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Study on keyhole and melt flow behaviors of laser welding of aluminum under reduced ambient pressures

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Abstract. Laser welding of aluminum alloy under reduced ambient pressure can produce less porosity defects. In this paper, the effect of reduced ambient pressures on porosity was investigated by a combination of experimental and numerical method. A novel numerical model was proposed to describe the keyhole and melt flow behaviors under reduced ambient pressures. Numerical results showed that, compared with atmospheric pressure, reduced ambient pressure would produce a more stable keyhole. The vortex of melt flow in molten pool became unapparent and even disappeared under reduced ambient pressures. The flow velocity of the melt on the keyhole wall became faster under reduced ambient pressures. The difference between boiling point and melting point decreased under reduced ambient pressure, which made a contribution to the formation of a thinner keyhole wall and hence improved the stability of keyhole. Higher recoil pressure would be produced under reduced ambient pressures, which was responsible for the weakened vortex and enhanced melt flow velocity. The formation of porosity during laser welding process could be effectively inhibited based on the above combined effects.

Keywords: Laser welding, Reduced ambient pressure, Keyhole, Melt flow, Porosity

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1. Introduction

Nowadays, deep penetration laser welding has been widely applied to aerospace, nuclear power, automotive, shipbuilding and other important industries [1]. For aluminium alloys, the main challenge of deep penetration is the formation of porosity due to the periodic plasma and unstable molten pool. Numbers of investigations have been conducted to inhibit the plasma and improve the stability of molten pool. The dual-spot laser welding is one of the effective methods, however, the penetration cannot be satisfactory [2]. In addition, the laser welding under reduced ambient pressure exhibits the great potential for improving quality of weld formation and processing stability during the laser deep penetration welding process [3]. Katayama et al. carried out a research on the laser welding characteristics of aluminum alloy under reduced ambient pressures. They found that the penetration depth grew sharply...
and the state of molten pool surface became calmer with the decrease of ambient pressure [4]. Hirano et al. found that the evaporation rate was reduced under reduced ambient pressure and the temperature of evaporation surface was lower than or around the boiling point [5]. The aforementioned research demonstrates that the ambient pressure has great effects on the dynamics of keyhole, molten pool and metallic vapor during laser welding process.

Many numerical models have been proposed for describing the physical process of deep penetration laser welding. These numerical models mainly considered the heat transfer behaviors and the free surface of keyhole in the welding process, which were used to predict the transient evolution of the self-consistent keyhole and molten pool dynamics [6]. Recently, Tan et al. developed a multiphase model for dynamics of keyhole, weld pool and vapor plume for deep penetration laser welding. Their transient multiphase model could describe the physical process more clearly [7]. Nevertheless, few of the comprehensive models have taken the effect of ambient pressure on the keyhole dynamics and molten pool behaviors into consideration.

In this paper, the laser welding characteristics of aluminium alloy under different pressures had been investigated, and a novel 3D multiphase transient model considering the effect of ambient pressure on the keyhole dynamics and molten pool behaviors had been proposed and validated.

2. Experimental procedure
Materials used in the present work were A 5083 aluminum alloy with the dimension of 240 mm (length) × 120 mm (width) × 10 mm (height). The equipment of laser welding under reduced ambient pressure was shown in Figure 1. The laser welding process was performed under various ambient pressure (101, 103, 105 Pa) within the vacuum chamber for comparison while the laser power and welding speed were constant (2kW and 0.8 m/min, respectively.) A -3mm defocused distance of laser beam was applied.

![Figure 1. The equipment of laser welding under reduced ambient pressure](image1)

![Figure 2. The solution domain and boundary conditions](image2)

3. Numerical simulation modeling
The governing equations of fluid dynamics and boundary conditions were solved numerically using commercial CFD software ANSYS Fluent Release 15.0, which is based on the finite volume method. The user-defined functions were written by C++ language in order to introduce the additional energy and momentum sources. The volume of fluid method was used to describe the flow physics of the liquid/vapor interface. The solution domain and boundary conditions for calculation are shown in Figure 2.

The dynamic behaviors of the keyhole and melt flow in the molten pool are mainly affected by two
primary driving forces: the recoil pressure and the surface tension. The recoil pressure (crucial force for keyhole forming), coherently related to the boiling point of materials, can be described mathematically as follow [8]:

$$P_r = 0.54P_{amb}\exp\left(\frac{\Delta H_{lv}}{RT_b}\left(T_b - T\right)\right)$$  \hspace{1cm} (1)

where, $P_{amb}$ is the ambient pressure, $R$ is the universal gas constant, $\Delta H_{lv}$ is the latent heat of evaporation, $T_b$ is the boiling point of the base metal under $P_{amb}$, and $T$ is the liquid temperature. The boiling point $T_b$ under different ambient pressures can be approximately calculated according to the Clausius-Clapeyron Equation:

$$\frac{d \ln(P)}{dT_a} = \frac{\Delta H_p}{RT_a}$$  \hspace{1cm} (2)

where, $P$ is the ambient pressure, $\Delta H_p$ is the phase change enthalpy, which can be treated as a constant, $R$ is the universal gas constant. The calculated results were shown in Figure 3.

![Figure 3. Boiling point under different ambient pressures](image)

![Figure 4. Weld appearances and cross-sections of joints under different pressures](image)

4. Results and discussion

4.1 Welding characteristics under different ambient pressures

The weld appearances, cross-sections and penetration depth of joint produced by atmospheric pressure and reduced pressures were shown in Figure 4. With the decrease of ambient pressure, the weld seam became narrower and the penetration depth become larger.

The penetration depth could reach 8.7 mm when the workpiece was welded under the pressure of $10^1$ Pa while only 4.9 mm under atmospheric pressure, as illustrated in Figure 4. A great difference was observed among seams produced under different ambient pressures. The weld beads profile of reduced ambient pressure welding was observed to present very parallel edges, compared with the "nail-head" shape weld bead obtained by the atmospheric pressure welding. It could be found that a severe metallic evaporation occurred under atmospheric pressure and this could be proven by the existence of plasma plume with large volume as referred in Figure 5(a). With the decrease of ambient pressures, the plasma plume were suppressed (as illustrated in Figure 5(b)) and even vanished under $10^1$ Pa as illustrated in Figure 5(c).
The ambient pressure has a significant influence on the formation of porosity in weld seam, as shown in Figure 6. Under atmospheric pressure, dense porosities (illustrated by the white areas) with large size were observed through the whole weld seam. With the decrease of the ambient pressures, the number and dimension of formed porosities under atmospheric pressure both was decreased sharply.

4.2 Simulation analysis
To investigate the effect of ambient pressure on the keyhole dynamics and molten pool behaviors, a novel model was proposed. In order to validate the numerical models developed in this study, the weld profiles obtained by laser welding under different pressures were compared with those from experiments. The comparative results were shown in Figure 7. A good accordance was existed between the experimental and numerical weld profiles. This indicated that the numerical models developed in this research was reasonable.

Figures 8, 9, 10 showed the transient keyhole evolution during laser welding under atmospheric pressure (10^5 Pa), 10^3 Pa and 10^1 Pa, respectively. It could be observed that there were less humps in the keyhole wall with the decrease of ambient pressures. In addition, the width and depth of keyhole both became larger due to a higher recoil pressure, which meant reduced ambient pressure increased the ratio of laser beam absorptivity. Figure 11 showed the variations of the keyhole depths during laser welding under different pressures. It could be seen that the variation of the keyhole depths became smaller under
the reduced ambient pressure, which indicated a higher welding process stability occurred. Thus, the formation of porosity generated in laser welding process could be effectively inhibited, as shown in Figure 6.

![Figure 11](image1.png)

**Figure 11.** The keyhole depth under different ambient pressures

Apart from these, the average temperatures of keyhole wall was around 2400K under atmospheric pressure as shown in Figure 12(a). When the ambient pressure was reduced to $10^5$Pa, the average temperatures of keyhole was 1700K, and even 1360K when the ambient pressure was $10^3$Pa, as shown in Figure 12(b) and (c). Therefore, the energy which was employed to vaporize the molten metal decreased and finally led to a deeper penetration, as shown in Figure 4.

![Figure 12](image2.png)

**Figure 12.** Temperature distributions of molten pool under different ambient pressures
(a) $10^5$Pa; (b) $10^3$ Pa; (c) $10^1$ Pa.

![Figure 13](image3.png)

**Figure 13.** Melt flow along the longitudinal section for laser welding under different ambient pressure
(a) $10^5$Pa; (b) $10^3$ Pa; (c) $10^1$ Pa.

Figure 13 showed the dynamic behaviors of the melt flow in the molten pool along the longitudinal section. Figure 13(a) showed that the melt flow pattern during laser welding under atmospheric pressure, it could be seen that two vortices were existed at the rear keyhole wall. The vortices would impacted the keyhole wall and caused the potential collapse of keyhole. In addition, the vortex of molten pool became unapparent (as seen in Figure 13(b)) and even disappeared (as seen in Figure...
13(c)) under reduced ambient pressures. The weaken vortex during laser welding would promote overflow of the contained gas and ensure a more stable welding process. It could be seen that the flow velocity of the melt on the keyhole wall became faster under reduced ambient pressures. The difference between boiling point and melting point decreased under reduced ambient pressures (as shown in Figure 3), which made a contribution to the formation of a thinner keyhole wall (as shown in Figure 13(b) and (c)) and finally improved the stability of keyhole.

5 Conclusions

The laser welding characteristics of aluminum alloy under different ambient pressures were investigated. Novel and verified numerical models were developed to describe the keyhole dynamics and melt flow behaviors to explain the laser welding characteristics of aluminum alloy under different ambient pressures. The obtained conclusions were listed as follows:

(1) Laser welding under reduced ambient pressure could improve the welding characteristics obviously. With the decrease of ambient pressure, the weld seam became narrower and deeper with less porosity defects.

(2) A novel numerical model was developed to describe the melt flow and keyhole dynamics behaviors during laser welding under different ambient pressures. Less humps with deeper depth of keyhole occurred with the decrease of ambient pressure.

(3) The average temperature of keyhole wall dropped sharply and the difference of boiling and melting point became smaller with the decrease of ambient pressure, which made a contribution to form a thinner keyhole wall and finally improve the stability of molten pool.

(4) The vortexes in the molten pool were weakened and the flow velocity of the melt on the keyhole wall became faster under reduced ambient pressure, which was in favor of a more stable molten pool.

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