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Study on properties of aluminum alloy welded by friction stir welding

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Abstract: In order to meet the special requirements of aerospace industry for materials of aluminum alloy, the precisely controlled heat treatment was studied. The 2219 aluminum alloy welded plate was prepared by friction stir welding, and its microstructure and mechanical properties were studied correspondingly. The reasons for strength reduction of welded joints are analyzed and summarized. The research results showed that the average tensile strength of the welded joints increased to 393 Mpa and the elongation increased to 12.6% of the base metal. With the special recrystallization technology of high temperature oscillation heat treatment, the fine grains can be maintained, the plasticity of aluminum alloy can be restored, which means that the softening problem can be eliminated and the mechanical strength can be improved.

1. Introduction

Aluminium alloy is the main structural material of aerospace industry equipment. In order to promote the development of aerospace technology, the efforts of five generations have been made. The first is aging heat treatment of high strength aluminium alloy; the other is over-aging heat treatment of high strength aluminium alloy to obtain good corrosion resistance; the third is aging heat treatment of high purity, high corrosion resistance aluminium alloy; the fourth is precise control of multi-scale second phase to obtain ultra-high corrosion resistance and the fatigue resistance of aluminium alloy; the fifth is the high hardenability of aluminium alloy [1]. With the development of materials technology, aluminium alloys are facing severe challenges of structural weight loss, high reliability and long life. 2 serial or 7 serial aluminium alloys with high strength and toughness are mainly used in space launch vehicles, as shown in Figure 1.

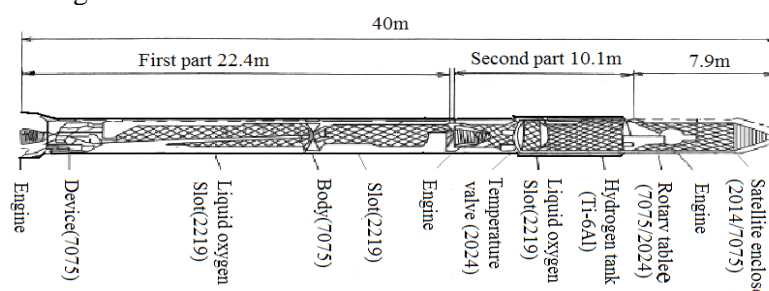


Figure 1. Materials of rocket parts.



The friction stir welding (FSW) is a new solid connection technology, which solves the traditional welding problems of aluminium alloy [2-5]. It is widely used in the manufacturing process of those aerospace equipment. There are many studies on the mechanism and properties of FSW welded aluminium alloys at home and abroad [6,7]. However, the thermal and mechanical damage will degrade the mechanical properties of the welded material. Generally, the results in engineering practice show that the ratio of weld metal strength to base metal strength is lower. Obviously, the advantages of high strength aluminium alloy are not fully utilized [8,9]. According to the analysis of 2219-AA FSW welded joint from the macro-and micro-viewpoint, it is necessary to control the precipitating of θ phase accurately through the way of special recrystallization technology in post-weld heat treatment. It is considered that the precipitation of θ phase is the cause of the decline of the joint performance, so a heat treatment method to improve the tensile strength of the joint is put forward. This study will provide useful reference for high strength aluminium alloys used in aerospace industry.

2. Experimental materials and method

The experimental material was 2219-AA plate with a size of 300 *200 *6 mm. The diameter of stirring needle was 6 mm and the shoulder diameter was 20 mm. The welding method was butt welding. The weldments were treated by post-weld heat treatment and then aged artificially at 165°C ~24h. The two kinds of post-weld heat treatment were the conventional heat treatment and the high temperature oscillation heat treatment. The conventional solid solution heat treatment was the method that the weldments were kept at constant temperature about 520°C for 50 minutes. The high temperature oscillation heat treatment was the method that the weldments were staid for a short time at temperature about 530°C, then rapidly cooled down below the solution temperature of aluminium alloy about 510°C, and repeatedly. It realized the temperature oscillation near 2219AA solution temperature. After welding or post-weld heat treatment, the samples were taken along the direction of weld seam, polished and corroded with mixed acid (1.0% HF + 1.5% HCl + 2.5% HNO₃ + 95.0% H₂O), and observed under Olympus optical microscope. Finally, the tensile properties were tested by CSS44100 electronic tester, and hardness was measured by HXZ 1000 digital tester.

3. Results and discussion

3.1 Metal flowing and nugget formation

Figure 2 is a schematic diagram of the theoretical model when the stirring needle rotates clockwise, in which the stirring needle has left thread. When the weldment is got caught in the shoulder of stirring needle and the bottom plate, the distance between the shoulder of stirring needle and bottom plate remains unchanged during the welding process. When the plastic metal flows along the thread surface axially, there must be an inlet and an outlet. At the entrance, it is possible to form an instantaneous cavity, in which the plasticized metal will be sucked. However, at the export, the plasticized metal will change the direction of flow and extrude the surrounding metal. The plasticized metal migrates violently along the axis of the stirring needle because of the suction of plasticized metal into the centre zone and the extrusion of plasticized metal from the extrusion zone.

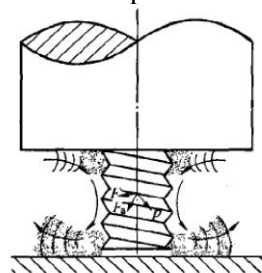


Figure 2. diagram of the flowing model.

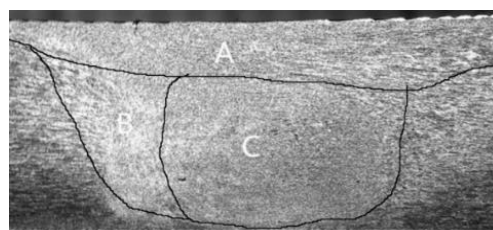


Figure 3. nugget divided into three areas.

In macrography, the nugget (NZ) is divided into three areas, as shown by the dotted line in Figure 3. The formation of these three areas is related to the role of shoulder, needle and pressure difference. Under the affection of pressure difference, as well as the action of needle and shoulder, the plastic metal on the retreat side is transferred to the advance side of weld beam. Therefore, a "horizontal circulation" zone is formed on the surface of the weld beam. In this region, the predicted transfer of plastic metals from the retreat side is much larger than that from the advance side. As a result of this movement, the plastic metals accumulate on the retreat side, so the structure on the advance side is looser, while on the retreat side, the plastic metals are denser.

Below the surface, far from the shoulder, the flowing mainly depends on the role of the stirring needle. The metals accumulated at the bottom begin to migrate upward in order to reduce the pressure difference. Therefore, the diffusion and migration of the plastic metals between the bottom plate and the surface, an "onion ring" zone is formed in the central of the weld beam.

The upper layer of the weld beam is in lower pressure near advance side, and the middle layer of the weld beam is also in the low pressure zone near advance side. Therefore, the pressure between the upper layer and the bottom will be strengthened in advance side. The pressure effect of the area where the bottom of the stirring needle points to the advance side will be greater, even the metal in the high-pressure area of the bottom will break through the interlayer area of the onion ring and flow to the advance side to form an intermingling area with the original base metal, that is, "onion tip" area. On the contrary, the pressure difference between the upper layer and the bottom is not so big like that in retreat side, the pressure is greatly weakened, which is not enough to break through the onion ring area.

3.2 Morphology and microstructure

However, the whole welded joints are divided into three zones in microstructure: nugget zone, thermo-mechanical affected zone (TMAZ) and heat affection zone (HAZ). The morphology of all zones is shown in Figure 4. In the HAZ, the welding thermal cycle results in the coarsening of the original grain of the base metal, as shown in Figure 4a. In NZ, the grains are broken and many small equiaxed structures are formed during grain growth because the grains undergo intense stirring and dynamic recrystallization, as shown in Figure 4b. In addition, in TMAZ, the combined action of strong stirring and welding thermal cycle takes place in FSW, resulting in local fragmentation and adhesion growth, as shown in Figure 4c.

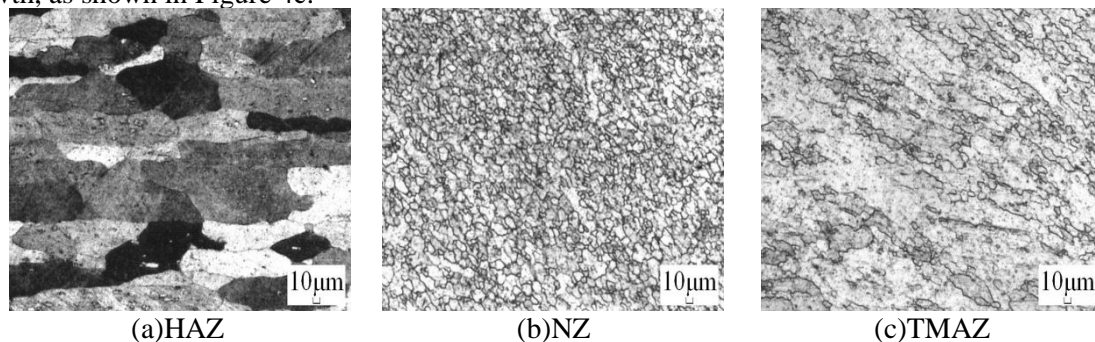


Figure 4. Microstructures in joint of 2219AA.

The morphology of different joints after post-weld heat treatment is shown as in Figure 5. After normal post-weld heat treatment, as shown in Figure 5b, it can be seen from the figure that the grains have undergone high temperature recrystallization, the structure in BM and HAZ keeps the same grain size or increases slightly, while the structure in NZ or TMAZ seems to grow abnormally. The grain size at the boundary between NZ and TMAZ is larger, and the grain growth direction is consistent with the thickness direction. The results show that under mechanical action, NZ grain boundaries are broken and the structure is formed again, and there are no particles on the grain boundaries, which results in lower grain boundaries energy. However, the energy threshold of grain growth is reduced

due to the large amount of deformation energy and dislocation stored in the grain. The adjacent grains are easy to merge even with large angle grain boundaries. Therefore, during the post-weld heat treatment process, abnormal grain growth is easy to occur, and NZ grain size has great thermal instability. Traditionally, the heteromorphic growth usually occurs when particles dissolve into the matrix above solution temperature, such as austenitizing process of steel, while in FSW-welded aluminium alloys, the heteromorphic growth occurs during recrystallization process at lower temperature.

In post-weld heat treatment, precise control temperature oscillates near the low limit of the solution temperature, stable precipitation is preferentially formed at the grain boundary to anchor the grain boundary, which can effectively inhibit the formation of coarse grains. When the temperature oscillation amplitude is greater than 90 °C, the grain diameter is about 20 microns, whole weld seam consists with fine grains, as shown in Figure 5c.

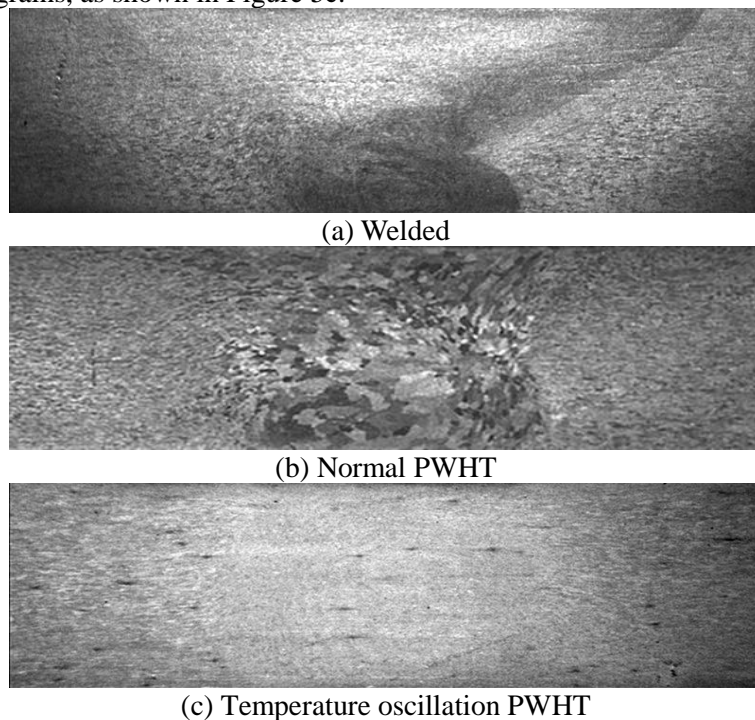


Figure 5. Morphology of FSW joints.

3.3 Mechanical tensile test

Table 1 is the test results of mechanical tensile properties of 2219 aluminium alloy welded by FSW. Under annealing conditions, the plasticity of the base metal is good, about 23%. When FSW welding is used, the plasticity of material is poor, and the fracture of most samples is located in the heat-affected zone. With the process of post-weld heat treatment, the plasticity decreases further, but the tensile strength increases under the condition of solution aging. The elongation is about 7.5%, the elongation of welded joints is reduced by about 50%, the average tensile strength is 300 MPa, and the fracture location is mostly on the advance side. The average tensile strength and elongation of the samples increased to 393 Mpa and 12.6% after high temperature solution treatment. This means that if grain size can be controlled during heat treatment, plasticity will be improved. The results show that the high temperature oscillation controls the grain size, maintains the fine grain structure, improves the plasticity to a certain extent, and improves the recovery rate of tensile strength.

Table 1. Mechanical properties of base metal and joints of 2219AA.

Sample number	Ultimate tensile (<i>Mpa</i>)	Elongation (%)	Fracture location	Note
1	150.3	23.1	-	BM
2	156.4	13.4	RS	Welded Joints
3	300.4	7.5	AS	Normal PWHT
4	393.0	12.6	AS	Precisely WHT

4. Conclusions

In this experiment, the way of the heat treatment is used to improve the tensile strength of aluminum alloy joints welded by FSW, restore the plasticity of metals, redistribute theta phase, prevent the softening of heat affected zone and eliminate the influence of these inherent weakening factors. Developing advanced heat treatment technology is the basic approach to improving performance and meeting requirements of aerospace aluminum alloy.

When the temperature oscillates near the low limit of the solution temperature, stable precipitation is preferentially formed at the grain boundary to anchor the grain boundary, which can effectively inhibit the formation of coarse grains. When the temperature oscillation amplitude is greater than 90 °C, the grain diameter is about 20 microns, and as a result the joint can restore ductility and eliminate softening. So high temperature oscillating solid solution heat treatment can effectively solve the thermal instability of nuggets in friction stir welding.

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