was increased from 7 kW to 7.5 kW. When the laser power continued to increase to 8 kW, the laser zone area accounted for a smaller percentage, the laser power was too large, the bottom of the weld collapsed, and the melt pool energy moved down to the collapse, resulting in a reduction in laser area energy.

![Figure 8](image1)

**Figure 8.** (a) Laser power share, (b) laser zone area share.

With the arc parameters unchanged, changing the laser power can affect the energy distribution inside the hybrid melt pool. The energy density of the molten pool affects the temperature of the molten pool. Combined with the driving force equation, temperature affects the magnitude of the driving force. Therefore, it is necessary to study the energy distribution in the molten pool by analyzing the melt flow as well as the keyhole and depth variation of the melt pool [28]. Through this simulation, after 30 ms, the melt pool enters the stabilization phase, and the melt flow is in dynamic equilibrium within a certain range. Figure 9 shows the temperature and velocity at the line segment measured by selecting different positions of the line segment at 35 ms of simulation. The WA line is located at the maximum width of the molten pool surface, perpendicular to the welding direction; the DL line is located directly below the keyhole, along the depth of the molten pool.

![Figure 9](image2)

**Figure 9.** Simulation of melt pool at 35 ms.

Figure 10 shows the temperature versus velocity variation at the widest part of the molten pool surface from the center to the edge, perpendicular to the welding direction, at the simulated 35 ms. As shown in Figure 10a, the molten pool temperature gradually
decreases from the center of the arc to the boundary. When the laser power is 7.5 kW, the molten pool surface temperature is higher than when it is 7 kW and 8 kW. As shown in Figure 10b, the melt flow rate on the molten pool surface decreases from the center of the molten pool to the edge of the melt pool. At laser power of 7.5 kW, the molten pool surface flow rate is higher than that at 7 kW and 8 kW. The flow rate below the arc is maximum under the effect of molten droplet impact and surface tension. In general, as the laser power increases, the molten pool absorbs more energy, the temperature increases, and the Marangoni force in the molten pool increases [19], leading to a more pronounced Marangoni effect and an increase in the melt flow rate. In this experiment, when the laser power is increased to 8 kW, the workpiece is collapsed, and some energy is shifted downward to the collapse. The molten pool energy is shifted downward, the energy in the upper arc region of the melt pool is reduced, the surface temperature of the molten pool decreases, and the molten pool rate decreases.

Figure 10 shows the temperature versus velocity variation of the molten pool directly below the keyhole along the depth direction at the simulated 35 ms. As shown in Figure 10a, the molten pool temperature below the keyhole gradually decreases as the depth increases. The molten pool temperature at laser power 7.5 kW is higher than that at 7 kW and 8 kW. As shown in Figure 10b, the melt at the edge of the keyhole zigzagged downward, and the melt below the keyhole flowed straight downward. The high-energy-density laser light is refracted in the keyhole several times, which promotes the absorption of laser energy by the keyhole. As the laser power increases to 7.5 kW, the melt flow rate increases below the keyhole, the molten pool energy shifts downward, and the temperature increases at the same depth. As the laser power increases to 8 kW, the workpiece is collapsed, the melt pool energy continues to move down to the collapsed area, and the loss of laser energy causes the melt pool temperature to decrease.

Figure 11 shows the temperature versus velocity variation of the molten pool directly below the keyhole along the depth direction at the simulated 35 ms. As shown in Figure 11a, the molten pool temperature below the keyhole gradually decreases as the depth increases. The molten pool temperature at laser power 7.5 kW is higher than that at 7 kW and 8 kW. As shown in Figure 11b, the melt at the edge of the keyhole zigzagged downward, and the melt below the keyhole flowed straight downward. The high-energy-density laser light is refracted in the keyhole several times, which promotes the absorption of laser energy by the keyhole. As the laser power increases to 7.5 kW, the melt flow rate increases below the keyhole, the molten pool energy shifts downward, and the temperature increases at the same depth. As the laser power increases to 8 kW, the workpiece is collapsed, the melt pool energy continues to move down to the collapsed area, and the loss of laser energy causes the melt pool temperature to decrease.

Figure 11. At simulated 35 ms: (a) Temperature of DL line, (b) speed of DL line.

Figure 11. At simulated 35 ms: (a) Temperature of WA line, (b) speed of WA line.
Since the main driving force for keyhole formation is the recoil pressure of the metal vapor generated by the high-energy-density laser, the laser power is the key factor affecting the lock hole depth [29]. Figure 12 shows the evolution of the keyhole at a laser power of 7.5 kW. At $T = 2$ ms, the laser acts on the workpiece, and the temperature in the laser radiation zone increases rapidly. At $T = 3$ ms, the temperature of the laser radiation area increased to 3100 K, and the metal vapor was generated. Due to the generation of metal vapor, the metal surface is recessed, and the recess becomes deeper and deeper under the action of recoil pressure, eventually forming a keyhole. As the welding process progresses, the keyhole size increases. The keyhole depth grows more pronounced than width. After the size of the keyhole increases to a certain extent, it will no longer increase and enter the oscillation stage.

![Temperature(k)](image)

Figure 12. Keyhole evolution at laser power 7.5 kW.

As shown in Figure 13, the transient evolution of the keyhole depth at three laser powers was obtained by simulation. It can be found that the keyhole depth increases rapidly and linearly from 0 ms to 8 ms. At this time, the recoil pressure is much higher than the surface tension, buoyancy, and other resistances that prevent the formation of the keyhole. At 8–30 ms, the growth trend of keyhole depth decreased, showing an oscillating growth state. At this time, with the increase of keyhole depth, resistance such as surface tension gradually increases, and the growth of keyhole depth slows down. After 30 ms, the recoil pressure and resistance reach a dynamic equilibrium, and the keyhole enters a stable oscillation state. In this stage, the keyhole depth varies regularly within a certain range. Analyzing the keyhole depth variation curve under different laser powers, it is found that increasing the laser power can shorten the time for the keyhole to enter the oscillation state. In addition, as the laser power increases, the keyhole depth also increases. Increasing the laser power can effectively increase the energy in the keyhole and increase the recoil pressure.
pressure. The increased recoil pressure increases the keyhole depth and the increasing trend of the keyhole depth.

![Figure 13. Keyhole depth for different laser powers.](image)

Figure 13 shows the variation of the molten pool depth below the keyhole with time for three laser powers. The results show that the depth of the molten pool increases rapidly and linearly from 0 ms to 8 ms. At 8–30 ms, the molten pool growth rate gradually decreases, and it is inclined growth at this time. After 30 ms, the molten pool depth no longer changes and enters a state of equilibrium. The changes of the molten pool depth in each stage correspond to the changes of the keyhole depth in each stage. As the laser power increases, the depth of the molten pool under the keyhole increases. The multiple reflections of the laser in the keyhole promote the absorption of the laser by the keyhole. With the increase of laser power, the depth of the keyhole increases, the laser energy is delivered to the deeper layer of the workpiece, and the melt pool depth increases [29].

![Figure 14. Depth of the melt pool below the keyhole at different laser powers.](image)
Figure 15 characterizes melt flow in a longitudinal section of a hybrid weld using various laser powers. The molten pool below the keyhole did not completely penetrate the workpiece at three laser powers, but the molten pool behind the keyhole did, which is consistent with the representation in Figure 14. As shown in Figure 15, the molten metal on the surface of the molten pool flows from the center of the arc to the rear of the molten pool, creating backflow under the influence of surface tension. Due to the impact of the molten droplet, the center of the arc produces an obvious depression zone. When the laser power is 7 kW, the molten metal in the depression area flows downward and produces backflow in the necking area. When the laser power is increased to 8 kW, the backflow gradually disappears, and the molten metal flows partly to the rear of the melt pool and partly to the melt pool below the keyhole. The width of the arc zone increases, and the depth of the laser zone increases. In the lower laser zone of the molten pool, the melt flows downward in the melt pool below the keyhole and backward and downward at the bottom of the molten pool. This action transfers energy deeper into the unmelted region, and eventually, the bottom metal melts. Combining the temperature profile and velocity profile of the D1 line, it is found that as the laser power increases, the temperature at the bottom of the molten pool increases, and the melt downward flow rate increases, prompting the mixed melt pool to completely penetrate the workpiece.

Figure 16 shows the measurement position of the microstructure. Four regions, D1, D2, D3, and D4, are selected on the cross section of the weld. Figure 17 shows the microstructure of the welded joint under the laser power of 7.5 kW. It can be seen from Figure 17a,c that the weld structure is a columnar solidified structure. In addition, the weld is mainly composed of bainite and ferrite. During laser-MIG hybrid welding of AH36 steel, the temperature of the molten pool rises rapidly and exceeds the melting point in a short time. When the hybrid heat source moves forward, the molten pool temperature behind the heat source decreases rapidly; heat is transmitted from the center of the weld at a higher temperature to the direction of the fusion line at a lower temperature. Moreover, the formed crystal dominant growth direction is opposite to the heat conduction direction. Then, it forms a columnar solidified structure. The columnar solidification structure at the root of the weld is smaller than that at the face of the weld because the cooling rate at the root of the weld is faster and the growth time of the columnar structure is shorter. It can be seen from Figure 17b,d that the heat-affected zone mainly contains martensite. This is caused by the rapid temperature rise and cooling of the heat-affected zone during laser-arc hybrid welding.
downward in the melt pool below the keyhole and backward and downward at the bottom of the molten pool. This action transfers energy deeper into the unmelted region, and eventually, the bottom metal melts. Combining the temperature profile and velocity profile of the D L line, it is found that as the laser power increases, the temperature at the bottom of the molten pool increases, and the melt downward flow rate increases, prompting the mixed melt pool to completely penetrate the workpiece.

Figure 15. Melt flow in the longitudinal section of a hybrid weld with different laser powers.

Figure 16 shows the measurement position of the microstructure. Four regions, D1, D2, D3, and D4, are selected on the cross section of the weld. Figure 17 shows the microstructure of the welded joint under the laser power of 7.5 kW. It can be seen from Figure 17a,c that the weld structure is a columnar solidified structure. In addition, the weld is mainly composed of bainite and ferrite. During laser-MIG hybrid welding of AH36 steel, the temperature of the molten pool rises rapidly and exceeds the melting point in a short time. When the hybrid heat source moves forward, the molten pool temperature behind the heat source decreases rapidly; heat is transmitted from the center of the weld at a higher temperature to the direction of the fusion line at a lower temperature. Moreover, the formed crystal dominant growth direction is opposite to the heat conduction direction. Then, it forms a columnar solidified structure. The columnar solidification structure at the root of the weld is smaller than that at the face of the weld because the cooling rate at the root of the weld is faster and the growth time of the columnar structure is shorter. It can be seen from Figure 17b,d that the heat-affected zone mainly contains martensite. This is caused by the rapid temperature rise and cooling of the heat-affected zone during laser-arc hybrid welding.

Figure 16. Location of microstructure selection.

Figure 17. Microstructure of joint with 7.5 kW laser power: (a) D1 point, (b) D1 point, (c) D3 point, (d) D4 point.

Figure 18 shows the microstructure of the weld head and the heat-affected zone under three laser powers (P = 7 kW, P = 7.5 kW, P = 8 kW). It can be seen that the microstructure of the same position under three laser powers is the same because the change of laser power is small, and the change of microstructure and size is not obvious.

Figure 19 shows the microhardness values of laser-MIG hybrid welding joints under different laser powers. It can be seen from Figure 19a that the heat-affected zone is dominated by martensite, where the average microhardness is the largest; it is 421 HV. The composition of the weld zone is mainly bainite and ferrite, and its average microhardness is 372 HV. The average microhardness of base metal is the lowest; it is 231 HV. It can be seen from Figure 19b that the microhardness of the weld center in the laser zone is greater than that in the arc zone. The average microhardness at the top of the weld is 350 HV, and that at the root of the weld is 381 HV.
5. Conclusions

The conclusion of this paper relates to the pure argon mixed welding of AH36 steel with thickness of 5 mm, as follows:

Figure 18. Microstructure of different laser powers: (a) 7 kW, D1 point; (b) 7 kW, D2 point; (c) 7.5 kW, D1 point; (d) 7.5 kW, D2 point; (e) 8 kW, D1 point; (f) 8 kW, D2 point.

Figure 19. Hardness curves of laser-MIG hybrid welded joints under different laser powers: (a) weld center along the cross-section direction; (b) weld center along the depth direction.
5. Conclusions

The conclusion of this paper relates to the pure argon mixed welding of AH36 steel with thickness of 5 mm, as follows:

(1) The results show that the weld forming effect is better when the laser power is 7.5 kW in the range of sensitive laser power. When the laser power is 7 kW, the weld bottom is poorly formed; when the laser power is 8 kW, the bottom of the welding seam collapses.

(2) Within the sensitive laser power range, when the laser power increases from 7 kW to 7.5 kW, the width of the molten pool increases, and the temperature rises. When the laser power increases from 7.5 kW to 8 kW, the width of the arc pool decreases, the width of the laser zone increases, and the temperature decreases.

(3) After the initial formation of the keyhole, its depth gradually entered the stage of linear growth, oscillation growth, and oscillation balance. Increasing the laser power can effectively shorten the time of the two growth stages and allow the keyhole to enter the balance stage earlier.

(4) In the longitudinal section, the melt pool fluid directly below the arc flowed downward and formed reflux in the neck zone. As the laser power increased, the backflow gradually decreased until it disappeared. Part of the molten metal flowed to the melt pool tail and another part flowed to the keyhole.

(5) During the oscillation balance state of the keyhole, the molten metal at the bottom of the keyhole flowed to the molten pool root in the reverse direction of welding, and it can also promote weld penetration.

(6) The heat-affected zone is dominated by martensite, where the average microhardness is the largest; it is 421 HV. The composition of the weld zone is mainly bainite and ferrite, and its average microhardness is 372 HV. The average microhardness of base metal is the lowest; it is 231 HV.

Author Contributions: Conceptualization, H.J., X.Y. and P.Z.; methodology, H.J. and X.Y.; validation, Z.Y., X.Y. and P.Z.; formal analysis, H.J.; investigation, H.J., D.W., X.Q. and X.H.; writing—original draft preparation, H.J.; writing—review and editing, X.Y.; project administration, X.Y. and K.F.; funding acquisition, P.Z., Z.Y. and K.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (grant number 52075317, grant number 51905333), Shanghai Science and Technology Committee Innovation Grant (grant number 19511106402), Shanghai Sailing Program (grant number 19YF1418100), State Key Laboratory of Metal Material for Marine Equipment and Application (grant number SKLMEA-K201906), a Karamay Science and Technology Major Project (grant number 2018ZD002B), and an Aid for Xinjiang Science and Technology Project (grant number 2019E0235).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.
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