Microstructure and mechanical properties of spray formed 7055 aluminum alloy by fiber laser-arc hybrid welding

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Abstract. The spray formed 7055 aluminum alloy with 4.2mm thickness was welded by laser-arc hybrid heat source. The microstructures and properties of the welded joints are studied. The results show that the weld appearance is very full and the weld zone is primary composed of equiaxed crystals. Those equiaxed crystals morphology in different positions are also different, and only a small amount of columnar crystals are locally formed in the fusion zone. The average microhardness values of the weld zone and the heat affected zone are lower than that of the base metal, reaching 64% and 82% respectively. The average tensile strength of welded joints with as-welded state reaches 51% of the base metal. However, the tensile properties of the joints are significantly improved after the two-stage solution and aging heat treatment, and the average tensile strength can reach 515MPa, which was about 84% of the strength of the base metal.

1. Introduction
Spray formed 7055 aluminum alloy has ultra-high strength and plasticity, so it has broad application prospects in the aerospace field. If this aluminum alloy adopts welding technology instead of traditional riveting, it will not only have a good weight reduction effect, but also have outstanding social benefits. At present, there are many researches on friction stir welding of this type of aluminum alloy [1-2], while researches on laser welding is relatively few. Wang Pengjian has carried out CO₂ laser welding of spray-formed 7055 aluminum alloy with 2mm thickness, and it is found that when 7055 filler wire is used, the internal pores of the joints are tendency to lessen, and the tensile strength of the welded joint can reach 372MPa [3]. When the thickness of base metal increases, the liquid surface tension of the welding pool is gradually insufficient to support its liquid gravity, which cause that the welding defects (such as surface depression, poor forming and so on) are more and more prone to produce. Ye Youli carried out self-fusion CO₂ laser welding for spray-formed 7055 aluminum alloy with 4mm thickness, and the tensile strength of the welded joint was only 243MPa, which is due to the collapse of the weld surface, internal pores and inclusions, and burning loss of enhanced alloying elements [4]. Compared with laser welding, laser-arc hybrid welding can improve weld formation, welding efficiency and quality obviously [5-6]. However, there are very few studies on the laser-arc hybrid welding of spray-formed 7055 aluminum alloy. Therefore, on the basis of the optimized laser-arc hybrid welding process of spray forming 7055 aluminum alloy, the microstructure of the welded joint was analyzed by the microscopic test method, the microhardness and tensile properties of the
Spray formed 7055-T76 aluminum alloy with 4.2 mm thickness and 5E06 filler wire with a diameter of 1.2mm are welded by laser-arc hybrid heat source. 7055 aluminum alloy belongs to Al-Zn-Mg-Cu series of high-strength aluminum alloys and has been used in various airframe and wings for a long time, so it is considered as one of the indispensable and important materials in the aerospace field [7-8]. 5E06 filler wire is a new type of micro-alloyed material by adding appropriate amounts of Er and Zr to 5A06 aluminum alloy. It has obvious effects in refining grains and improving thermal stability [9]. The chemical composition of the base metal and filler wire is shown in Table 1. The size of the plate is 300mm × 100mm, and the oil and the oxide film on the surface of the plate are removed by chemical cleaning before welding.

Table 1 Chemical compositions of 7055 aluminum alloy and 5E06 filler wire (wt %)

| Material | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Zr  | Er  | Al  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 7055     | 0.10 | 0.15 | 2.0-2.6 | 0.05 | 1.8-2.3 | 0.04 | 7.6-8.4 | 0.06 | 0.08-0.25 | / | Bal. |
| 5E06     | 0.015 | 0.10 | <0.01 | 0.87 | 5.67 | <0.01 | <0.01 | <0.01 | 0.10 | 0.22 | Bal. |

The fiber laser-MIG arc hybrid welding system was used in the experiment. The laser is the main heat source, and the paraxial arc is the additional heat source. The laser guides the arc and both act on the same molten pool. The normal rated power of the laser is 5kW, and the laser mode is multimode. A six-axis manipulator drives hybrid torch to realize the moving welding. The arc welding system adopts a push-pull aluminum welding special machine. The laser is transmitted through optical fiber and focused on the surface of the workpiece by a HIGHYAG laser head. The focal length of the focusing mirror is 250mm, the focal spot diameter is Φ0.525mm, and its axis is 10° to the normal of the welding plane. During the welding process, the side blowing shielding gas and the back shielding gas are introduced to the welding pool and the high temperature area of the weld to achieve all-round protection.

The butt welding method was adopted, and the welding seam was perpendicular to the extrusion direction of the sheet. The optimized welding parameters include the welding speed of 1.5m/min, the laser power of 4kW, the arc current of 80A, and the defocusing amount of 0mm. After welding, the metallographic samples and tensile samples were transversely intercepted. The microstructure of the cross-section of the weld was observed by using a VHX-5000 ultra-depth optical microscope. The microhardness values of each area of the welded joint were tested by an HXD-1000 TMC/LCD digital microhardness tester (measurement load with 0.1N and loading time with 10s). And the room temperature tensile properties of welded joints, including as-weld state and heat-treated state, were tested by Z100kN electronic universal material testing machine.

3. Results and discussion

3.1. Weld Macroforming

The overall formation of the spray formed 7055 aluminum alloy by laser self-fusion welding is poor. The depth of the depression on the front surface of the weld is about 0.2-0.5mm, and the local undercut on the back surface of the weld is obvious, as shown in Fig. 1a. When the laser-arc hybrid welding is used, the weld is fully formed (Fig. 1b). In the hybrid welding process, the filler wire is melted by the action of the pulsed arc and enters the molten pool with droplet transfer mode, which increases the liquid metal content and is more conducive to the backfilling and spreading of the weld metal. Meanwhile, under the action of the hybrid heat source, the geometrical size transition between the weld and the base metal is smooth, and there is no local undercut defect at the weld toe. Compared with the laser self-fusion welding, the heat input of the hybrid welding is larger, and the volume of the
The molten pool is relatively larger, so the fusion width of the hybrid welding is relatively wider. Therefore, laser arc hybrid welding can significantly improve the weld macro-forming of the spray-formed 7055 aluminum alloy, and the better joint quality is obtained.

![Macroscopic appearance of weld bead](image)

**Fig. 1** Macroscopic appearance of weld bead

### 3.2. Microstructure of welded joints

The grains of the spray-formed 7055 aluminum alloy are in an extruded and elongated state, and the microstructure has obvious directionality. A large number of fine second phases are precipitated in the grains and grain boundaries. The precipitation include most of η' (MgZn2) and a small amount of S (CuMgAl2). After fiber laser-arc hybrid welding, the cross-section of the welded joint is nearly X-shaped, as shown in Fig. 2a. This is closely related to the action mode of the heat source in the welding process. The power density of the fiber laser is as high as $3 \times 10^6$ J/cm², and it is very easy to generate penetrating keyhole through the thickness of the base metal. The metal vapor/plasma in the keyhole erupts upward and downward respectively, and it is dynamically gathers at the exit of the keyhole. These metal vapors/plasmas and the keyhole form a "two-point and one-line" heat source [10], which is also the main reason for the cross-sectional morphology of the nearly X-shaped weld. Meanwhile, the metal vapor/plasma ejected upward from the keyhole increases the stability of the arc and promotes the energy coupling effect in the hybrid welding process [11]. It can cause the upper part of the molten pool wider. With the distance far away from the welding heat source, the molten pool solidifies rapidly to form a weld.
Welded joints include weld zone, fusion zone and heat-affected zone (HAZ). Most of the weld zone is composed of equiaxed grains, and only a small amount of columnar grains are formed near the fusion zone, as shown in Figure 2d. The closer to the center of the weld, the more developed the secondary dendrites of the equiaxed grains. In the center of the weld, the average size of the equiaxed grains in the upper part is slightly larger than that in the lower part, but significantly smaller than that in the middle part. The fusion zone is very narrow and presents fine-grained layer structure with 20-100μm width. The HAZ is slightly darker than that of the base metal, and the closer to the fusion zone, the greater the number and size of the second phase precipitated at the grain boundaries and inside the grains.

When the spray-formed 7055 aluminum alloy is in molten state, a large number of solute elements are dispersed. Under rapid welding conditions, the molten pool solidifies rapidly, and there is a large degree of supercooling in the center of the molten pool, which leads to lots of equiaxed crystals formation. The Er element in the filler wire can react with Al preferentially to form the refractory particle Al₃Er [12], which are very beneficial to the heterogeneous nucleation during the solidification of molten pool. The filler wire enters the top of the molten pool by the form of liquid droplets. Limited by the thickness of the plate, the upper and lower convection of the molten pool may not be completely sufficient. The content of Er and Zr elements in the upper part of the molten pool is relatively high, so compared with the middle part of the weld, the equiaxed grains in the upper part of the weld are relatively refined. In the central part of the thickness direction and near the fusion zone, the heat dissipation is the fastest than the other parts during the solidification process, resulting in a small amount of columnar dendritic grains structure.

The formation of the fine-grained layer in the fusion zone is closely related to the chemical compositions of the base metal. Near the edge of the molten pool, the temperature is slightly higher than the melting point of the base metal, and the moving speed of the liquid fluid is very low. A large number of refractory particles, such as Al₃Ti, Al₃Zr and Al₃(Ti, Zr), are gathered in this part. All of these phases conform to the "interface correspondence principle", and are more conducive to the heterogeneous nucleation of the molten pool and further refine the grains.

Under the action of the hybrid heat source, the base metal is melted and solidified rapidly, and recrystallizes to form a welded joint. The microstructure of the weld zone is mainly composed of α(Al), η(MgZn₂), T(Mg₃Zn₄Al₃) and S(CuMgAl₃), that is, black α+T, α+S binary eutectic, α+η+T ternary eutectic and inclusion phases are distributed on the white α phase. Besides, there are some tiny pores and inclusions in the weld with a size of about 10-30μm. These tiny pores and inclusions may have a certain impact on the mechanical properties of the welded joints.
3.3. Microhardness of welded joints
The microhardness test was carried out on the upper, middle and lower part of the cross section of the spray-formed 7055 aluminum alloy welded joint, respectively. The specific test positions are shown in Fig. 2a, and the test results are shown in Fig. 3. It can be seen that the welded joint has serious softening phenomenon. The microhardness value of the weld zone is significantly lower than that of other areas, and there is a slight difference in the thickness direction. The average microhardness value of the upper and lower parts of the weld is slightly higher than that of the middle part. The average microhardness value of the entire weld zone is 92HV, reaching 64% of the base metal. The width of the fine-grained layer in the fusion zone is only about 20-100µm, so it is difficult to locate and measure the hardness value in this zone. The average microhardness value of the heat-affected zone is 119HV, which is about 82% of the base metal. The weld zone is softest, so the comprehensive mechanical properties of this part may also be the lowest.

3.4. Tensile properties of welded joints
The laser arc hybrid welded joints of spray-formed 7055 aluminum alloy were prepared as standard tensile specimens, and the tensile properties of the joints in the as-welded and heat-treated states were obtained by tensile tests. The heat treatment method with two-stage is used, including 455°C/2h+475°C/2h solid solution and 120°C/5h+160°C/12h aging. It can be found that the average tensile strength of the joints in as-weld state is 311MPa, which reaches 51% of the level of the base metal. However, it can be improved significantly after the heat treatment, and the average tensile strength of the joints reaches 515MPa, which is about 84% of the strength of the base metal. Whether in the as-welded or heat-treated state, the joints are all fractured in the weld zone. Therefore, the solution and aging heat treatment is the best method to improve the mechanical properties of spray-formed 7055 aluminum alloy welded joints.

| State of welded joints | Ultimate Strength Rm/MPa | Yield strength R_y/MPa | Elongation after fracture A/% | Fracture location |
|------------------------|--------------------------|------------------------|-----------------------------|------------------|
| As-weld state          | 311                      | 303                    | 4.29                        | 4 specimens, weld zone |
| Heat-treated state     | 515                      | 452                    | 1.22                        | 3 specimens, weld zone |
| Base metal             | 610                      | 426                    | 14.3                        | -                |

4. Conclusions
1) Laser arc hybrid welding can significantly improve the weld surface formation of spray-formed 7055 aluminum alloy, and overcome the defects such as surface depression and collapse by laser self-
fusion welding.

2) The cross-section of the joints obtained by the optimized laser arc hybrid welding is nearly X-shaped. The weld zone is mainly composed of equiaxed grains. There is only a small amount of columnar grain structure near the fusion zone. The fusion zone presents a fine-grained layer structure.

3) The 7055 aluminum alloy has serious joint softening phenomenon, and the average microhardness values of the weld zone and the HAZ reach 64% and 82% of the base metal respectively.

4) The average tensile strength of the welded joints reach 311MPa, and that could be improved significantly after solution and aging heat treatment, reaching 515MPa.

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