Study on Fracture of Aluminum Alloy Joints Welded by Friction Stir Welding

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Abstract. The precisely controlled heat treatment was studied in order to meet the special requirements of aerospace industry for materials of aluminum alloy. 2219 aluminum alloy welded plate was prepared by friction stir welding, its microstructure and mechanical properties were studied, and the reasons for strength reduction of welded joints were analyzed and summarized correspondingly. The results shows that the plasticity of joints of 2219 aluminium alloy is poor after FSW, the elongation is reduced about 50% to that of base material. With the process of general post-weld heat treatment technology, the plasticity is further reduced, the elongation is reduced about 50% to that of welded joints. But after high temperature solution treatment, the average elongation of the joints increase to corresponding level of as-welded joints, which is about 12.6%. In this precisely controlled 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

Friction stir welding (FSW) is a revolutionary joining technology which has been studied, developed and applied in recent years. In this method, a rotating tool with a special shoulder and a pin moves between plates [1,2]. As the rotating tool moves along the weld beam, the imaginary heat is generated between the base metal and the tool shoulder. The weld beam experiences rather lower temperature than that of fusion welding, and the adjacent base metal is also undergone by lower temperature, which is generally beneficial to the deformation and residual stress state of the welded joint [3,4].

FSW can solve the traditional welding problems of aluminium alloy, which is the main structural material of aerospace industry equipment [5]. However, FSW technology is still on the stage of development and application, and there are still many aspects to be studied meticulously. For example, for heat-treated strengthened aluminum alloy, there is a lack of research related to welding thermal cycle in order to reveal the evolution of precipitation phases of aluminium alloy in essence, which is helpful for understanding of friction stir welding mechanism. The research on the evolution of precipitation phases is mostly focused on the experimental observation. In the field of welding technology, the literature on the evolution after heat treatment is relatively few, especially the structure and mechanical properties effected by welding technology and post-weld heat treatment technology is not comprehensive enough. The thermal and mechanical damage will degrade the mechanical properties of the welded material [6,7]. 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. Post-weld heat treatment is a very important means to further improve the mechanical properties for aluminium alloy. Therefore, we need grasp the influence of post-weld heat treatment on properties in order to formulate reasonable welding process and
appropriate post-weld heat treatment process, as well as understand the mechanism of friction stir welding itself.

2. Experiments

The material used in this experiment was 2219 aluminium alloy sheet with thickness about 6mm. The butt joint was adopted to weld on FSW large gantry machine. The chemical composition of 2219 aluminium alloy was shown in Table 1. The stirring tool was cylindrical pin with threads, in which the diameter of the pin was 6 mm and the diameter of the shoulder was 20 mm. The rotating speed was 500-1500 r/min, and the welding speed was 100-400 mm/min. Before welding, the weldment surface was trimmed, the oxide film on the surface was removed by the sandpaper, and the oil stain on the surface was cleaned by the acetone. The welding parameters that can be changed during the welding process include the rotating speed, the welding speed and the pressure of the shoulder on the welded plate. Welding parameters were shown in Table 2. In welding, the line energy depended on the pressure, the friction coefficient, the diameter of the shoulder, the diameter of the pin, and the ratio of rotational speed to welding speed. Moreover, the pressure of shoulder was generally constant in the welding process.

| Table 1. Chemical composition of 2219 AA. |
|----------------------------------------|
| Element  | Cu  | Mn  | Ti  | Zr  | Si  | Fe  | Ni  | Al  | Content (\%m.) |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|----------------|
| Cu       | 6.38|     |     |     |     |     |     |     | 0.32           |
| Mn       |     | 0.32|     |     |     |     |     |     | 0.064          |
| Ti       |     |     | 0.18|     |     |     |     |     | 0.18           |
| Zr       |     |     |     | 0.18|     |     |     |     | 0.084          |
| Si       |     |     |     |     | 0.18|     |     |     | 0.18           |
| Fe       |     |     |     |     |     | 0.18|     |     | 0.032          |
| Ni       |     |     |     |     |     |     | 0.032|    | remained       |

| Table 2. Welding parameters of 2219 AA by FSW. |
|-----------------------------------------------|
| Sample No. | Rot.speed(r/min) | W. speed(mm/min) |
|-----------|------------------|------------------|
| 1         | 1000             | 100              |
| 2         | 1000             | 170              |
| 3         | 1000             | 300              |
| 4         | 1000             | 400              |
| 5         | 1000             | 200              |
| 6         | 500              | 200              |
| 7         | 850              | 200              |
| 8         | 1000             | 200              |
| 9         | 1200             | 200              |
| 10        | 1500             | 200              |

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. However, 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.

Figure 1. Diagram of the size of tensile specimen.
The shape and size of the tensile specimen are shown in Figure 1. The specimen size: the length is 180mm, the width is 18mm, the thickness is 5mm and the roughness is 3.2. According to the plate thickness and stratification, the number of specimens in each group is number 4. Before the test, the effective part of the working section is measured and marked with length of 50 mm on the back of the tensile specimen. During the test, the specimen is clamped in the upper chuck, the position of the upper chuck is adjusted to a suitable height, and then the end of the specimen is clamped in the lower chuck. Attention should be paid to the vertical placement of the specimen. If the phenomenon of skidding is found, the upper and lower chucks need to be loosened, and the specimen should be removed and reinstalled again. When starting the machine, the oil inlet valve is rotated slowly and the pulling force is loaded on specimen uniformly.

3. Results and Discussion

Figure 2 shows the macrography of the joint of FSW. Generally, metal flow depends on welding speed, rotation of the tool which stirs the material, profile and shape of pin to drive the metal behind the tool. When the weldment is got caught in the shoulder of tool and the bottom rigid plate, the distance between the shoulder of tool and bottom plate remains unchanged during the welding process. The plasticized metal migrates violently along the axis of the pin because of the suction of plasticized metal into the centre zone and the extrusion of plasticized metal from the extrusion zone. The metal flow pattern observed in the nugget is very obvious in different welds. Therefore, a "horizontal circulation" zone is formed on the surface of the weld beam, and an "onion ring" zone is formed in the central of the weld beam. The asymmetric pattern of material flow is more obviously observed, and fingering structure is observed as marked in figure.

![Figure 2. Macrography of the nugget.](image1)

The weak position of welded joints is tested by the means of that the specimens are stretched on a stretcher. Figure 3 shows the comparison of specimen before and after fracture, and Figure 4 shows the
After the specimen is broken by the stretcher, record the maximum load, loosen the oil inlet valve of machine, and return the pointer to zero in the dial of machine. After the experiment is finished, measure the post-fracture size of the specimen, i.e. the length, thickness and width.

![Diagram of load with displacement on the tensile specimen.](image)

**Figure 4.** Diagram of load with displacement on specimen.

Table 3 is the test results of mechanical tensile properties of joints. The plasticity of the base metal is good, which is about 23%. But the plasticity of material is poor (about 13%) after FSW, and the fracture of most specimens is located in HAZ. The hardness measurement results were indicated the fluctuations at the welded zone and obtained the greater hardness values than the base materials. With the process of post-weld heat treatment, the plasticity decreases further, the elongation is about 7.5%, but the tensile strength increases under the condition of solution aging. The elongation is reduced about 50% to that of welded joint, the average tensile strength is 300 MPa, and the fracture location is on the advance side. After high temperature solution treatment, the average tensile strength and elongation of the samples increased again to 393 Mpa and 12.6%. It means that the 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.

Moreover, The influence of welding parameters such as welding speed has a great influence on the productivity of FSW of aluminium alloy. As the welding speed is improved, the welding quality is high, and the joint performance is excellent. At the lowest and the highest welding speed, the tensile strength is lower, which can be due to the reason of the increase of virtual heat and the inadequacy of virtual heat generation. The increase of welding speed leads to the increase of tensile strength to the maximum value, while the further increase of welding speed leads to the decrease of tensile strength.

| Group number | Ult. tensile (Mpa) | 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     |

Figure 5 shows the morphology of tensile fracture of the joints. The results show that perfect weld joints have good fracture morphology like the fracture of base metal, as shown in figure 5a. If the welding defect such as porosity and voids are located on the cross section where fracture occurs, which is also due to the non-metallurgical bonding and the weak bonding of grains in the nugget zone in the advance side, as shown in Figure 5b. The abnormal growth of grains is easy to be caused by the
solution at high temperature and long time in post-weld heat treatment, which seriously affects the mechanical properties of the joints. After solution and aging treatment, the grain grows into coarse grains, and the fracture form is intergranular fracture, as shown in Figure 5c.

(a) ductile fracture  (b) fracture for porosity  (c) Intergranular fracture

Figure 5. Morphology of tensile fracture of the joints.

4. Conclusions
In this experiment, the fracture behavior of 2219 aluminum alloy joints welded by FSW is studied. The way of the heat treatment is used to improve the tensile strength, and to restore the plasticity of metals. The plasticity of joints is poor after FSW, the elongation is reduced about 50% to that of base material of 2219 aluminium alloy, and the fracture of most specimens is located in HAZ. With the process of general post-weld heat treatment technology, the plasticity decreases further, the elongation is reduced again about 50% to that of welded joints. After high temperature solution treatment, the average elongation of the specimens increased to corresponding level of as-welded joints, which is about 12.6%. Developing advanced heat treatment technology is the basic approach to improving performance and meeting requirements of aerospace aluminum alloy.

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6. References
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