

Microstructure and property research on welded joints of 7xxx aluminum alloy welding wire TIG for 7075 aluminum alloy

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Received 30 October 2021; accepted 25 November 2021

Abstract 7xxx welding wire was self-made by spray forming ingots drawn to series welding wires products, and then TIG butt welding test is used for 5 mm thick 7075 high-strength aluminium alloy. After welding, the stress relief + solid-solution aging heat treatment (T6) were performed to joints, and the mechanical properties and microstructure of the joints before and after heat treatment were comparative analyzed. The results show that the properties of the heat-affected zone (HAZ) of the joint before heat treatment decreases, and the joint is softened. The welded joints tensile strength is 271.8MPa, the elongation is 5.6%, and the average hardness of the weld is 118. 4HV. The second phase particles such as η (MgZn₂), S(Al₂CuMg), Al₁₃Fe₄ are distributed in a network layer, with no apparent element segregation. After heat treatment, the structure of each area of the joint is coarsened, and a small amount of Fe-containing impurity phases are distributed. The η and S phases are dissolved in the matrix. The hardness of each area of the joint is increased to 155 HV, and the softening zone is disappeared, this leads the joint elongation close to 16.9%. The tensile strength is increased to 511.8 MPa, reaching 94% of the base metal tensile strength.

Key words 7xxx aluminium alloy welding wire, TIG welding on 7075 aluminium alloy, heat treatment, microstructure and properties

0 Introduction

7075 aluminium alloy belongs to the Al-Zn-Mg-Cu series heat-treatable and strengthened aluminium alloy in the 7xxx aluminium alloy. It has the advantages of high specific strength, good processing performance, and high fracture toughness. It is widely used in aerospace, military defence, rail transportation, Shipbuilding and other fields^[1-4]. The poor weldability of 7xxx aluminium alloy, the cracking of the precipitated phase and the over-aging problem have always been the bottleneck restricting its welding application^[5-7]. Shama^[8] and Ma Zhihua^[9] used friction stir welding to weld 7xxx aluminium alloys and the resulting joints. The strength can reach up to 85% of the power of the base

metal. However, due to the inflexible friction stir welding method, the narrow adaptation range of the joint strategy, the large equipment that is not suitable for on-site welding, etc. Nowadays, 7075 aluminium alloy generally uses 5xxx aluminium alloy welding wire for welding, and the maximum joint strength can only reach 60% of the base metal strength^[10]. The softening of the heat-affected zone of the 7xxx series aluminium alloy welding joint is unavoidable, and the welding heat input is the softening of the joint has a significant effect. The greater the welding heat input, the more serious the softening of the joint^[11], however, the weld seam obtained by welding with 5xxx aluminium alloy welding wire cannot be strengthened by heat treatment to improve the weld performance, which is the crux of the current 7xxx series aluminium alloy fusion welding problem.

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doi: 10.12073/j.cw.20211030001

Daniel Oropeza used self-made titanium carbide reinforced 7075 welding wire TIG to weld 7075 aluminium alloy. The strength of the joint after heat treatment can reach up to 84% of the power of the base metal^[12], using 7xxx series aluminium alloy welding wire to weld 7075 aluminium alloy, which is rarely reported in China.

7075 aluminium alloy welding wires were self-made in this paper, and TIG welding was used for butt welding of 5 mm thick 7075 high-strength aluminium alloy. After welding, the stress relief + solid-solution aging heat treatment (T6) were performed to joints. The joints' mechanical properties, microhardness, and microstructure properties be-

fore and after heat treatment were compared and analyzed.

1 Experimental materials and test methods

7075/T6 high-strength aluminum alloy test plate with a $150 \text{ mm} \times 75 \text{ mm} \times 5 \text{ mm}$ was selected as base material, with a tensile strength of 545 MPa, yield strength of 475 MPa, and an elongation rate of 8%. The welding material is a self-made 1.2 mm 7075 welding wire made of spray-formed blanks and then drawn to products. The chemical compositions of base metal and welding wire are shown in Table 1.

Table 1 Chemical composition of base metal and welding wire (mass fraction, %)

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
7075/T6 sample	0.08	0.20	1.41	0.06	2.55	0.20	5.60	0.02	≤ 0.05	Balance
7075 welding wire	< 0.01	0.03	2.18	0.16	1.96	< 0.01	5.80	< 0.01	≤ 0.05	Balance

The welding machine of TIG 4300i AC/DC inverter AC/DC argon arc welding machine made by ESAB company, with AC connection, and the shielding gas is 99.99% pure argon. The base material is beveled at 60° , leaving 2 mm blunt edges, after many welding trials, the process parameters were 3 mm/s welding speed, 200 cm/min wire feeding speed, 60% duty cycle, 120 Hz frequency, 3.2 mm arc length, and current of 165 A to obtain a welded joint. The self-made 7075 welding wire, the typical form and the macro morphology of the weld bead are shown in Fig. 1.

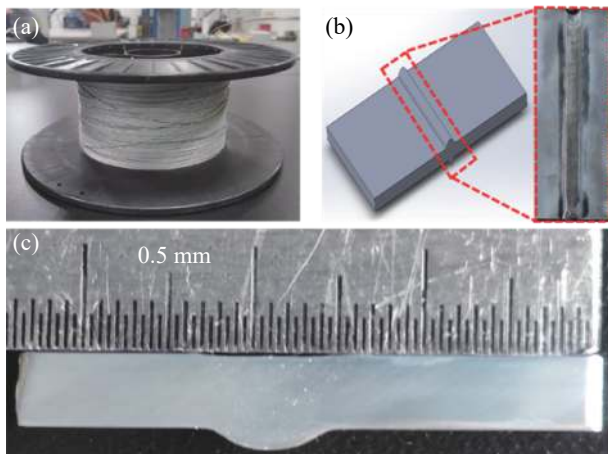


Fig. 1 Welding material and joint macro-morphology (a) Self-made 7075 welding wire (b) Joint form and weld appearance (c) Macroscopic appearance of joint cross section

It can be seen that using self-made welding wire for TIG butt welding of 7075 high-strength aluminum alloy, under

the premise of using appropriate process parameters, the weld is formed well without obvious macroscopic defects. Due to the easy hydrogen absorption of aluminum alloy melt, several pores can be observed in the cross-section of the weld.

The process of stress relief + solid-solution + aging heat treatment were performed on the joint after welding, and the typical samples heat treatment and no heat treatment were respectively cut in the direction perpendicular to the weld bead.

To test the mechanical properties of the welded joints, the tensile specimen as shown in Fig. 2 was processed in the direction perpendicular to the TIG weld, and the room temperature tensile test with a loading speed of 1 mm/min was carried out on the WDW3200 electronic universal tensile testing machine. Six similar specimens are tested for each weldment.

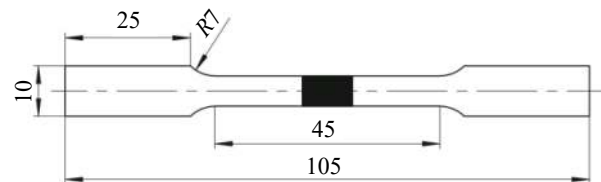


Fig. 2 Tensile sample diagram (mm)

Use the LECO AMH43 digital micro-hardness tester to measure the Vickers hardness of the joint with a load of 200 g and keep 12s. The location of the hardness test is shown in Fig. 3.

Use standard polishing methods to prepare metallo-

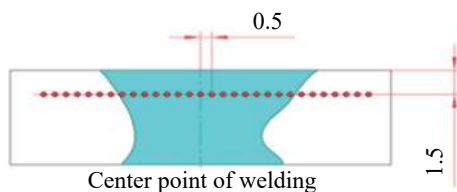


Fig. 3 Schematic diagram of hardness test dot position (mm)

graphic samples for corrosion with Keller reagent. And the microstructure of the welded joints was observed under a Leica-DMi8 metallographic microscope. The D8 Advance ECO X-ray Diffraction (XRD) instrument was used to analyze the phase composition of the welded joints. Sigma 500 scanning electron microscope (SEM) combined with energy spectrometer (EDS) was used to observe and analyze the joints, fracture morphology, precipitated phases and element distribution.

2 Results and analysis

2.1 Analysis of joint tensile properties and microhardness

Before and after heat treatment, the joint specimens were broken in the fusion zone. The room temperature tensile stress-strain curve and SEM morphology of the joint before and after heat treatment are shown in Fig. 4.

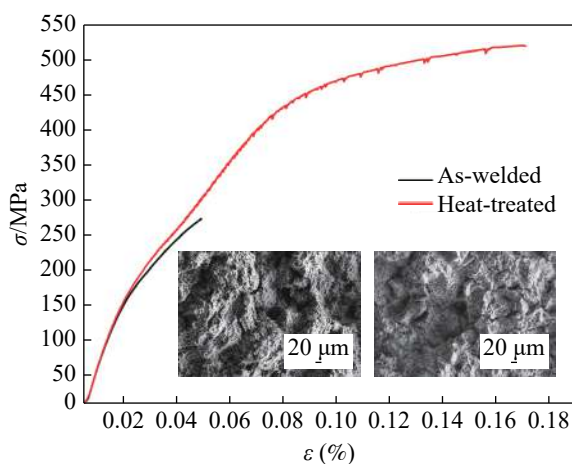


Fig. 4 Room temperature tensile stress-strain curve of joints before and after heat treatment

It can be seen from Fig. 4 that:

(1) The initial stress-strain curve of the joint before and after heat treatment completely overlaps in the tension test at room temperature. With the increase of stress, the joint stress-strain curves before and after heat treatment separate.

The strength limit and the elongation after fracture are significantly improved compared with the model before heat treatment. Because the yield stage is not apparent, the yield limit cannot be compared.

(2) Before heat treatment, the tensile strength of the joint sample was 271.8 MPa, the elongation rate was 5.6%, and the joint force reached 50% of the base metal strength, indicating that the self-made 7xxx series welding wire was used for 7075 aluminum alloy butt welding. The strength value of 7075 aluminum alloy joint reached the existing literature 5xxx series welding wire welding^[10].

(3) After heat treatment, the tensile strength of the joint sample is 511.8 MPa, and the elongation is close to 16.9%, which is 1.9 times higher than the joint strength before heat treatment, and the extension is increased by three times.

This proved that 7xxx series welding wire TIG welding 7075 aluminum alloy and heat treatment can significantly improve the mechanical properties of the welded joint. After heat treatment, the joint strength can reach 94% of the base metal strength, and the elongation rate goes twice the base metal.

(4) The cross-sections of the samples before and after heat treatment have the same structural characteristics. There are a large number of dimples on the section, with prominent ductile fracture characteristics. The small surface section structures of rock sugar shape partly occur on the cross-sectional. Agglomerated second phase particles can be observed between the small surface section structures designs, indicating that the joint fracture mechanism is a ductile-brittle compound.

Fig. 5 shows the Vickers microhardness distribution of the cross-section of the joint before and after heat treatment. Before heat treatment, the hardness of the joint showed a "W" distribution, and the average hardness of the weld was

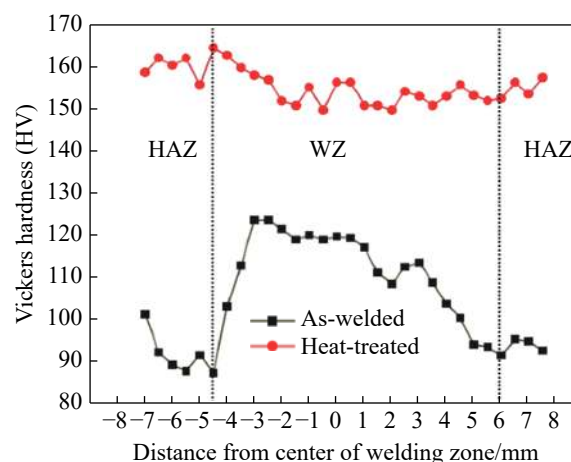


Fig. 5 Vickers microhardness of joint cross section before and after heat treatment

118.4 HV. Several reasons include burning segregation of alloying elements in the fusion zone, showed in Fig. 6 and Fig. 7, some of the second phases are clumped (Fig. 7 c) and the heat-affected area is over-aged, the precipitation phase grows up (Fig. 7 c), the grains grow up (Fig. 6 b), etc. As a result, the hardness of the fusion zone decreases sharply, and the position close to the fusion line drops to a minimum of 87 HV. The obvious decrease in the hardness of the fusion zone and the heat-affected zone causes the softening of the joint and affects the performance of the joint.

After the heat treatment, the joint is subjected to solid solution strengthening, homogenization and aging strengthening. The cross-section hardness distribution no longer has the typical fusion weld “W” distribution characteristics.

The overall hardness of each zone of the joint has been dramatically increased to a similar level, with an average hardness of 155 HV, which eliminates the softening of the joint caused by the decrease in the hardness of the heat-affected zone.

It is worth noting that the hardness of the heat-affected zone even exceeds that of the weld. The reason is that the internal as-cast structure of the weld is not as good as the rolled structure of the base metal through deformation strengthening.

2.2 Joint microstructure analysis

Fig. 6 shows the metallographic structure of the joint before and after heat treatment, in which Fig. 6 a, b, c is respectively the structure of each zone before heat treatment. The distribution of black precipitates at the grain boundar-

ies can be observed in each zone. Fig. 6 c shows that the base material is a typical rolled structure, and the grains are band-like or fibrous along the deformation direction. Fig. 6 b shows that the heat-affected zone is recrystallized and incompletely recrystallized due to the thermal welding cycle. The crystal grains are irregular dendrites and are coarser than the base material.

Fig. 6 a shows that the weld is an equiaxed crystal structure. The crystallization process is accompanied by the release of latent crystallization heat, outward heat conduction, and more alloy impurities in the molten pool to promote nucleation. The inside of the molten pool quickly reaches a local thermal equilibrium to form an Equiaxed crystal structure.

Fig. 6 d–f shows the structure of each zone after heat treatment compare to the joint before heat treatment. Due to the complete dynamic recrystallization, the irregular dendrites in the heat-affected zone transform into the columnar crystal structure, and the fusion zone is small. The same equiaxed crystal and columnar crystal structures are transformed into coarser equiaxed and columnar crystals due to the same reason. Except for a few insoluble second phase particles dispersed on the grain boundary, most of the black precipitated phases in each zone are dissolved in the matrix. Still, the grain structure has been significantly coarsened.

2.3 SEM observation and XRD analysis of the precipitated phase of the joint

Fig. 7 shows the SEM images of the precipitated phases in the joint structure before and after heat treatment.

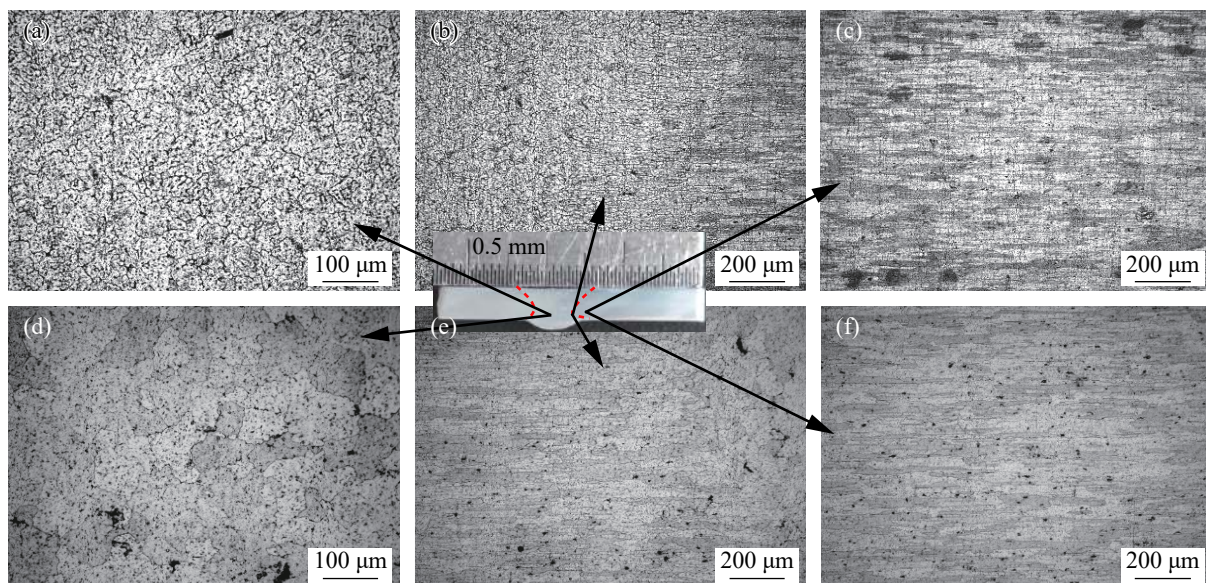


Fig. 6 Microstructure of the joint (a) WZ as-welded (b) HAZ as-welded (c) BM as-welded (d) WZ heat-treated (e) HAZ heat-treated (f) BM heat-treated

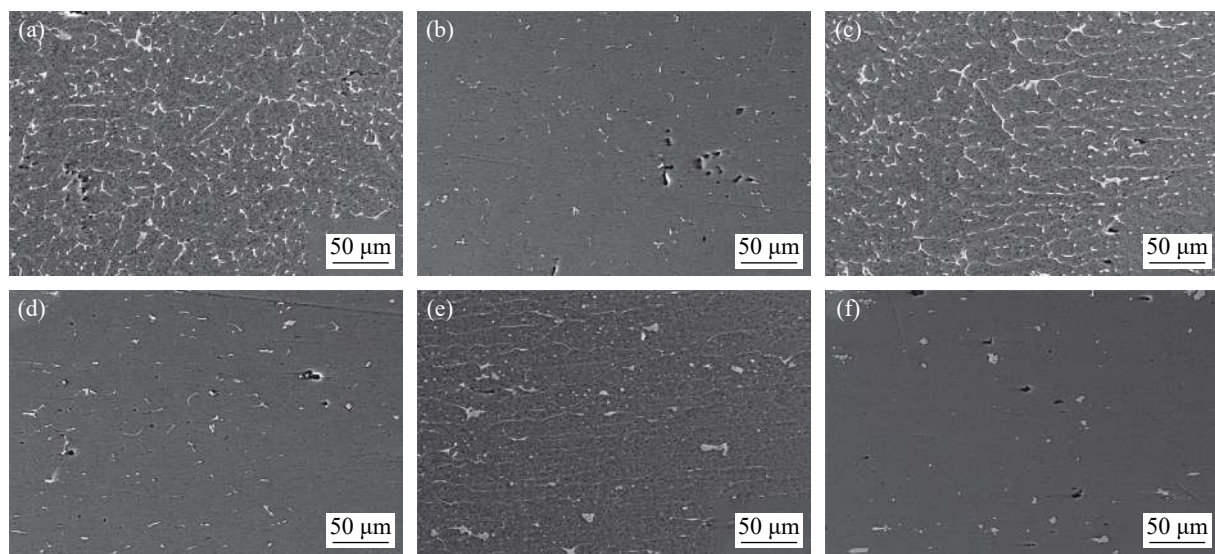


Fig. 7 SEM images of precipitates (a) WZ as-welded (b) WZ heat-treated (c) HAZ as-welded (d) HAZ heat-treated (e) BM as-welded (f) BM heat-treated

Fig. 7 a, Fig. 7 c, Fig. 7 e show the joint weld area, weld-fusion-heat-affected zone and base material before heat treatment which light-colored part in the figure is the precipitated phase of the eutectic structure. It can be seen from Fig. 7 a that there are a large number of coarse second-phase particles in the weld structure before heat treatment, and these second-phase particles are densely distributed on the grain boundaries, even in a continuous distribution state.

The composition of the second phase particles is more complicated. Through XRD pattern analysis, as shown in Fig. 8 a, it is found that the precipitated phase is mainly composed of η (MgZn₂), S(Al₂CuMg), Al₁₃Fe₄ and AlCu₃ to form some eutectic structures distributed in the grain boundaries. The area is shown in Fig. 7 c contains the weld-fusion-heat-affected zone. It can be observed that the sediments have similar characteristics to the weld zone in morphology, type and distribution, and they are also densely distributed on the grain boundaries. It is a network layered structure, but due to the severe segregation of alloy elements in the fusion zone, some second phase particles are more coarsely distributed in a block shape.

Fig. 7 e shows that the residual phases on the grain boundaries of the base material are aligned along the rolling direction. Fig. 7 b, d, f respectively corresponds to the joint weld area, weld-fusion-heat-affected zone and base metal after heat treatment. It can be found that after heat treatment, the second phase in each area is significantly reduced. Already dissolved in the matrix, there are only a few small insoluble particles.

For Cu-containing alloys, when the ratio of Zn/Mg>1.5, the second phase in the alloy is easily dissolved^[13], com-

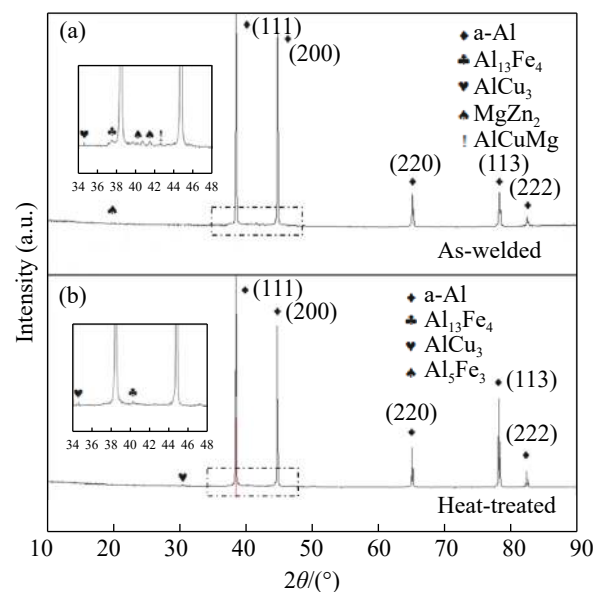


Fig. 8 XRD patterns of weld structure before and after heat treatment (a) Before heat treatment (b) After heat treatment

bined with the XRD pattern analysis of the weld after heat treatment in Fig. 8 b, it can be observed that both η (MgZn₂) and S (Al₂CuMg) phases have been completely dissolved, the Fe-containing impurity phases Al₁₃Fe₄, Al₅Fe₃ and AlCu₃ are scattered in the matrix in the form of dots and blocks.

Fig. 9 is the element distribution diagram of the weld structure before and after heat treatment. Fig. 9 a shows the distribution of elements in the weld structure before heat

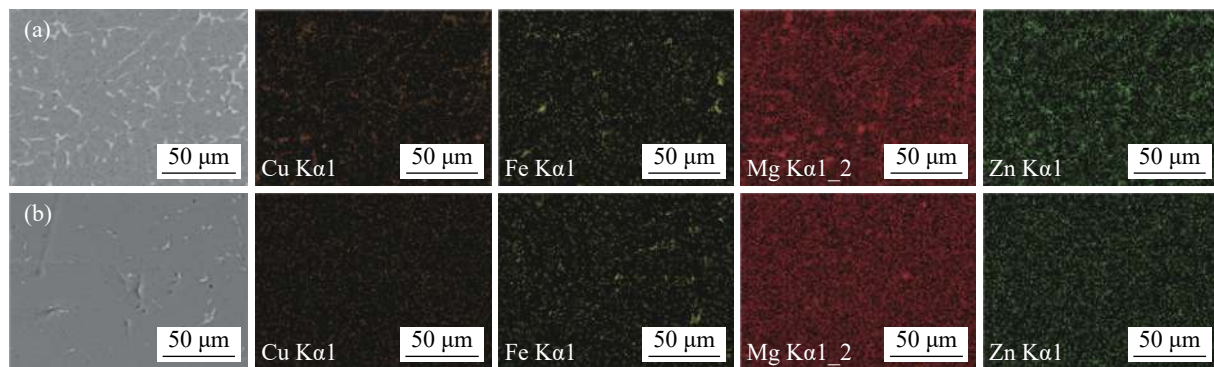


Fig. 9 Element distribution diagram of weld structure before and after heat treatment (a) Before heat treatment (b) After heat treatment

treatment. It can be observed that the element distribution in the weld structure before heat treatment is uneven. Cu, Fe, Mg, and Zn all have a certain degree of segregation, and the segregation of Cu and Fe is severe.

From Fig. 9 b, the distribution of the elements in the weld structure after heat treatment tends to be uniform. However, the Fe element segregation is still apparent because the Fe-containing second phase particles are difficult to dissolve.

3 Conclusions

(1) For 7xxx welding wire 7075 aluminum alloy butt welding joints before heat treatment, it has the properties of the tensile strength 271.8 MPa. The average hardness of the weld is 118.4 HV, the hardness of the fusion zone and heat-affected zone decreases to 87 HV. $\eta(\text{MgZn}_2)$, $\text{S}(\text{Al}_2\text{CuMg})$, $\text{Al}_{13}\text{Fe}_4$ and other eutectic structure precipitated phases are distributed in the grain boundary of each area of the joint in the form of a network. The particularly serious element segregation exists in the fusion zone and the heat-affected zone. The properties of the heat-affected zone deteriorate, which causes the area to soften, leads to a decrease in the overall mechanical properties of the joint.

(2) After the joint is subjected to stress relief + solid-solution + aging heat treatment, the grain structure of each joint area is coarsened. However, due to the disappearance of the coarse network layered precipitated phases, most of the second phases, including $\eta(\text{MgZn}_2)$ and $\text{S}(\text{Al}_2\text{CuMg})$, dissolve into the matrix, resulting in solid solution strengthening. As a result, the overall hardness of each zone is increased to 155 HV, the softening zone is eliminated, and the mechanical properties of the joint are greatly improved. The elongation is close to 16.9%, and the tensile strength is increased to 511.8 MPa, reaching 94% of the base material's tensile strength.

(3) TIG welding of 7075 high-strength aluminum alloy is carried out with the 7xxx welding wire formed by the spray-formed blank and then drawn. Although the welding seam hardness is much higher than the 5xxx welding wire, the joint softening phenomenon caused by the deterioration of heat-affected zone performance is still inevitable. Due to the barrel effect, the final mechanical properties of the joint are only equivalent to the commonly used 5xxx welding wire. After the joint heat treatment, it can effectively eliminate the softening zone and significantly improve the overall mechanical properties of the joint, which becomes the outstanding feature and advantage of 7xxx welding wire welding 7075 high-strength aluminum alloy.

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