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Effect of post-weld heat treatment on microstructure and mechanical properties of 7055 aluminum alloy electron beam welded joint

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Abstract

The spray forming 7055 aluminum alloy is welded by electron beam welding (EBW). After welding, the single solution treatments under different temperatures and then aging treatment (STA) and the stepped solution treatment and then aging treatment (SSTA) are carried out for the welded joints respectively. The effect of different post-weld heat treatment (PWHT) procedures on the microstructure and mechanical properties of welded joints is systematically investigated. Results show that, in as-welded condition, the fusion zone mainly consists of $\alpha$-Al phase, and there are some precipitated phases such as $\text{Mg}_3\text{Al}_2\text{Zn}_{49}$, $\text{Al}_7\text{Cu}_2\text{Fe}$, $\text{Al}_2\text{CuMg}$, and a small amount of phase $\text{MgZn}_2$ in weld metal. After PWHT, the continuous network structures at grain boundary disappear. There are only a few isolated particle phases at grain boundary, and many ellipsoidal $\eta'$ phases and rod-like $\eta$ phases are precipitated within grains. The mechanical property of welded joint is improved after PWHT. Compared with that of in STA condition, the strengthening effect to welded joint is more obvious after SSTA. In SSTA condition, the hardness of weld zone is close to that of base metal (BM), and the tensile strength of welded joint reaches 486.2 MPa, which is 85.6% of that of BM. There are many equiaxed dimples on the tensile fracture surface, and the joint mainly presents the characteristic of ductile fracture.

1. Introduction

The $7\times\times\times$ aluminum alloys such as 7055 Al have high strength. Compared with that of the high-strength steels, high-strength aluminum alloys have high specific strength (strength to weight ratio) due to their low density. Consequently, as one types of the light-weight and high-strength structural materials, the $7\times\times\times$ aluminum alloys are widely used in the aerospace and rail transportation fields, etc [1, 2]. Compared with that by the traditional casting process, when the $7\times\times\times$ aluminum alloys are prepared by the spray forming process, their mechanical property can be further improved. Spray forming technology belongs to one of the advanced material preparation technologies, which has the advantage of low cost and high efficiency. During the spray forming process, the molten metal is atomized into dispersive droplets by gas such as nitrogen at a certain temperature, and the droplets are deposited onto the substrate under a certain pressure. Due to the rapid cooling rate, the materials such as aluminum alloy prepared by the spray forming process is dense, and the segregation of alloying elements is greatly reduced. Moreover, the equiaxed grains are fine and the precipitated phases distribute uniformly in the Al matrix. Consequently, the 7055 aluminum alloy prepared by the spray forming technology has excellent mechanical performance [3–5].

Welding is often used in the industrial fields to fabricate structural components. Some $7\times\times\times$ series aluminum alloys were welded by using different welding procedures, such as gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), laser beam welding (LBW) and hybrid laser welding [6–9]. During the welding
of the 7××× series aluminum alloys, the welding defects such as gas pores and hot cracking were probably generated, which resulted in the poor mechanical property of welded joint [10]. Compared with that of the other fusion welding processes, electron beam welding (EBW) has the characteristics of high energy density, large depth-to-width ratio of weldment and narrow heat-affected zone (HAZ), etc. Moreover, EBW is usually conducted in vacuum environment, and the active metals such as aluminum alloys can be well protected, thus the welded joint with good quality will easily be obtained. The welding parameters are easily adjusted during EBW, and the adaptability to the shape and dimension of workpiece is better than that of friction stir welding (FSW). Consequently, EBW has great advantages in the welding of 7××× series aluminum alloys.

In as-welded (AW) condition, the fusion zone (FZ) was under-aged and the heat-affected zone (HAZ) was over-aged, thus the strength coefficient of joint was relatively low [11]. In order to improve the mechanical performance of welded joint, the appropriate post-weld heat treatment (PWHT) was necessary to carry out for the 7××× aluminum alloy joints. The 7075 alloy joint by GTAW was treated at 140 °C for 10 h [6]. Many strengthening phases were precipitated in FZ and HAZ after PWHT, and the hardness and tensile strength of joint were obviously increased. The artificial aging treatment of 125 °C/24 h was carried out for the AA7075 alloy joints [12]. Results showed that the fatigue life of both GTAW and GMAW joints was increased by 20% to 25% after PWHT.

Sharma et al [13] reported that the mechanical property of 7039 alloy FSW joint was improved to a certain extent after aging treatment. Gholami et al [14] found that, compared with that of double aging treatment, the microhardness of joint was significantly improved after single aging treatment. Because the volume fraction of fine spherical phases in weldment was higher than that of by single aging treatment. The mechanical properties of welded joints are significantly improved after solution treatment and then artificial aging treatment [15, 16]. Because the agglomerated precipitates were dissolved into the Al matrix, and many fine MgZn2 phases were precipitated in the weld zone. The precipitation of MgZn2 phase and the interaction with dislocations were advantageous to the mechanical properties of 7××× aluminum alloy joint.

As mentioned above, 7055 aluminum alloy has good mechanical properties, and EBW has great advantages for the welding of 7055 aluminum alloy. However, the mechanical properties of welded joint are not high enough in AW condition. In order to increase the tensile strength of welded joint, it is necessary to perform PWHT after welding. On the whole, the research on the 7055 aluminum alloy EBW joint and its PWHT process is insufficient. In present work, the effect of different PWHTs on the microstructure and mechanical properties of 7055 alloy EBW joints are systematically investigated.

### 2. Material and experimental procedure

The base metal (BM) is the spray forming 7055 aluminum alloy, and its chemical composition is as follows (wt.%): Al-8.2Zn-2.2Mg-2.1Cu-0.13Fe-0.12Zr-0.09Si-0.03Cr-0.05Ti. The BM is machined to welding sample with the dimensions of 100 mm × 50 mm × 4 mm. Before welding, the sample surface is thoroughly cleaned. The butt joint is used, and it is welded by EBW along the longitudinal direction of sample. After some attempt welding, the optimized welding parameters are determined as follows: the pressure of vacuum chamber is 5 × 10⁻³ Pa, acceleration voltage 60 kV, working distance 300 mm, electron beam current 15 mA, welding speed 10 mm s⁻¹, and focusing current 599 mA. In order to improve the fluidity of molten pool and reduce the weld porosity, electron beam scanning with the circular pattern is added during welding, and the scanning frequency is 500 Hz and scanning amplitude 1%.

After welding, the different PWHT procedures are carried out for the welded joints respectively. The heat treatment procedures involve the single solution treatment under different temperatures and then aging treatment (STA), and the stepped solution treatment and then aging treatment (SSTA). The different PWHT procedures of welded joints are summarized in Table 1.

| Sample No. | Solution treatment | Aging treatment |
|------------|-------------------|----------------|
| STA1       | 450 °C/1.5 h      | 120 °C/24 h    |
| STA2       | 475 °C/1.5 h      | 120 °C/24 h    |
| STA3       | 500 °C/1.5 h      | 120 °C/24 h    |
| SSTA       | 450 °C/1 h + 480 °C/0.5 h | 120 °C/24 h |

Many researchers [17, 18, 19, 20] found that, compared with that of double aging treatment, the mechanical properties of joint were significantly increased. Moreover, the hardness and tensile strength of joint were obviously increased. The artificial aging treatment of 125 °C/24 h was carried out for the AA7075 alloy joints [12]. Results showed that the fatigue life of both GTAW and GMAW joints was increased by 20% to 25% after PWHT.
2.5% HNO₃ + 1.5% HCl + 1% HF + 95% H₂O. The MM6 optical microscope (OM) and Quanta 200 scanning electron microscope (SEM) are used to observe the microstructure of welded joint respectively. The D8 Advance x-ray diffractometer (XRD) is used to inspect the phase constituent of FZ. The energy dispersive spectrometer (EDS) is used to analyze the chemical composition of micro-region. The JEM-2100F transmission electron microscope (TEM) is used to investigate the precipitated phases in weldment. The TEM sample is prepared by the following steps: mechanically grinding to the thickness of about 60 μm, then punching thin foils with the diameter of 3 mm, and thinning by twin-jet electropolishing. According to the standard GB/T 2651-2008/ISO 4136:2001, the CMT-5105 electronic universal material testing machine is used to test the tensile strength of joints, and the loading speed is 1 mm min⁻¹ during stretching. The microhardness of weld zone is measured by using HXS-1000A hardness tester with the load of 200 g and duration time of 15 s.

3. Results and discussion

3.1. Microstructure

Figure 1 shows the microstructure of joint transition zone (TZ) before and after PWHT. Usually, the welded joint can be divided into FZ, fusion line (FL) and HAZ. The microstructure in different regions is obviously different. In AW condition, the microstructure of TZ is shown in figure 1(a). No welding defects such as crack and gas pores are generated in weldment, which means that the formation of weld is well. The grains in HAZ are coarser owing to the effect of weld thermal cycle. The primary phases are generated within grains. Moreover, the equiaxed grains zone (EQZ) with the width of about 15 μm is formed along FL, and the average of grain size is 3.9 μm. The reason for the formation of EQZ is as follows: There is a small amount of element Zr in BM, and the Al₃Zr particles are easily formed along FL during welding. The lattice constant of Al₃Zr is 0.409 nm, and the lattice mismatch with Al matrix (lattice constant 0.405 nm) is lower than 5%, which meets the conditions of heterogeneous nucleation in the structure and size of nucleus. In addition, the Al₃Zr particles have higher thermal stability, and they can be acted as the nucleus during solidification process. Consequently, the fine EQZ was formed along FL [17, 18].

Figures 1(b)–(d) shows the microstructure of joint TZ after STA1, STA2 and STA3 respectively. From STA1 to STA3, with the elevation of solid-solution temperature, the primary phases in HAZ are gradually decreased, and the EQZ gradually disappears. As shown in figure 1(b), some primary phases along grain boundary are dissolved, but some spherical particles are generated. During solution treatment process, the alloying elements are dissolved into the Al matrix, and the supersaturated solid solution is formed after rapid cooling. If the primary phases at grain boundary are not fully dissolved, they will absorb solute atoms from the matrix and grow.
up in the subsequent aging process. These particles are easily resulting in stress concentration and become the source of cracks. As shown in figure 1(c), the EQZ disappears after STA2. Simultaneously, primary phases are significantly reduced in HAZ, and there are a small amount of spherical particles at grain boundary. As shown in figure 1(d), when the solid-solution temperature is risen to 500 °C, most of the primary phases in HAZ are transformed into the fine particle phases. After SSTA, the microstructure of joint TZ is shown in figure 1(e). It is similar to that of after STA2, but the spherical particles in HAZ and EQZ are further reduced.

In the right sides of figures 1(a)–(e), the microstructure of FZ is obviously different before and after PWHT. As shown in figure 1(a), in AW condition, the equiaxed grains distribute uniformly in FZ, and the average of grain size is 5.1 μm. After STA1, STA2 and STA3, the microstructure of FZ is shown in figures 1(b)–(d) respectively. With the elevation of solid-solution temperature, the particle phases within grains are gradually decreased. The grain sizes are increased to 6.7 μm or 7.1 μm after STA1 or STA2 respectively. When the solid-solution temperature is risen to 500 °C, the grain boundaries become indistinctly. Grain boundaries have resistance to the motion of dislocations, and the piles up of dislocations at grain boundaries will result in a counterforce on the dislocation source within grains. Grain boundaries would be melted at higher temperature, which was disadvantageous to the tensile strength of welded joint [19]. Figure 1(e) shows the microstructure of FZ after STA3. Compared with that of after STA2, the spherical particles in FZ are further reduced after SSTA. The grains do not obviously grow up, and the average of grain size is 7.3 μm in FZ.

In order to understand the phase composition and distribution in FZ, SEM observation and EDS analysis are performed before and after PWHT. In AW condition, SEM image of FZ is shown in figure 2(a). It has almost no precipitated phase within the equiaxed grains, but there are continuous network primary phases at grain boundaries, as shown in figure 2(b). The EDS analysis of point A is carried out, and the corresponding result is shown in figure 2(c), which indicates that such primary phases are enriched with alloying elements Zn, Mg and Cu.

After STA2, SEM image of FZ is shown in figure 3(a). Compared with that of in AW condition, the aggregation of primary phases at grain boundaries is significantly reduced. As shown in figure 3(b), many fine strengthening phases are precipitated within grains, and there are a few isolated spherical particles with the size of 1–2 μm at grain boundaries. EDS analyses are carried out for the spherical particle at point A and the needle-like phase at point B, and the corresponding results are shown in figures 3(c) and (d) respectively. There are alloying elements Cu and Mg at point A, which is supposed to be the AlCuMg phase. Besides the elements Cu and Mg, there is a certain amount of element Fe at point B. The needle-like phase was probably the Al₇Cu₂Fe phase [20]. Compared with that in AW condition, no network primary phase distributes at grain boundaries after STA2, and there are only a few isolated spherical phases. In addition, it has no element Zn in the primary phase, and the content of elements Mg and Cu are decreased. At the solution temperature, the ratio of diffusion coefficient for elements Cu: Mg: Zn was about 1: 2.6: 4.9. Consequently, the element Zn was preferentially dissolved into the Al matrix [21]. Alloying elements are dissolved in Al matrix, which is conducive to the precipitation of strengthening phases.

After SSTA, SEM image of FZ is shown in figure 4(a). Compared with that of after STA2, the aggregation of primary phases at grain boundaries is further reduced. As shown in figure 4(b), there are a small amount of primary phases with the size of 0.5–1.0 μm at grain boundaries. The EDS analysis of point A is shown in figure 4(c). There are alloying elements Cu and Mg in this region. Compared with that of the corresponding region in figure 3(b), the contents of elements Cu and Mg within primary phases are further reduced. More alloying elements can be dissolved into the Al matrix during stepped solution treatment process. Consequently, the phase composition and distribution in FZ are greatly improved after SSTA.

XRD analyses are carried out for the FZ under different conditions. As shown in figure 5, in AW condition, the FZ mainly consists of α-Al phase, and there are some precipitated phases, such as Mg₃₂(Al, Zn)₄₉, Al₇Cu₂Fe,
Al₂CuMg phase and a small amount of MgZn₂ phase. After STA2, the quantity of Mg₃₂(Al,Zn)₄⁹ and Al₂CuMg phases is decreased, but the quantity of main strengthening phases MgZn₂ is increased. After SSTA, besides a small amount of phases Al₂CuMg and Al₅Cu₂Fe, the strengthening phases MgZn₂ are significantly precipitated in weldment, which is advantageous to the mechanical performance of welded joint.

TEM analysis is carried out for the precipitated phases in FZ. Generally, the precipitation sequence of secondary phases in Al–Zn–Mg–Cu alloy was as follows [22, 23]: supersaturated solid solution (SSSₐ) → G.P. zone → metastable γ’(MgZn₂) → stable γ(MgZn₂). In AW condition, the bright field image of weldment is shown in figure 3(a). There are some spherical G.P. zones with the radius of about 3 nm in weldment. TEM image of weldment after STA2 is shown in figure 3(b). A large number of strengthening phases are precipitated
in the Al matrix. There are the ellipsoidal $\eta'$ phase with the width of 6–10 nm and the rod-like $\eta$ phase with the length of 10–20 nm [24, 25]. After SSTA, TEM image of weldment is shown in figure 6 (c). Compared with that of after STA2, the size of strengthening phases is not obviously varied, while the quantity of strengthening phases is greatly increased. According to the Orowan mechanism, the motion of dislocations will be hindered and dislocations can only bypass the $\eta'$ phase and $\eta$ phase. When the radius of precipitation phase is unchanged, the strengthening effect will be enhanced with the increase of the quantity of precipitated phase. Consequently, the mechanical performance of welded joint can be further improved.

3.2. Microhardness
Along the direction of ‘FZ-HAZ-BM’, the microhardness of weld zone is measured, and the spacing between two measuring points is about 0.1 mm. The distribution curves of microhardness under different conditions are shown in figure 7. In AW condition, the hardness is the minimum in FZ, and the average of hardness is 131 HV, which is lower than that of BM (201 HV). The hardness in HAZ is also lower than that of BM. According to the microstructure analysis of welded joint, as shown in figure 1 (a), the EQZ is formed along FL, which results in the effect of grain refinement strengthening. Consequently, the hardness is greatly increased in this region. Under the effect of weld thermal cycle during welding, the strengthening phases in HAZ aggregated and grew up, thus the effect of precipitation strengthening was weakened [26]. Compared with that of in AW condition, the hardness of weld zone is obviously improved after PWHT. After STA1, due to insufficient solution treatment at the temperature of 450 °C, the hardness in FZ and HAZ is only increased to 162 HV and 180 HV, respectively. After STA2, STA3 and SSTA, the hardness of weld zone is close to that of BM. Compared with that of after STA2, the hardness of weld zone is slightly increased after SSTA. Because single solution treatment is sufficient at the temperature of 500 °C, the hardness of weld zone is the maximum, and the average of hardness is 194 HV. After PWHT, the hardness of weld zone is a little lower than that of BM, the main reasons are as follows: (1) during EBW, the temperature of molten pool exceeds the boiling
point of elements Zn and Mg, which probably cause the evaporation and burning loss of some alloying elements; (2) due to the effect of weld thermal cycle, the grains in HAZ are coarser than that in BM.

3.3. Tensile strength
Results of tensile tests for the BM and welded joints under different conditions are given in table 2, and the corresponding stress-strain curves are shown in figure 8. The data in table 2 is the average of three measurements. In AW condition, the tensile strength of welded joint is 371.7 MPa, which is 65.4% of that of BM. In STA conditions, with the variation of solution temperature, the tensile strength and elongation of welded joints are varied accordingly. After STA2, the tensile strength of welded joint is 464.8 MPa. In SSTA condition, the mechanical performance of welded joint is further improved, and the maximum tensile strength reaches 486.2 MPa, which is 85.6% of that of BM. Although the tensile strength of welded joint is significantly increased after PWHT, weld metal is the weak area of welded joint, and all joints fail in weldment during stretching.

3.4. Fracture analysis
SEM observation is carried out for the tensile fractures of welded joints under different conditions. SEM images of fracture in AW condition are shown in figures 9(a) and (d). As shown in figure 9(a), the fracture morphology of joint is relatively flat. There are a small amount of dimples on the fracture surface, as shown in figure 9(d). The continuous network primary phases at grain boundaries probably become the propagation paths of crack, and the joint mainly presents the characteristic of intergranular fracture. After STA2, the fracture morphologies of joint are shown in figures 9(b) and (e). Compared with that of in AW condition, the plasticity of welded joint is improved to a certain extent after PWHT. As shown in figure 9(b), cleavage facets appear in the fracture. There are many dimples on the fracture surface, as shown in figure 9(e), and it presents the mixed mode of ductile and brittle fracture. After SSTA, the fracture morphologies of joint are shown in figures 9(c) and (f). There are more equiaxed dimples on the fracture surface, as shown in figure 9(c). In addition, there are some secondary phases distributed at the bottom of dimples, as shown in figure 9(f), and it mainly presents the characteristic of ductile fracture. Obviously, the plasticity of welded joint is further improved after SSTA. The secondary phases can effectively hinder the motion of dislocations, which is advantageous to the tensile strength of welded joint.

Table 2. Results of tensile tests of BM and welded joints under different conditions.

| Sample no. | Tensile strength (MPa) | Elongation (%) |
|------------|------------------------|----------------|
| BM         | 568.0 ± 9.7            | 8.1 ± 0.8      |
| AW         | 371.7 ± 6.6            | 2.1 ± 0.3      |
| STA1       | 414.1 ± 9.3            | 3.6 ± 0.5      |
| STA2       | 464.8 ± 8.5            | 4.3 ± 0.6      |
| STA3       | 443.5 ± 11.0           | 2.9 ± 0.4      |
| SSTA       | 486.2 ± 5.9            | 5.5 ± 0.5      |
4. Conclusions

In AW condition, the FZ is composed of $\alpha$-Al matrix and some precipitated phases such as $\text{Mg}_32\text{(Al, Zn)}_{49}$, $\text{Al}_2\text{Cu}_2\text{Fe}$, $\text{Al}_2\text{CuMg}$, and a small amount of phase $\text{MgZn}_2$. After PWHT, the continuous network structures at grain boundary disappear. There are only a few isolated particle phases at grain boundary, and many ellipsoidal $\eta'$ phases and rod-like $\eta$ phases are precipitated within grains. The precipitation of strengthening phase can increase the resistance to dislocation motion, which is beneficial to the tensile strength of welded joint.

Under the condition of single solution treatment and then aging treatment, the aggregation of alloying elements at grain boundary is gradually decreased with the elevation of solution temperature. However, the grain boundaries will be melted at higher temperature, which is disadvantageous to joint strength. After single solution treatment at the temperature of 475 °C and then aging treatment (STA2), the tensile strength of welded joint reaches 464.8 MPa. After SSTA, the aggregation of alloying elements at grain boundary is significantly reduced, and more strengthening phases are precipitated in weld zone. As a result, the tensile strength of welded joint is further improved, and it reaches 486.2 MPa, which is 85.6% of that of BM.

Figure 8. Stress-strain curves of BM and welded joints under different conditions.

Figure 9. SEM images of fracture morphologies under different conditions: (a) AW, (b) STA2, (c) SSTA, (d) local magnification of (a), (e) local magnification of (b), (f) local magnification of (c).
In AW condition, continuous network structures distributed at grain boundary easily become the path of crack propagation, and the joint mainly presents the characteristic of intergranular fracture. After STA2, the network structures at grain boundary disappear, and a large number of strengthening phases are precipitated within grains. The joint presents the mixed mode of ductile and brittle fracture. After SSTA, there are more strengthening phases in weld zone, and the tensile strength and plasticity of welded joint is further improved.

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