Effect of different filler wires on weld formation for fiber laser welding 6A02 Aluminum alloy

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Abstract. 6A02 aluminum alloy was welded by fibre laser welding with two different filler wires (ER4043 and ER5356). The weld appearance, microstructure and mechanical properties were analysed. The results show the welding course with ER4043 is more stable than that with ER5356, and the welding spatters of the former are smaller than that of the latter. The microstructure of the weld zone, including columnar-grains near the fusion zone and mixed microstructures (columnar grains and equiaxed grains) in the weld center zone, is finer with ER5356 than that with ER4043. So the average microhardness value of the former is higher than the latter. A great number of low melting point eutectic phases disperse in grains boundary. Due to the eutectic phases distributing more in two zones (overheat zone near the fusion zone and the weld center zone) than other zones, the welded joints have these two low hardness and weak strength zones. The ultimate strength and the elongations after fracture of the welded joints with ER4043 are lower than that with ER5356 slightly. However, the former are improved obviously and higher than the latter after heat treatment. The tensile properties of all joints can reach to the base material level. And the tensile fractures always occur near the fusion zone.

1. Introduction
The filler wire is used during the laser welding course, which could reduce assembly accuracy before welding, improve the weld surface forming and mechanical properties of welded joints [1-3]. So the possibilities and the application scope of the laser welding are expanded significantly [4]. Recently, the fiber laser is developed rapidly, which has better light beam quality and brightness [5] than the other types of laser. Compared with the conventional YAG laser or CO₂ laser, the fiber laser has very high power density. Therefore, the fiber laser is easier to realize the full penetration welding of the thin-walled structures of aluminum alloy, and the good quality of the welded joints in the condition of high welding speed is easier to achieve [6]. Now the weldability, structures and mechanical properties of the aluminum alloy by using YAG laser or CO₂ laser have been widely studied [1, 4]. However, the studies about fiber laser welding are relatively limited, especially in the condition of high welding speed. For these reasons, the experimental of 6A02 aluminum alloy was carried out by using the system of the fiber laser welding with filler wire. Two different filler wires were used during the welding course, and some full penetration welds were obtained. The different chemical compositions of filler wires may have some influence on the microstructure and properties of the welded joints, which will be systematically analysed. The results will provide data reference for accelerating the application of aluminum alloys in the aviation field.
2. Experimental

The 6A02-T6 aluminum alloy sheet with 1.0mm thickness and two types of filler wires (ER4043 and ER5356) are used for butt-welding. Their chemical compositions are shown in table 1. The 6A02 alloy is Al-Mg-Si aluminum alloy, which can be strengthened by solid solution and aging heat treatment. It not only has good plasticity and moderate strength, but also is a kind of structural material with good resistance to corrosion. So it is often used in aircraft and engine parts with high plasticity and corrosion resistance [7]. The filler wire ER4043 is rich in Si element, and has good crack resistance. The filler wire ER5356 is rich in Mg element, which has good thermal cracking resistance and high strength. The size of workpieces is 200mm×100mm. And the surfaces of the workpieces were cleaned by chemical method before welding. The diameters of two types of filler wires are Ø1.0mm.

| Material | Mg   | Cu   | Ti | Fe  | Si   | Mn   | Zn | Cr | 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  |
| ER5356   | 4.5-5.5 | 0.1 | 0.15 | 0.4 | 0.25 | 0.05-0.2 | 0.25 | 0.05-0.2 | Bal  |

The experiments have been carried out by the welding system which is based on high power fiber laser and push-pull wire feeding system. The laser beam wavelength is 1.06μm. The normal output power of the laser is 5kW. The laser beam is transferred through fiber to the workpiece after being reflected and 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 workpiece is static, and the laser head is driven by a six-axis robot to realize the welding. The high temperature zone near the molten pool is protected by argon during the welding. The optimized welding parameters, including the welding speed of 6m/min, the laser power of 2kW, and the wire feed rate of 2m/min are chosen in the fiber laser welding with filler wire for the butt-joints.

Metallographic specimens and standard tensile samples 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 joint is observed by optical microscope. And microhardness of the joint are measured on hardness tester (HXD-1000) by holding a test load of 0.1N for 10s. The tensile samples are shown in Fig. 1 and the tensile tests were carried out at room temperature by using Z100kN universal test system. The tensile properties of joints after reasonable heat treatment were also tested. 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.

![Fig. 1 Dimension of the tensile sample](image-url)
3. Results and discussion

3.1. Macroscopic morphology analysis of the welded joints

The distance between laser and filler wire is an important geometric parameter during the laser welding with filler wire. It should be controlled in the range of 1.0mm to 1.5mm. The wire is heated by plasma/metal vapor cloud, direct laser irradiation and the radiation of the molten pool rapidly. So the wire is transformed into small droplets and filled into the molten pool with the mode of surface tension transition, which is similar to the short circuit transition of argon arc welding, as shown in Fig. 2. The high power density of the fiber laser is good to maintain the dynamic balance of the keyhole. The molten pool with small volume could be obtained easily under the condition of high welding speed. And the filler wire could not only make up the evaporation loss of some alloy elements (such as Mg), but also be helpful to backfill of liquid metal [8]. Therefore, the weld bead is very full, and the surface appearance of the weld is very good. The spatter is closely related to the stability of welding course and joint quality [9]. When the welding spatters are less, the welding course is more stable and the joint with high quality is easier to be obtained. The results show that the spatters are produced very little by filling either ER4043 or ER5356 wire. And no excessive defects are found in the welded joints with the help of X-ray inspection. The Si element could increase the fluidity of the molten pool, which cause that spatters is rarely produced in the welding process. Therefore, compared with the spatters by filling ER5356 wire, the spatters by filling ER4043 wire is less. And the welding course of the latter is more stable. Meanwhile, element Si of the filler wire could be helpful to increase the volume of molten pool under the same welding condition. It is calculated that the weld area of the cross section is about 4.02mm$^2$ with ER4043 wire, while the weld area is about only 2.37mm$^2$ with ER5356 wire, as shown in Fig. 3.

![Fig. 2 Droplet transition of filler wire](image1)

![Fig. 3 Cross-section of welded joints of 6A02 aluminum alloy by fiber laser welding with filler wire ER4043 (a), (c) and filler wire ER5356 (b), (d)](image2)

(a) and (b) the front surface of weld bead; (b) and (d) cross-section of joints

3.2. Microstructure of welded joint by fiber laser welding with filler wire

The microstructures of the welded joints by using filler wire ER5356 and ER4043 are shown in Fig. 4. The fusion zone and the heat-affected zone (HAZ) are very narrow. And their width is about 3 to 6 grains of the base metal. Due to the liquid metal of the molten pool is always in an overheat state, spontaneous nucleation is very difficult, and heterogeneous nucleation is the chief solidification mode of liquid metal [10-11]. Columnar crystals microstructure depends on the sectional melted grains of the fusion zone, and rapidly grows along the maximal temperature gradient direction. In general, the maximal temperature gradient direction is always vertical to the fusion line. So the columnar crystals microstructure is formed perpendicular to fusion line. The high welding speed means the heat input is very low, which is only 20J/mm by using present welding parameters. This causes that the temperature
gradient of solid-liquid interface of molten pool is very large and the linear velocity of the grain growth is very fast. So the columnar microstructure is very small, and its width is only 1/4 to 1/2 grains of the base metal. The columnar microstructure is distributed from the fusion line to the weld center. Mass of solute elements is pushed to the center of the molten pool by the columnar crystals’ growth. When the composition overcooling reach to a certain degree, unmelted suspending particles in the liquid pool are suitable for nucleation and growth of equiaxed grains. Therefore, the mixed microstructure characteristics of columnar grains and equiaxed grains are formed in the weld center zone. The microstructure of the weld bead presents hypoeutectic characteristic, including primary $\alpha$-Al and fine eutectic structure ($\alpha$-Al + Si binary phases, $\alpha$-Al + Mg2Si binary phases, and $\alpha$-Al + Mg2Si + Si ternary phases).

Fig. 4 Microstructure of joint with filler wire ER4043 (a), (b) and ER5356 (c), (d) (a) and (c) the fusion zone in cross-section of joints; (b) and (d) weld center in cross-section of joints

The weld area of cross section by using wire ER4043 is bigger than that by using wire ER5356, which means the volume of molten pool of the former is larger than that of the latter during the welding course. The larger volume of molten pool means the longer high temperature residence time of the liquid metal. It could result in the more obvious growth of the grains. Meanwhile, element Si could promote formation of low melting point eutectic structures in the molten pool, which could increase the composition overcooling in front of solid-liquid interface. And the growth of the grains in weld zone is accelerated. Therefore, the microstructure in the weld zone by using wire ER4043 are coarser than that by using wire ER5356. The grains in the fusion zone are sectional melted and some low melting point eutectic structures gather at triangle grain boundary near the HAZ. In addition, the microstructure near the fusion zone of the welded joint is different obviously, so the position near the fusion zone is likely to become the weak part of the welded joint.

3.3. Microhardness of welded joint by fiber laser welding with filler wire

The 6A02 aluminum alloy is a typical aging strengthening material. The joint softening phenomenon will appear after rapid melting and solidification of the base metal. The softening degree of the joint by filling wire ER4043 is more serious than that by filling wire ER5356, as shown in Fig. 5. This is not only closely related to the content of element Si and Mg, but also affected by the microstructure of the welded joints. The wire ER4043 is rich in element Si, which could promote the formation of low melting point eutectic structures. So the softening degree of the joint with wire ER4043 is increased.
The wire ER5356 is rich in element Mg, which could be conducive to generate strengthening phases Mg2Si. And the microstructure of the joint with wire ER5356 is relatively refined. So the microhardness of the weld zone with wire ER5356 is higher than that with wire ER4043.

Meanwhile, two low hardness zones are located near the fusion zone and the weld center. A large number of low melting point eutectic structure are dispersed in the grain boundaries of the weld center zone, which cause the microhardness of this zone is lower than other zones. The grains of the fusion zone are sectional melted, and some low melting point eutectic phases always gather near the fusion zone. So the softening degree near the fusion zone is more serious than adjacent zones slightly. The microstructure of the base metal includes mass of fine strengthening phases Mg2Si, and those phases present characteristic of dispersion distribution. So the microhardness value of base metal is higher than that of the other zones. When the tensile properties of the welded joints are tested, the fracture of the samples will be possible to occur near the two low hardness zones.

![Microhardness distribution of welded joints in transverse direction](image)

**Fig. 5** Microhardness distribution of welded joints in transverse direction

3.4. Tensile properties of welded joint by fiber laser welding with filler wire

The welded joints in the welding state and heat treatment state were made into standard tensile specimens respectively, and all weld reinforcement were removed. Then the tensile test of those joints was carried out, and the results are shown in stable 2. It is found that the tensile properties of joints with filler wire ER5356 is better than that with filler wire ER4043 in welding state. This is not only related to grain size of the weld zone, but also closely related to the content of element Mg. According to the Hal-Petch formula, the finer grain size means the higher tensile properties. When the wire ER5356 is used, the grain structure is relatively fine and the strengthening element Mg is added into the molten pool, which is conducive to the formation of more strengthening phase Mg2Si. The fracture occurs near the fusion line, which means that the zone near the fusion line is the weakest zone of the joints. The differences of the grain morphology near the fusion zone are larger than that in weld centre zone. So the position near the fusion zone is easy to cause non-uniform deformation and formation of stress concentration in the process of tensile deformation. And the deformation extent of the fusion zone is very small during the tensile testing, which causes this position is easily to be broken. However, in the weld center zone, the strain difference between the inner of grain and grain boundary is tiny and the deformation of the weld zone is uniform under the same external force. So the crack is not easy to initiate and propagate in the fine grains.

Excitedly, the heat treatment is carried out after welding, and the joints with better properties are obtained easily. The strengthening phase Mg2Si would maximize precipitation during solution and aging course of heat treatment. The tensile strength and yield strength of 0.2% reach the base material level. The elongation is also improved significantly, which could reach 20.99%. Meanwhile, it is also found that the tensile properties of welded joint with filler wire ER4043 are better than that with filler wire ER5356.
Table 2 Tensile test average results of welding joints of 6A02 aluminum alloy

| State of the tensile specimens | Ultimate strength /MPa | Yield strength of 0.2%/MPa | Elongation after fracture/% |
|-------------------------------|-------------------------|---------------------------|-----------------------------|
| With filler wire ER4043 in welding state | 236.92 | 186.86 | 2.93 |
| With filler wire ER5356 in welding state | 267.78 | 193.64 | 3.28 |
| With filler wire ER4043 in heat treatment state | 356.78 | 318.12 | 20.99 |
| With filler wire ER5356 in heat treatment state | 336.52 | 310.77 | 20.58 |
| The base material level | 295 | 225 | 11 |

4. Conclusions
1) The weld bead by fiber laser welding with filler wire is very full. It can be inferred that the welding course with filler wire ER4043 is more stable than that with filler wire ER5356 from the welding spatters amount. And the volume of the molten pool of the former is larger than that of the latter.
2) The microstructure characteristics of 6A02 aluminum alloy welded by fiber laser welding with filler wire are the columnar microstructure near the fusion line and the mixed microstructures (including columnar grains and equiaxed grains) in the weld center zone. And the microstructure presents hypoeutectic characteristic. Moreover, the microstructure in the weld zone with filler wire ER4043 are coarser than that with filler wire ER5356, and the microhardness of the former is lower than that of the latter.
3) Two low hardness zones are located near the fusion zone and the weld center of the welded joints. And the fracture of the joints usually occurs near the fusion zone either with or without the solution and aging treatment. The tensile properties with filler wire ER5356 is better than that with filler wire ER4043 in welding state. However, the latter is better than the former after the heat treatment. The tensile strength and yield strength of 0.2% could reach the base material level. And the elongation is also improved significantly, which could reach 20.99%.

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