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Porosity in fiber laser formation of 5A06 aluminum alloy †

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Abstract

The mechanism of porosity formation and its suppression methods in laser formation of aluminum alloy have been studied using a 4kW fiber laser to weld 5A06 aluminum alloy with SAl-Mg5 filler. It was found that the porosity formation is closely related to the stability of the keyhole and fluctuation of the molten pool in the laser welding aluminum alloy. The filling wire increased the instability of the keyhole and weld pool, thus further increasing the amount of gas cavities in the joint. Prefabrication of a suitable gap for the butt joint can provide a natural passage for the flow of the liquid metal, which can weaken, and even completely eliminate the disturbance of the filling wire on the formation of keyhole. The gap can also provide a passage for the escape of the bubble. Thus, this method can greatly decrease the sheet's susceptibility to porosity. Moreover, for a thin sheet, if the power of the laser is sufficient to form a keyhole with stable penetration through the weld sheet, a weld bead without porosity can also be obtained because closing the keyhole is almost impossible.

Keywords: Aluminum alloy; Fiber laser; Filler wire; Laser formation; Porosity

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1. Introduction

The industrial applications of laser have increasingly become widespread [1-4]. However, porosity poses a serious problem in the high power laser welding of aluminum alloy because it deteriorates mechanical properties, particularly, tensile strength and elongation. Numerous studies have been carried out on the formation of porosity in high power laser welding [5-14]. Matsunawa, et al. [15] conducted systematic studies on the mechanism of porosity formation in CW CO_2 laser welding using high speed optical and X-ray transmission methods. They estimated that the local evaporation of the metal on the keyhole front wall was the prime reason for the formation of large bubbles; the bubbles were trapped by the solidifying wall during the floating up and remained in a state of porosity. Gas analysis showed that the major gas in the large cavities was a shielding gas, confirming that the cavities were primarily formed by metal vapor together with the swirled shielding gas and air. Compared with laser autogenous welding, wire was added into the laser welding process (i.e., laser welding with filler wire), which complicates the dynamics of the keyhole and molten pool, thus increasing the probability of porosity formation. This necessitates an understanding of the formation mechanism of porosity and its suppression measures in order to obtain a good welded joint during laser welding with filler wire. Numerous studies exist on this topic [16-21], but reports on the formation mechanism of porosity are rarely discussed. In this work, the mechanism of porosity formation and its suppression methods were studied using a 4 kW fiber laser to weld 5A06 aluminum alloy with SAl-Mg5 filler.

2. Experimentations

The base material used in this study was 5A06 aluminum alloy with a thickness of 2.0 and 4.0 mm. SAl-Mg5 aluminum wire (1.0 mm in diameter) was used as filler wire. The chemical compositions of the base material and filler wire are listed in Table 1. The welding direction was along the rolling direction of the aluminum alloy plate (150 mm × 100 mm). Argon gas was used as shielding gas with a flow rate of 16 l/min.

Experiments were carried out by YLR-4000 CW Ytterbium Fiber Laser and a VR7000 Fronius wire feeder. The filler wire was supplied just ahead of the laser beam at an angle of 30° with respect to the normal surface to prevent the laser from leaking through the gap of the butt joint. The focus point of the laser beam was set at the substrate surface (Fig. 1). The parameters of the laser welding experiments are shown in Table 2.

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3. Results and discussion

3.1 Porosities distribution in the joints

Porosity distribution in the joints and their corresponding welding parameters are shown in Fig. 2 and Table 3, respectively.

Table 1. Composition of 5A06 and SAl-Mg5 (%).

Compositions	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
5A06 (Wt. %)	0.4	0.4	0.1	0.5-0.8	5.8-6.8	0.2	0.02-0.1	Bal.
SAl-Mg5 (Wt. %)	0.4	0.4	-	0.2-0.6	4.7-5.7	-	0.05-0.2	Bal.

Table 2. Parameters of laser welding condition.

Laser power P (kW)	Wire feed speed V_F/ (m/min)	Welding speed V_W/ (m/ min)	Sheet thickness (mm)
2.6-4.0	0.0-10.0	1.2-2.0	2.0, 4.0

Table 3. Welding procedures.

No.	Laser power P (kW)	Welding speed V_W (m/min)	Wire feed speed V_F (m/min)	Sheet thickness (mm)	Gap (mm)
1	3	2	0	4.0	-
2	3	2	4	4.0	-
3	3.5	1.2	7	4.0	0
4	3.8	1.2	7	4.0	0
5	3.8	1.2	7	4.0	0.4
6	2.6	2	7	2.0	0

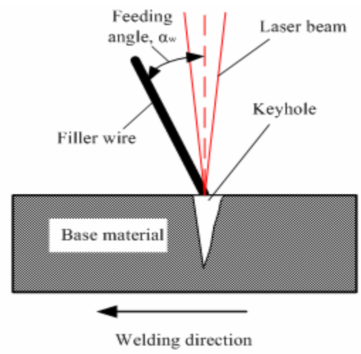


Fig. 1. The sketch of laser welding with filling wire.

In Fig. 2, No. 1 and No. 2 show that large porosities exist in the joints both with and without filling wire when the keyhole did not penetrate the plate. Moreover, the amount of porosity greatly increased when the filler wire was added. This indicates that the introduction of the filler wire increased susceptibility to porosity when the keyhole did not penetrate the plate. There are two explanations for this. First, the filling wire increased the instability of the keyhole and weld pool. The fluctuations of the filler wire in terms of speed and/or feed-in position was inevitable because the wire feeding system cannot be absolutely stable. Therefore, the laser energy used to generate the keyhole and weld pool result in a corresponding fluctuation in the laser welding with filler wire, which can lead to the instability of keyhole and weld pool. Secondly, the filler wire had a larger specific area compared with the base material, which can lead to more impurity. Oxide and hydride are dragged into the molten pool, which led to increased porosity. However, the size of maximal porosity in No. 2 (with filling wire) became smaller than in No. 1 (without filling wire). This phenomenon can be attributed to the fact that a laser beam was used to melt the filler wire, which could have reduced molten pool overheating, and consequently caused the size of the maximal porosity existing in the molten pool to become smaller.

The amount of porosity decreased when a full penetration bead was obtained. However, a much large porosity could still exist in the joints if the welding conditions have not been controlled properly (see No. 4 in Fig. 2). Porosity can be completely avoided when a gap of 0.4 mm was prefabricated for the butt joint of a 4 mm sheet or when the sheet thickness is 2.0 mm (see No. 5 and No. 6 in Fig. 2). Under these two conditions, the weld penetration depths were uniform and greater than the thickness of the test panel. Further discussions on this topic shall be presented in the next section.

3.2 Micrographs analysis

The scanning electron microscope (SEM) observations (Fig. 3) show that porosity can be classified into two broad categories based on size and microscopic features. The first category is comprised of large and irregular beads (Fig. 3(b)), which are

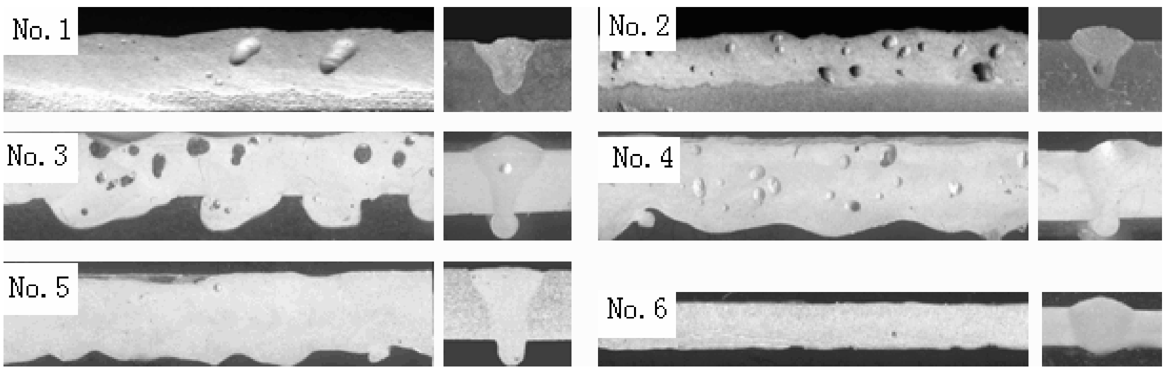


Fig. 2. The vertical and cross section of bead with different welding procedures (see Table 3).

referred to as gas cavity. The second category is comprised of small and spherical (Fig. 3(c)) beads also known as hydrogen pore. A crystal growth step can be clearly observed in the wall of the gas cavity (Fig. 3(d)), indicating that gas cavity formation just ahead of the solidification of the molten pool. Furthermore, rapid oscillation also occurred inside the gas cavity during its growth. In other words, the formation of gas cavity can be attributed to the instability of the keyhole and the oscillation of the molten pool. Note that the growth step as observed inside gas cavity did not manifest inside the small hydrogen pore (Fig. 3(c)). Thus, we can conclude that the formation mechanism of the hydrogen pore is different from that of the gas cavity. It has been generally acknowledged that the formation of a hydrogen pore can be attributed to the precipitation of hydrogen because hydrogen solubility in aluminum greatly varies between solid and liquid states. Meanwhile, tips of dendrites appeared round due to the compressive stress of hydrogen gas in the pore (Fig. 3(e)).

3.3 Formation mechanism of gas cavity

Fig. 3 illustrates that the hydrogen pore is generally small in size; its effect on the mechanical properties can be ignored compared with large porosity (gas cavity). For this purpose, we only discussed in this paper the formation mechanism of large porosity (gas cavity).

As mentioned earlier, gas cavity formation is closely related to the stability of the keyhole and the oscillation of the molten pool. This indicates that factors that improve keyhole stability can reduce the quantity of gas cavities in the laser welding for 5A06 aluminum alloy. In general, the bottom diameter of the keyhole gradually decreased because of the reflection of the irradiation laser in the wall of the keyhole, and not because of the direct irradiation of the laser beam. The tip of the keyhole was bent away from the welding direction due to the drag force in the liquid metal. Since the tip of the keyhole is so tiny, it can be easily closed by the flow of molten metal. Fig 4a shows that it became a bubble in the molten pool with the sweep of the keyhole. A bubble usually becomes a gas cavity in the weld bead because it is often difficult for bubbles to escape from the molten pool at high crystallization rates of laser welding.

In laser welding with filler wire, when the keyhole could not penetrate the test plate, the depth of penetration was reduced from 3.12 mm (without filler wire) (see No. 1 in Fig. 2) to 2.78mm (with filler wire) (see No. 2 in Fig. 2). This is because a part of the laser beam was used to melt the filler wire; thus, the laser energy used to produce a keyhole was lower than laser autogenous welding. Based on No.1 and No. 2 in Fig. 2, we can also see that more gas cavities were formed by laser welding with wire filler than by welding without wire filler. This could possibly be due to several reasons. First, the wire feeding system might not have been absolutely stable; hence, fluctuations of the filler wire in terms of speed and/or feed-in position resulted in a fluctuating laser energy used to generate the keyhole. The penetration depth of the keyhole might have caused extra fluctuation by the laser welding with filler wire. Second,

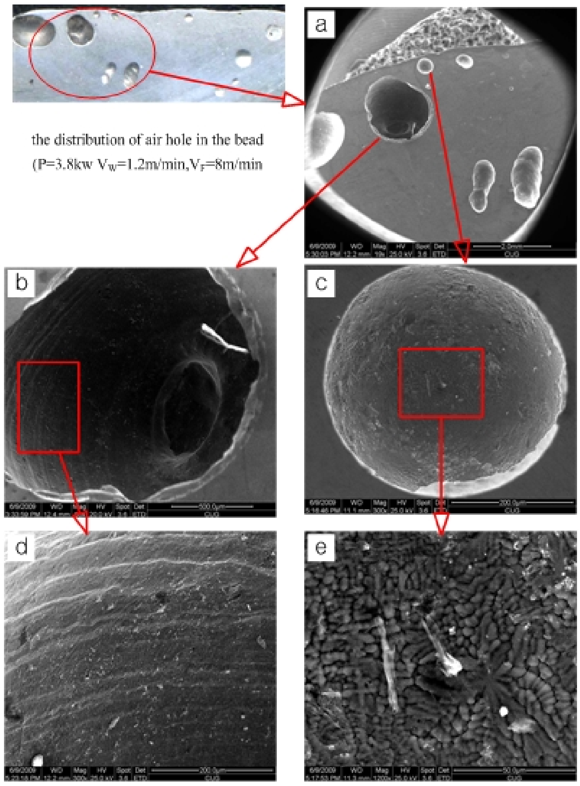


Fig. 3. SEM of gas cavity and hydrogen porosity in the bead.

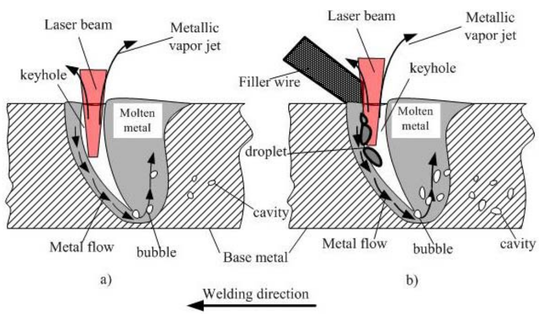


Fig. 4. Cavity formation in laser welding on the board without (a) and with (b) filler wire.

the filling wire was heated and melted using a laser beam to form a globular droplet periodically, and the droplet was periodically transferred to the weld pool. These periodical processes might have resulted in the disturbance of laser transfer and instability of the keyhole and molten pool. Fig. 4 shows the role of the filler wire in increasing the probability of the formation of the cavity.

In welding a butt joint with a 4.0 mm test plate and a zero-mm welding gap, the test panel was critically penetrated with a 3.5 kW laser power. The depth of penetration fluctuated at larger scopes, and numerous larger gas cavities were found in the vertical section of the weld (see No. 3 in Fig. 2). When the laser power was increased to 3.8 kW, fluctuations in the depth

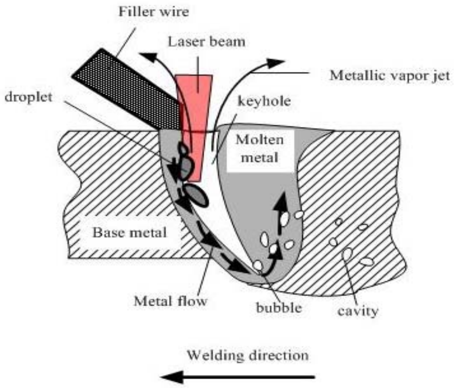
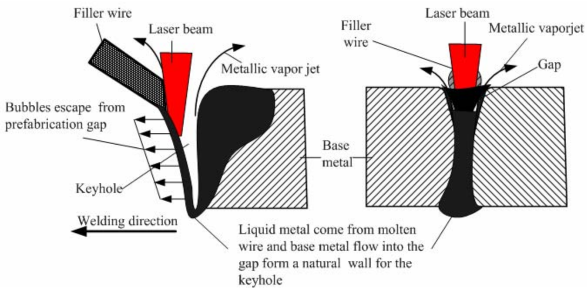


Fig. 5. Gas cavity formation in laser welding with filler wire (the depth of penetration exceed the thickness of test plate).



(a) Vertical section (b) Cross section

Fig. 6. Gas cavity eliminations in laser butt welding with a gap of 0.4 mm.

of penetration became smaller, and the test panel was completely penetrated. In addition, the number of gas cavities decreased due to the increase in the stability of the keyhole; however, gas cavities still existed in the bead and were considerably severe (see No. 4 in Fig. 2).The fluctuations of the keyhole are at a maximum value in the critical penetration condition, which explains the increase in the number of gas cavities in the bead. Improvement in the number of gas cavities is also very inconspicuous even when the test plate was fully penetrated with the 3.8 kW laser. A reason for this is that the fluctuations of the keyhole had not been eliminated and the penetration of the bead varied (see No. 4 in Fig. 2) despite the test plate having been completely penetrated. This is an indication that the keyhole did not fully penetrate the molten metal, as exhibited in Fig. 5. As a result, the formation mechanism of gas cavities under these circumstances is similar to those in a non-penetrating welding process (see No. 1 and No. 2 in Fig. 2), except that the depth of the keyhole is deeper.

The bead with few gas cavities was obtained when prefabricated to a gap of 0.4 mm for the butt joint of a 4.0 mm sheet (see Table 3 and Fig. 2). The penetration of the bead was uniform and greater than the thickness of the test panel. All evidence indicates that the gap increased the stability of the keyhole. This could be due to several reasons. First, the size of the gap is similar to the diameter of the keyhole. Hence, the resistance pressure, which has to be overcome to form the keyhole by the laser beam, is suddenly reduced, a situation favored for a steady keyhole. The prefabricated gap can be equivalent

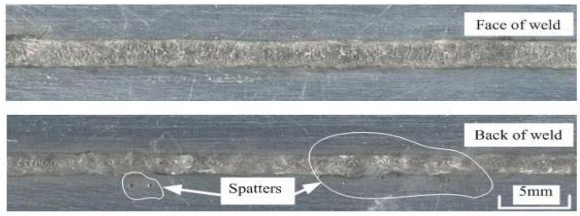


Fig. 7. Macrograph of laser butt welding 2mm 5A06 aluminum alloy with filling wire (detailed welding procedures are shown in Table 3).

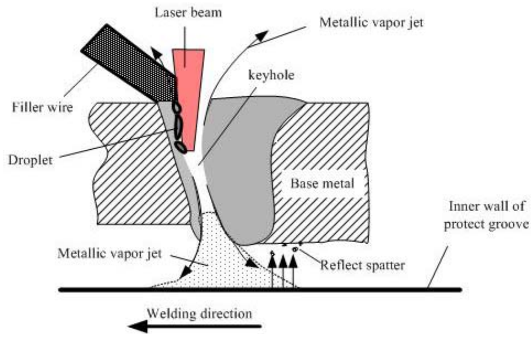


Fig. 8. Gas cavity eliminations in laser butt welding 2 mm board with filler wire.

steady keyhole. The prefabricated gap can be equivalent to an artificial keyhole for the laser beam, which is rather difficult to close when the power of the laser is sufficient to melt the filler wire, thereby reducing the probability of entrapped shielding gas. Second, the gap can provide a natural passage for the flow of liquid metal, which can weaken and even completely eliminate the disturbance of the keyhole and molten metal coming from the metal transfer of the filler wire. Third, it is empty in the leading end of the keyhole except for a thin liquid metal, which is a product of the molten wire and the base metal; this could provide an extra passage for the escape of bubbles forming in the molten pool (Fig. 6).

A weld bead without gas cavity was obtained, and the depth of penetration was uniform when the thickness of the test panel was reduced to 2 mm (see Table 3 and Fig. 2). The macrograph of the bead is rather good for both sides. Nevertheless, some small spatters reflected by the metallic vapor jet were observed at the back of the sample (Fig. 7), indicating that the keyhole of the laser welding completely penetrated through the melting metal. The small spatter is the splash reflected by the metallic vapor jet from the bottom of the protection groove (Fig. 8). Therefore, it is reasonable to attribute gas cavity eliminations in laser butt welding of the keyhole (i.e., for the 2 mm board with filler wire) to the body-sized hole. In such cases, closing the keyhole is almost impossible, and the metallic vapor jet can disrupt both the top and bottom part of keyhole. Therefore, the formation factors (i.e., metal vapor together with the swirled shielding gas and air) for the large porosities were all removed.

Based on the above mentioned analysis, we can conclude that the elimination of a gas cavity in a laser-welding aluminum alloy with filler wire is more difficult because the filler wire can disrupt the stability of the keyhole. A weld bead without gas cavity can be obtained when the thickness of the test panel is small or if the power of the laser is sufficient to form a keyhole with stable penetration through the test panel. In addition, an appropriate gap can increase the stability of the keyhole, which can also decrease probability of forming a gas cavity.

4. Conclusions

(1) Gas cavity formation is closely related to the stability of the keyhole and fluctuations in the molten pool. The filling wire in laser welding aluminum alloy can increase the probability of gas cavity formation because the filling wire can disturb the stability of the keyhole and cause fluctuations in the molten pool.

(2) In laser welding with wire filling, pre-fabricating a suitable gap for the butt joint can greatly decrease susceptibility to gas cavities (large porosities). This indicates that the gap can increase the stability of the keyhole and weld pool, which then contributes to the gap assisting in the formation of the keyhole. Moreover, it can also provide a passage through which the bubbles can escape and as a natural flowing passage of the liquid metal.

(3) In laser welding with wire filling, when the power of the laser is sufficient to form a keyhole with stable penetration though the test panel, a weld bead without gas cavity can be obtained because closing the keyhole is almost impossible.

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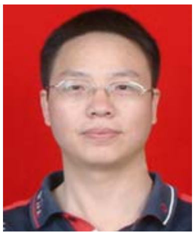

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