Plastic damage and deformation defect of friction stir welding for aluminum alloy

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Abstract: 2219 aluminum alloy plates were welded by friction stir welding, which was a solid bonding technology to solve the traditional problems for aluminium alloy welding. The morphology, microstructure and mechanical properties of the joint were investigated. Through analyzing the flowing pattern of the plastically deformed metal in the nugget zone, the strength weakening of the joint were analyzed and summarized. The reason of weakening strength was due to the plastic deformation and damage of the metal, which resulted in the defect formation and the mutational interface. The results show that the well-formed weld beam is similar to the base metal, which has the plastic fracture morphology. However, if there are pores, holes and other welding defects in the weld beam, the fracture morphology is brittle fracture, then the tensile strength is about 70% of base metal and the elongation is about 7%, which means that the advantages of high strength aluminium alloy are not fully utilized.

1. Introduction
Friction stir welding (FSW) is a kind of welding method for aluminum alloy, which realizes solid phase bonding through thermomechanical effect. Many studies have focused on the formation mechanism and properties of aluminum alloy with FSW. KE studied the principle of formation for welding nugget [1]. Wang studied the rheological properties of welded metals [2]. Murr studied the dynamic recrystallization of FSW process [3]. The FSW study of 2219AA shows that theta phase plays a reinforcing role in the matrix material. Solution aging treatment can effectively eliminate the softening and improve the strength [4-6]. At the same time, the differences of 2219AA welding methods are compared, and the results show that the strength and plasticity of FSW joints are better than those of general fusion welding joints. However, in FSW, the strength ratio of welded metal to base metal is about 50-80%. To explore the reasons for the decline in intensity, and based on the FSW analysis of 2219AA joint, the plastic loss, defects and precipitation θ phase are considered and researched as the main reasons leading to the decline of performance.

2. Experimental Materials and Methods
The experimental materials were 2219AA high strength aluminum alloy rolled plates with a thickness of 6mm, which were welded on FSW large gantry welder by means of butt joint. The chemical composition of 2219AA was shown in table 1. The test material was 300×200×6 mm. The diameter of the mixing head was 6mm, the diameter of the shoulder was 20mm, the rotation speed was 600-2000 r /min, and the welding speed was 100-400 mm /min. The plates were simply cleaned and trimmed.
before welding, the oxide film on the surface was removed by sanding, and the surface was cleaned with acetone to remove oil stains. The welding parameters can be changed in the welding process include the rotating speed of the stirring head, the welding speed, and the pressure of the shoulder on the welded plate. Finally, the samples were observed under OLYMPUS optical microscope, tested tensile by CSS44100 electronic tester, and measured hardness by HXZ-1000 digital tester.

### Table 1. Chemical composition of 2219AA.

|      | Cu  | Mn | Ti  | Zr  | Si  | Fe  | Ni  | Al  |
|------|-----|----|-----|-----|-----|-----|-----|-----|
|      | 6.38| 0.32| 0.064| 0.18| 0.084| 0.18| 0.032| remained |

3. **Test of Mechanical Properties**

Table 2 shows the tensile test results of friction stir welding of 2219AA joint. After welding, the tensile strength of 2219AA joint reaches 65~75% of the base metal. In these samples, the strength and plasticity are better when there are no obvious defects in weld beam, while the strength and plasticity are worse when there are defects in weld beam. Most of the samples fracture in the HAZ zone on the advancing side of the weld beam.

### Table 2. Mechanical properties of base metal and joints of 2219AA

| Sample No. | Rot.speed (r/min) | Weld speed (mm/min) | Ult. tensile (Mpa) | Elongation (%) | Fracture location | Defects |
|------------|------------------|---------------------|-------------------|----------------|--------------------|---------|
| BM         | -                | -                   | 427.3             | 12.1           | -                  | -       |
| 1          | 1000             | 100                 | 314.4             | 8.4            | RS                | flash   |
| 2          | 1000             | 200                 | 276.4             | 3.9            | AS                |         |
| 3          | 1000             | 300                 | 293.0             | 6.6            | AS                | wormhole|
| 4          | 850              | 200                 | 314.6             | 9.4            | AS                |         |
| 5          | 800              | 300                 | 322.5             | 9.2            | AS                |         |
| 6          | 600              | 300                 | 272.5             | 5.6            | AS                | tunnel  |

In No.1, No.2 and No.3 samples, the rotational speed is 1000 r/min, but the welding speed is 100, 200, 300 mm/min respectively, the heat input of the ratio of rotational speed to welding speed decreases gradually. As the ratio increases or decreases, the welded seam appear with the welded defect of flash or wormhole. This can be explained by the fact that when the heat input is too high, the overheated external plastic metal becomes too wide and overflows beyond the extrusion range of the shoulder, leading to severe flashes. On the contrary, the lower the heat input leading inadequate material flow will lead to welding defects of wormhole. When the rotational speed decreases, the heat input decreases, such as No.4 and No.5 specimens, but the tensile strength can reach more than 300 MPa and the elongation can reach more than 9%. But the heat input is too low, the connection is difficult, even lead to welding defects of tunnel, such as specimen No.6, the samples has weak strength and poor plasticity.

![Fracture Morphology](image)

Figure 1 shows the fracture 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 1.
1a. The fracture are of sheared-shape when samples have no any internal defects and of V-shape otherwise. 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 advancing side, as shown in Figure 1b. 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 1c.

4. Plastic damage and deformation defect

4.1 various interfaces and defects in different zones
Welded joints are divided into three zones: nugget zone (NZ), thermomechanical affected zone (TMAZ) and heat affected zone (HAZ). The microstructures of all regions are shown in Figure 2. In HAZ, the thermal cycling in the weld leads to the coarsening of the original structure of the base metal, as shown in Figure 2a. In NZ, compared with other regions, the recrystallized grains have broken up before they grow up, forming many fine equiaxed structures, as shown in Figure 2b. In TMAZ, the grains undergo the stirring and thermal cycling in FSW, resulting in local grain fragmentation and growth, as shown in Figure 2c.

![Microstructures in joint of 2219AA.](image)

![Defects in NZ and interface between NZ and TMAZ.](image)

The rotation and motion of the mixing needle will cause the asymmetry of the advancing side (AS) and the retreating side (RS) of the joint. This asymmetry is manifested by the direction of the organization, which is more obvious at AS than that at RS. As shown in Figure 3a, there is an obvious interface between NZ and TMAZ on the upper weld beam. As shown in Figure 3b, there is also an obvious interface between NZ and the base metal at the bottom of the weld beam. As shown in Figure 3c, in the middle of the weld beam, it is easy to form welding defects. These interfaces or defects will lead to the decrease of mechanical properties of the joint, so the fracture is likely to occur on the AS of the joints.
4.2 Plastic damage of nugget grains
The heat input is unevenly distributed along the plate thickness. The upper zone of NZ absorbs most of the heat generated by the shoulder, while the bottom zone contacts the steel plate, resulting in a large loss of thermal conductivity. Therefore, the temperature along the thickness of the plate is from wide to narrow, from high to low. Due to short welding time, low temperature and large mixing flow, partial recrystallization in NZ was not completed. Figure 4 shows the microstructure of grains at different zones at different temperatures. In Figure 4a, in the upper NZ, the broken grains are compacted after recrystallization in whole or in part, and the metallographic observation shows a good metallic luster. The grains in this region have obvious arrangement trend, and it can be observed that they are inclined down at a certain angle. Dynamic recrystallization has occurred in this zone because of the strong heat input. In Figure 4b, in the middle of NZ, the grains in this area show the morphology of rheology, and the slanting angle is larger than that of the upper. No obvious grain boundary was observed, indicating that the rheological velocity was higher than the recrystallization velocity, and the grains were deformed rather than granular. In Figure 4c, at the bottom of NZ, the grain is also granular. Compared with the granular grain in the upper NZ, the grain is finer, but the grain boundary is not clear. The grains in this area are in the low temperature, or only partially recrystallized, so this area is mainly in the mixed state between broken grains. At the same time, the residual second phase can be observed.

4.3 Growth of θ phase
Solution and dissolution are the basis of heat treatment (by quenching and aging) for aluminium alloys, which can be strengthened by heat treatment. There are a large number of alloying elements that can be dissolved into aluminium. The main alloying elements in 2219 aluminium alloys are copper, and the main components are α phase (Al), θ phase (Al₂Cu), T phase (CuMn₂Al₁₂) and a small amount of TiAl₃. Among them, α is the matrix solid solution and θ is the second phase. When the content of Cu is 5%, the solid solution temperature is about 528°C to 542°C. Redissolution of precipitated phase will occur when this temperature is reached. Considering the uneven distribution and fluctuation of Cu element composition, the solid solution temperature varies in different regions, and the range of solid solution temperature can be extended to 510~550°C. The nugget grains is formed under the action of mechanical crushing, so there is no second phase particles on the grain boundary, or even no solute segregation on the grain boundary, so there is no pinning effect of the second phase particles, which leads to the potential barrier needed to break through in grain boundary migration. At a lower level, adjacent grains are easy to merge even at large angle grain boundaries. As a result of temperature and mixing of the welding process, the behavior and behavior of θ particles precipitated are different. In NZ, the larger particles are broken, and basically become smaller particles. On the other hand, because the temperature is the highest in NZ, some θ particles precipitated melt into the matrix, resulting in a decrease in the number of θ particles, so there are no large particles. However, in the HAZ or TMAZ, the particles increase to a maximum size of about 15 μm, as shown in figure 5. The characteristics of θ particles in TMAZ are that some θ particles are large in size and some are small in size. The reason
may be that the θ particles continues to grow on the basis of the original size, while the other small size θ particles are the result of re-precipitation. The overall arrangement of the θ particles in each zone shows an obvious direction, which is consistent with the flow direction of the plastic metal. θ particles has a great influence on the strength of welded joints after welding. Due to the uneven distribution of θ particles precipitated, this is one of the reasons why the tensile strength of welded joints is not high enough.

![Figure 5. Distributions of the θ particles in joints.](image)

5. Conclusions
The welded joints can be divided into three zones. There are obvious differences in the microstructures of these regions: fine equiaxed grains are formed in NZ, bending deformation occurs in TMAZ and coarse grains are formed in HAZ. Plastic damage and deformation defect of friction stir welding for aluminum alloy is obvious, they form special structures in some specific areas, which determine the performance of friction stir joints. Moreover, the distribution of the θ phase is different in different regions, and there is a trend of aggregation and growth in HAZ. Therefore, the strength ratio of 2219AA is less than 75% due to plastic damage, defects and softening of heat affected zone. Welding parameters are disadvantageous for improving plastic damage and preventing defects, which leads to the shrinkage of FSW parameter window.

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