Laser welding 6A02 aluminum alloy with filler wire under high welding speed

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Abstract. The experimental of fiber laser welding 6A02 aluminum alloy with filler wire was carried out, and high welding speed with 6m/min was used. The effects of different wire feeding speeds on cross-section shapes of welds, joints’ microstructure and tensile properties were analyzed. The laser energy melting the base metal to achieve the keyhole effect is defined as relative heat input. It is affected by the wire feeding speed, which leads to the changes of the penetration state of laser welding and the coarsening degree of the microstructure of the joint. The microstructure of the joints presents the columnar grains near the fusion zone and the mixed grains (columnar grains + equiaxed grains) in the weld center zone. For the joints with full weld formation, the microstructure of joint with as-welded state by using wire feeding speed of 4m/min is finer than that with wire feeding speed of 2m/min slightly. And the tensile strength of joints of the former is a little higher than that of the latter. The average ultimate strength of the joints in the as-welded state could reach 245MPa, while that in the heat-treated state could reach 373MPa. All of the tensile fractures occur near the fusion zone. However, the angles between the fracture surfaces and the base metal surfaces are different significantly by observing the tensile fracture positions of as-welded and heat-treated joints.

1. Introduction
Compared with the YAG laser or CO₂ laser, the fiber laser has better beam quality, higher output power and smaller focusing spot [1-2]. The laser power density is the ratio of the laser power to the spot area, so the power density of the fiber laser is very high. Chen L [3] found that the formation of keyhole, heat source model, weld pool behavior and the weld appearance are affected by the dual threshold of laser power density and heat input. If the laser power density is higher, the metal material is easier to melt, vaporize and produce keyhole effect to achieve penetration fusion welding. The heat input is inversely proportional to welding speed. The higher welding speed means the lower welding heat input, which causes that the heat affected zone (HAZ) of the joint becomes narrower and the welding deformation and residual stress of joint become smaller. Therefore, when thin-walled structures are welded by the fiber laser, the good quality welded joints are easily obtained with high welding speed.

When aluminum alloy is welded by laser welding without filler wire, the small surface tension and good fluidity of molten metal are easy to produce weld defects, such as depression, collapse, leakage and so on. Those defects could be overcome effectively by filling wire during the welding course [4]. So the application field of laser welding has been widened significantly. However, it is found that the
full welding joint could be obtained in a wide range of wire feeding speed [5]. Different wire feeding speeds not only affect weld width and reinforcement, but also affect the microstructure and properties of welded joints. Based on the previous experiment, two typical joints with different wire feeding speeds and same high welding speed are selected, and the differences of the weld cross-section morphology, microstructure and tensile properties of the joints are studied. It will provide data reference for the further popularization and application of fiber laser welding aluminum alloy with high welding speed.

2. Experimental
The 6A02-T6 aluminum alloy with 1.0mm thickness and ER4043 filler wires with Ø1.0mm diameter are used. Their chemical compositions are shown in table 1. The size of workpieces is 200mm×100mm. The surfaces of the workpieces were cleaned by chemical method before welding in order to remove the oil and oxide film thoroughly.

| Material      | Mg   | Cu   | Ti | Fe  | Si   | Mn   | Zn | Al  |
|---------------|------|------|----|-----|------|------|----|-----|
| 6A02-T6       | 0.45-0.9 | 0.2-0.6 | 0.15 | 0.5 | 0.5-1.2 | 0.15-0.35 | 0.2 | Bal |
| ER4043        | ≤0.05 | ≤0.3 | ≤0.2 | ≤0.8 | 4.5-6.0 | ≤0.05 | ≤0.1 | Bal |

The experiments have been carried out by a welding system. The system includes a high power fiber laser and a push-pull wire feeder. The laser beam is transferred through fiber to the workpiece after being focused by lens. The focal distance of the focus lens is 160mm, and the focused spot diameter is Ø0.28mm. The axle direction of the laser beam leans 10° to the normal direction of the workpiece. The defocusing amount is 0mm in all welding courses. The transverse offset of the laser and the filler wire in welding plane is controlled in the range of ±0.2mm. And the longitudinal offset is about 1mm before welding, as shown in Figure 1. The workpiece is static, and the laser head is driven by a six-axis robot to realize the welding. The high temperature zones near the molten pool are protected by argon during the welding.

![Figure 1. The sketch of laser welding with filler wire.](image)

Metallographic specimens and standard tensile samples (Figure 2) are intercepted from the workpieces after welding. The alkali solution with 2～3% NaOH is used to corrode the metallographic
specimen. The microstructure of the joints is observed by optical microscope. The tensile samples, including as-welded and heat-treated states, are tested at room temperature by using Z100kN universal test system. The heat treatment includes solution and aging. The former is carried out at 530°C for 50 minutes and the latter is carried out at 165°C for 8 hours.

3. Results and discussion

3.1. Macroscopic morphology of the welded joints

According to the penetration state of the back side of the weld, laser welding generate four typical joint characteristics [1]. They are overpenetration, moderate penetration, only pool penetration and non-penetration respectively. When the high welding speed of 6m/min and the laser power of 2kW are used, the self-melting welding joint presents an overpenetration characteristic, and the front surface of the weld is slightly concave, as shown in Figure 3a. When the wire is filled during the welding course, the weld seam becomes full. When the wire feeding speed is increased, the penetration state of the welded joint gradually changes from overpenetration to moderate penetration, as shown in Figure 3b and Figure 3c. Since the penetration of the fiber laser is very strong, it is difficult to obtain the state of only pool penetration. When the wire feeding speed is increased to a certain threshold (the condition is 5m/min), the weld formation is unstable, for example, full penetration and non-penetration are alternately present, and insufficient melting of the filler wire causes many welding defects.

Compared with Figure 3b and Figure 3c, when the wire feeding speed is higher, the weld width is narrower and the reinforcement is higher slightly. The cross-section melting zones of the welded joints are extracted separately in order to calculate their areas. The area of the cross-section melting zone with wire feeding speed of 2m/min is 2.72 mm², while that with wire feeding speed of 4 m/min is 2.57 mm². This is not only related to the wire feeding speed changing the penetration state of laser welding, but also closely related to the effects of filler wire on the reflection and absorption of laser energy.

In the process of laser welding with filler wire, a part of the laser energy melts the base metal to achieve the keyhole effect welding, a part of the laser energy is absorbed by the filler wire, and the rest of the laser energy is reflected by the filler wire and the base metal [1]. The reflected laser energy by
the filler wire is related to the wire feeding speed. When the wire feeding speed is increased, the reflection of the laser is enhanced [6-8]. Under the experimental conditions, the filler wire is transformed into the molten pool by the surface tension transition mode, which is similar to the short circuit transition of argon arc welding. When the edge of the filler wire contacts the solid surface of the base metal, the wire is prone to local bending, as shown in Figure 4. When the other welding parameters are constant and the wire feeding speed is higher, the bending of the filler wire is intensified. Meanwhile, the more continuously feeding wire requires absorbing more laser energy to melt it. Therefore, compared with the wire feeding speed of 2 m/min, when the wire feeding speed is 4 m/min, the laser energy of achieving the keyhole effect welding is relatively less, which cause that the front width and the back width of the weld bead are tendency to become narrower.

3.2. Microstructure of the welded joints

The microstructures of the welded joints with two wire feeding speeds are shown in Figure 5. It can be seen that the columnar crystal structure depends on the unmelted base metal grains of the fusion zone, grows toward the center of the weld, and runs through the entire weld zone. In some localized areas of the weld center, the grains adhere to the interfaces of the unmelted suspended particles in the molten pool, rapidly nucleate and grow to form equiaxed crystal structure. Therefore, the weld center exhibits the mixed structure characteristics of columnar crystal and equiaxed crystal under high welding speed.

![Figure 5. Microstructure of joints with wire feeding speed of 2m/min (a), (c) and 4m/min (b), (d); (a) and (b) the fusion zone in cross-section of joints; (b) and (d) weld center in cross-section of joints.](image)

The keyhole effect of laser penetration welding is accompanied by severe metal evaporation and vaporization, which causes burning loss of some low-boiling elements (such as Mg). Moreover, the rate of the burning loss decreases with increasing welding speed [9]. The condition of high welding speed largely limits the burning loss of low-boiling elements. The Si-rich filler wire of ER4043 is transformed into the molten pool, which relatively increases the Si content of the pool. Along with the rapid solidification of the molten pool, more hypoeutectic structures (including α-Al + Si binary eutectic, α-Al + Mg2Si binary eutectic and α-Al + Mg2Si + Si ternary eutectic) are more likely to generate between the primary α-Al grain boundaries. The faster the wire feeding speed, the higher the relative content of the Si-containing eutectic structures in the weld, which is tendency to coarsen the microstructure. However, the higher wire feeding speed also cause that the cross-section melting area of the weld zone is smaller, which means the volume of the molten pool is smaller and the relative...
welding heat input is lower. So the grains tend to be refined. Comparing Figure 5a and Figure 5b, it is found that the columnar crystal structure near the fusion zone does not differ much. Comparing Figure 5c and Figure 5d, it is found that the weld microstructure with wire feeding speed of 4m/min is slightly finer than that with wire feeding speed of 2m/min. Therefore, the effect of the relative welding heat input on the weld microstructure is more obvious.

The microstructure of the welded joint after the heat treatment is shown in Figure 6. It can be seen that a large amount of dispersed strengthening phases are precipitated uniformly, regardless of the position near the fusion zone or the center zone of the weld. It could also be predicted that the strength and plasticity of the welded joint could be improved significantly by the heat treatment.

3.3. Tensile properties of the welded joints

The welded joints were prepared into the standard tensile specimens (removal of the front and back reinforcement). The tensile properties of the as-welded and heat-treated states were tested. The results are shown in Table 2. It is found that the average ultimate strength and yield strength of the joints are higher slightly when the wire feeding speed is higher, whether it is in the as-welded state or heat-treated state. However, the elongation after fracture is less affected by the wire feeding speed. It is also found that the average ultimate strength of the joints in the as-welded state can reach 245MPa. After the heat treatment, both the strength and the elongation of the welded joints are improved significantly.

| State of tensile samples | Wire feeding speed /m·min<sup>−1</sup> | Ultimate strength /MPa | Yield strength /MPa | Elongation after fracture /% |
|--------------------------|-----------------------------|------------------------|---------------------|-----------------------------|
| As-welded                | 2                           | 237                    | 187                 | 2.93                        |
|                          | 4                           | 245                    | 188                 | 2.75                        |
| Heat-treated             | 2                           | 357                    | 318                 | 20.99                       |
|                          | 4                           | 373                    | 333                 | 21.29                       |

6A02 alloy is an age-strengthened aluminum alloy. The base metal undergoes rapid melting and solidification during the laser welding process, only a small amount of strengthening phase particles are dispersed inside the grains, and a large number of low-melting eutectic structures are distributed in the grain boundaries (seen in Figure 5). So the joints exhibit a certain softening phenomenon. The difference of the grain morphology near the fusion zone is the largest, and the stress concentration is more likely to occur. It is not conducive to the uniform deformation of the grains during the tensile test, and the probability of cracking from this zone is often greater than other zones. The as-welded joints are prone to cracking near the fusion zone on one side of the base metal, and extend about 45° to the vicinity of the fusion zone on the other side of the base metal, as shown in Figure 7. After the heat treatment, the strength of the weld zone is improved greatly. All fractures occur around the fusion zone, and the fracture surfaces are substantially perpendicular to the surface of the base metal.
4. Conclusions

1) Under the condition of high welding speed, the wire feeding speed should be controlled within a certain range in order to obtain well-formed welded joint. As the wire feeding speed increases, the relative welding heat input absorbed by the base metal decreases, resulting in a narrower weld width and a change in the penetration state.

2) The columnar structure grows from the fusion zone to the weld centre zone, and microstructure of the weld centre presents mixed structure of columnar crystals and equiaxed dendrites. When the wire feeding speed is increased within a certain range, the microstructure of the welded joint tends to be refined.

3) Whether as-welded state or heat-treated state, the tensile strength of the welded joint with the wire feeding speed of 4 m/min is higher slightly than that with the wire feeding speed of 2 m/min; and the elongation after fracture is affected minimally by the wire feeding speed. The angles between the fracture surfaces of the joints and the surfaces of the base metal with the as-welded and heat-treated states are different significantly. The angles of the joints with the as-welded state are about 45°, while the angles of the joints with the heat-treated state are about 90°.

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