Study on the distribution, element characteristics, and formation mechanism of porosity during laser welding for Ti-6Al-4V bottom-locking joint

Xufeng Kang · Tingyan Yan · Leilei Wang · Qiyu Gao · Xiaohong Zhan

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Abstract
The bottom-locking joint is widely used in the aerospace manufacturing field as an imperative connection structure. The laser welding experiment for the Ti-6Al-4V titanium alloy bottom-locking joint is carried out in the present paper. Meanwhile, porosity in the weld seam including the process porosity and metallurgical porosity is investigated. Furthermore, it is novel that the distribution, element characteristics, and formation mechanism of process porosities and metallurgical porosities in the bottom-locking joint are comprehensively analysed based on the porosity morphology, microstructure, and element analysis of the resultant bottom-locking joints. The process porosity, which mainly appeared in the weld seam centre, is formed by the combined effect of two mechanisms which closely related to the dynamic behaviour of the molten pool and the stability of the keyhole. Besides, a large number of micropores with a diameter of 2–5 µm are observed on the surface of the process porosity, whose formation is related to the evaporation of elements. Moreover, the tensile stress generated during the solidification and shrinkage of the molten metal is the main factor leading to microcracks in the micropores. The nucleation characteristics of bubbles cause metallurgical porosities to be mainly distributed at the bottom of the weld seam.

Keywords Ti-6Al-4V · Laser welding · Bottom-locking joint · Porosity · Formation mechanism

1 Introduction

Ti-6Al-4V titanium alloy is extensively used in the modern aerospace industry, as critical components [1, 2], due to its excellent structural properties such as low density, high specific strength and outstanding corrosion resistance [3, 4]. The bottom-locking joint, composed of a butt joint with a certain depth and a lap joint, is the main connection form of the fork ring and the short shell of the launch vehicle tank [5–7]. Compared to other welding methods, laser welding is suitable for welding large-scale titanium alloy structural components in aerospace due to its high energy density, high welding efficiency, small welding deformation and outstanding welding integrity [8–11]. However, subsurface defects like porosity can hardly be avoided in the fusion welding [12–16]. Due to the active elements, highly saturated vapour pressure and the instability of the keyhole, two types of porosity, metallurgical porosities and process porosities, will be easily generated during the laser welding process of Ti-6Al-4 V bottom-locking joint which is a non-penetrating welding structure [17–19].

Many scholars have carried out relevant research on the porosity defect during the laser welding process. Zhao et al. [20] found that the formation of process porosity is because the tip of the keyhole is easily closed by the molten metal stream and separated to form a process bubble. Chen et al. [21] focused on the metallurgical porosity defects under different welding parameters to study the influence of the laser power and weld speed on the porosity distribution, formation mechanism and mechanical properties during the dual laser bilateral synchronous welding process. Ke et al. [22] presented a numerical framework of process porosity formation and methods to suppress porosity in laser oscillating welding. Huang et al. [23] have reported the instability of the keyhole and bubble being captured by the solidification interface, which is believed to be the main factors affecting the formation of porosity in laser welding. In addition, the effect of magnesium content on keyhole-induced porosity formation and distribution in aluminium alloys laser welding was also studied, where weld depth increases in the welding direction with increasing Mg, and a longer time is required to reach the quasi-steady state [24]. Panwisawas et al. [25] established a physics-based
model to simulate the formation of the keyhole and porosity during laser welding of Ti-6Al-4V titanium alloy. Qi et al. [7] analysed the microstructure and tensile performance of the TA15 titanium alloy bottom-locking joints by laser welding.

The above articles mainly explored on the problem of porosity defects during laser welding process of butt joints. However, few studies have been conducted on the distribution characteristics and formation mechanism of porosity during laser welding of titanium alloy bottom-locking joint. Therefore, this paper aims at the porosity defect of laser welding for Ti-6Al-4V bottom-locking joint, establishing the relationship between morphology, distribution, element characteristics and formation mechanism of porosity.

In the present paper, the process porosities and metallurgical porosities in the bottom-locking joint by laser welding are observed and analysed using optical microscopy (OM), scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS). Based on the results, the distribution, element characteristics and formation mechanism of porosity during laser welding of Ti-6Al-4V bottom-locking joint are deeply revealed.

2 Experimental work

2.1 Materials

The material used in this paper is Ti-6Al-4V titanium alloy, and the specific chemical composition is shown in Table 1. The base material cross-section and EDS results are shown in Fig. 1. Two sizes of base metal are used in the experiment, one is plates with a dimension of 500×80×1.2 mm³, and the other is 500×50×2.5 mm³ with a 500×1.0×0.8-mm³ bulge on the side. The dimensions of weldments are shown in Fig. 2.

### 2.2 Experiment equipment and method

The TruDisk-12003 laser machine and KUKA robot are performed in the laser welding experiment. The movement of the laser head is controlled by the KUKA robot (Fig. 3).

Prior to welding, the weldment surface is brushed with abrasive paper and then wiped with acetone to remove impurities. The laser welding for the bottom-locking joint is a kind of laser self-fusion welding. During the welding process, the laser penetrates the plates and melts the bulge to achieve the purpose of bottom locking, and what Fig. 4 shows is the schematic diagram of laser welding for the Ti-6Al-4 V bottom-locking joint. For the welding parameters, the laser power is 0.5 kW, the defocus is +2 mm, the welding speed is 1.0 m·min⁻¹ and the welding gap ranges from 0 to 0.2 mm. During the welding process, the pure Ar is used as a shielding gas to prevent the air from both the upper and bottom of the molten pool. The detailed process parameters of the laser welding experiment are shown in Table 2. The metallographic specimens were obtained by wire electrical discharge machining after the welding experiment and then corroded by Keller’s reagent. Finally, the metallographic specimens were analysed by OM, SEM and EDS.

| Table 1 Chemical composition of Ti-6Al-4V titanium alloy (wt.%) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
|                | Al  | V   | Fe  | O   | C   | N   | H   |
|----------------|-----|-----|-----|-----|-----|-----|-----|
|                | 5.5 | 2.5 | ≤0.3| ≤0.02|≤0.1|≤0.05|≤0.015|
|                | 6.8 | 4.3 |     |     |     |     |     |

**Fig. 1** Ti-6Al-4V titanium alloy: (a) base metal cross-section; (b) EDS results of base metal
3 Results and discussion

3.1 Distribution characteristics of porosity

Figure 5 clearly shows the morphology of the process porosities and metallurgical porosities in the weld seam cross-section. The process porosities are generally large and roughly ellipsoidal shape, mainly distributed in the weld seam centre. At the same time, the metallurgical porosities with small size and regular spherical shape are scattered around the process porosities. According to the analysis, the process porosities are mainly due to the poor stability of the laser keyhole. During the welding process, the keyhole is instantly unstable and collapses, resulting in the formation of process porosities, which are distributed in the weld seam centre.

Figure 6 illustrates the morphology of the metallurgical porosities. There are no obvious process porosities in the cross-section, but a few metallurgical porosities are distributed at the bottom of the weld seam. Compared with process porosities, metallurgical porosities are smaller in size and have smooth inner walls.

3.2 Formation mechanism of process porosity

Figure 7a illustrates the morphology of the process porosities whose sizes range from 130 to 380 µm, and the shapes are full ellipses. The microstructure of the inner wall of the process porosity and the EDS results detected at the marked zone 1 and zone 2 are shown in Fig. 7c, d. According to the EDS results, the substance in zone 1 should be an oxide or other impurity. Besides, Fig. 7 reveals that the content of the Al element was reduced, while the content of the V element increased compared with the base metal.

Given the above analysis of the morphology, element characteristics of process porosity, the formation mechanism of process porosity formed during laser welding of
the bottom-locking joint is illustrated in Fig. 8. It is worth pointing out that the oxidation film on the bulge is hard to be polished thoroughly, resulting in the instability of the molten pool and the keyhole. Under the action of the high-energy laser heat source, the metal on the surface of the workpiece will melt and produce metal vapour. The keyhole is formed under the continuous induction of the reaction force generated during the continuous injection of metal vapour, and it will be inclined relative to the welding direction during the welding process. Besides, because the laser is continuously reflected and absorbed on the keyhole wall, the diameter of the keyhole will gradually decrease along the plate thickness direction.

Figure 8b–g show that the formation of process porosity is the result of the combined effect of two mechanisms in the process of laser welding the Ti-6Al-4 V bottom-locking joint. As described in Fig. 8b–d, one is that the tip of the keyhole is closed by the strong molten metal vortex, which causes the inner wall of the keyhole to stick, thereby the process bubble is separated; the other is that the local laser energy concentration causes the metal element at a certain position on the front wall of the keyhole to evaporate, forming high-speed metal vapour streams. The back wall of the keyhole is dented under the impact of the metal vapour stream, and involves the shielding gas, then collapses under the dynamic behaviour of the molten metal vortex, forming a process bubble. Figure 8e–g illustrate the whole process of this formation mechanism.

Whether the bubbles can turn into porosities depends on the escape velocity of the bubbles and the solidification velocity of the molten metal. When the escape velocity of the bubbles is greater than the solidification velocity of the molten metal, the bubbles can escape and no porosities will be formed in the weld seam. Nevertheless, the fast welding speed leads to a fast solidification velocity of the molten metal, and the bubbles are easily captured by the solidified metal and remained in the weld seam. The Stokes Law [26] is expressed as follows:

$$V_E = \frac{2}{9} \times \left( \frac{\rho_L - \rho_G}{\eta} \right) \rho_G g R^2$$

where $V_E$ is the escape velocity of the bubble, $\rho_L$ is the density of the molten metal, $\rho_G$ is the density of the gas in the molten pool, $g$ is the acceleration of gravity, $R$ is the radius of the bubble and $\eta$ is the viscosity of the molten metal.

Process porosity is large in scale and therefore has a large escape velocity. However, the solidification process of molten metal during laser welding is also very rapid. These two factors together lead to the distribution characteristics of process porosities, which process porosities mainly distribute in the weld seam centre.

![Fig. 4](image)

**Table 2** Laser welding test parameters of bottom-locking joint

| Case | Gap (mm) | Laser power (kW) | Welding speed (m·min⁻¹) | Upper shielding gas flow (L·min⁻¹) | Bottom shielding gas flow (L·min⁻¹) |
|------|----------|------------------|--------------------------|----------------------------------|-----------------------------------|
| 1    | 0        | 0.5              | 1.0                      | 30                               | 5                                 |
| 2    | 0.05     | 0.5              | 1.0                      | 30                               | 5                                 |
| 3    | 0.1      | 0.5              | 1.0                      | 30                               | 9                                 |
| 4    | 0.2      | 0.5              | 1.0                      | 30                               | 9                                 |
In addition, the morphology and element characteristics of process porosity can also be explained. The process bubble is essentially a cavity formed by the collapse of the keyhole, so it has the characteristic of large size. Since the formation of process porosity is the result of the joint action of two mechanisms, some shielding gas or metal vapour, which makes the process bubble maintain a high and stable saturated vapour pressure, is always involved when the process bubble is formed. Meanwhile, under the action of the surface tension of the surrounding molten metal, the process bubble tends to shrink into a spherical shape. When the produced process bubble is long strips, the bubble will shrink into several spheres in series, and finally forms chain-spherical process porosity, as shown in Fig. 9a.

Figure 9b illustrates the microstructure of the process porosity and the EDS results in zone 1. It is worth noting that there are many micropores with a size of 2–5 μm, and the EDS results of the micropore reveal that there is no obvious difference in element contents compared with the inner wall of the process porosity. The element characteristics and the formation mechanism of the micropore are explained in Fig. 9c-f. For the element characteristics, that is, the decrease of Al element and the increase of V element in the inner wall of the process porosity. This is because the process bubble contains V and Al vapour inside, and the freezing point of the V element (1890 °C) is relatively high causing V vapour to condense on the inner wall of the process bubble during the cooling stage. The condensation of V vapour causes the vapour pressure in the process bubble to drop. At the same time, the Al vapour has not yet solidified because of its low freezing point (660 °C), so it quickly escapes under the action of the pressure difference between the inside and outside of the process bubble. This difference in the freezing point of metal elements leads to
the accumulation and loss of elements in the inner wall of the process porosity.

In view of the above analysis of element characteristics of the process porosity, the formation mechanism of these micropores can be explained in depth. The formation process of the micropore goes through three stages: equilibrium stage, negative pressure stage and burst stage. When the molten pool has not been cooled and solidified, the vapour pressure inside and outside the bubble is roughly equal, and it is in the equilibrium stage; thereafter, as the V vapour condenses, the vapour pressure inside the bubble decreases, the pressure difference between the inside and outside of the bubble causes the Al vapour to compress, and it is in the negative pressure stage; compressed Al vapour ultimately formed strong streams, which break through the bubble causing the gaps on the surface of the bubble—it is in the burst stage. Because the surrounding molten metal is about to solidify at this time, the process bubble has not yet shrunk into a regular shape under the action of surface tension, and it is finally captured by the solidified metal and forms process porosity with a large number of micropores.

In addition, Fig. 10 shows the microcrack on the surface of the micropore and its formation mechanism. Due to the short solidification time of the surrounding molten metal, the micropores have been captured by the solidified metal before completely closed, with microcracks already existing on their surface. The tensile stress generated during the solidification and shrinkage of molten metal is the main factor leading to microcrack development. In this process, the micropores are sensitive sources of microcracks, which are subjected to different degrees of tensile stress, then the microcracks extend and develop on the surface of the micropores.
The morphology of the metallurgical porosity and the EDS results are shown in Fig. 11. The inner wall of the metallurgical porosity is smooth with a few impurity particles and no obvious accumulation or loss of elements. The formation of the metallurgical porosity for Ti-6Al-4V titanium alloy is mainly owing to the H₂O, which derives from the oxidation film and the surrounding atmosphere. In the high-temperature molten pool, H₂O will directly decompose or react with metal elements to generate hydrogen atoms.

In the nucleation stage, supersaturated hydrogen atoms nucleate at the solid–liquid interface and the suspended impurities. The nucleation energy required for nucleation satisfies the following equation [26]:

$$ W = - (P_G - P_L) V + \sigma S \left[ 1 - \frac{S_a}{S} (1 - \cos \theta) \right] $$

where $W$ is the energy required for bubble nucleation, $P_G$ is the pressure generated in the bubble, $P_L$ is the pressure generated by the external liquid, $V$ is the volume of the bubble, $\sigma$ is the tension between the phases, $S_a$ is the active area of the adsorption force, $S$ is the bubble nucleus surface area and $\theta$ is wetting angle.

During the laser welding process of the Ti-6Al-4V bottom-locking joint, the metallurgical bubbles are more likely to nucleate at the suspended impurities and the solid–liquid interface in the molten metal at the crystallisation front. At this time, $\theta$ is any value, the ratio of $S_a/S$ is large and the nucleation energy required for metallurgical bubbles to attach to these surfaces is the smallest.

**Fig. 8** The formation mechanism of process porosity: (a) the schematic diagram of laser welding of bottom-locking joint; (b–d) the process in which the tip of the keyhole is collapsed to form a process porosity; (e–g) the process of forming a process porosity induced by metal evaporation.

### 3.3 Formation mechanism of metallurgical porosity

The morphology of the metallurgical porosity and the EDS results are shown in Fig. 11. The inner wall of the metallurgical porosity is smooth with a few impurity particles and no obvious accumulation or loss of elements. The formation of the metallurgical porosity for Ti-6Al-4V titanium alloy is mainly owing to the H₂O, which derives from the oxidation film and the surrounding atmosphere. In the high-temperature molten pool, H₂O will directly decompose or react with metal elements to generate hydrogen atoms.

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Figure 12 shows the formation mechanism of metallurgical porosity. The solubility of hydrogen in titanium decreases with the increase in temperature. Consequently, in the high-temperature molten pool, the hydrogen is supersaturated and precipitated on suspended tiny impurities or solid–liquid interface, forming a metallurgical bubble to flow in the molten pool. As described in Eq. (1), the metallurgical bubble is small which results in a low escape velocity for it. In the process of rapid cooling of molten metal, the metallurgical bubble is easily captured, thereby forming

Figure 9 The formation mechanism of the micropore: (a) the chain-spherical process porosity; (b) process porosity with micropores; (c) equilibrium stage; (d) negative pressure stage; (e) burst stage; (f) the formation of micropores

Fig. 10 Microcracks on the surface of the micropores: (a, b) the morphology of the microcracks; (c, d) the formation mechanism of the microcracks
Fig. 11  The metallurgical porosity: (a) the morphology; (b) the EDS results

Fig. 12  The formation mechanism of metallurgical porosity: (a, b) the precipitation of hydrogen and the formation of metallurgical bubbles; (c, d) the process of metallurgical bubbles being captured by solidified metal
metallurgical porosity at the bottom of the weld seam. Figure 12c, d show the process of metallurgical bubbles being captured by solidified metal.

4 Conclusions

In this work, the distribution, element characteristics and formation mechanism of process porosity and metallurgical porosity in laser welding for Ti-6Al-4V titanium alloy bottom-locking joint are investigated. Furthermore, the formation mechanism of the micropore and the microcrack in the process porosity are analysed. The main conclusions from this paper are summarised as follows:

1. The formation of process porosity is the result of the joint action of two mechanisms. One is that the tip of the keyhole is closed by the strong molten metal vortex and isolated to form a process bubble; the other is that the local element evaporation causes the back wall of the keyhole to be dented and collapse under the dynamic behaviour of the molten metal vortex to form a process bubble. The bubble is caught before escaping to form the process porosity mainly appearing in the weld seam centre.

2. The formation of metallurgical porosity is closely related to the precipitation of hydrogen including the metallurgical bubble nucleation process, and thus, metallurgical porosities are mostly distributed at the bottom of the weld seam.

3. In the process porosity, there is the accumulation of V element and the loss of Al element, while this element characteristic does not appear in the metallurgical porosity. This behaviour of the accumulation and loss of elements further affects the morphology and microstructure of the process porosity. The strong steams formed by the compression of Al vapour break through the inner wall of the process porosity, resulting in the formation of the micropores with a diameter between 2 and 5 μm.

4. Microcracks originate and extend on the surface of the micropores, and the tensile stress generated during the solidification and shrinkage of molten metal is considered to be the main factor leading to the microcracks distributed on the surface of the micropores.

Author contribution All authors contributed to the study conception and design. Material preparation and welding experiment were performed by XK and LW. The grinding and polishing of metallographic samples were completed by TY and JL. Data collection and analysis were led by XK with contributions from all authors. The first draft of the manuscript was written by XK and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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