Experimental study on friction stir spot welding of 5A06 aluminum alloy

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Abstract. In this paper, 5A06 aluminum alloy was filled with friction stir spot welding. Mechanical properties and metallographic tests were carried out on the welded joint. By observing the microstructure of the weld, the effects of different welding parameters on the mechanical properties and cross section formation of the filler friction stir spot welded joint were analyzed. The results show that the welding time has the greatest influence on the shear resistance and tensile properties of the friction spot welding joint, and the increase of the rotation speed of the spot welding tool will enhance the tensile properties of the joint.

1. Introduction
A keyhole with diameter of the probe will be left at the place where the probe is away from the weldment at the end because of the characteristics of the friction stir welding process [1]. For straight brad, the keyhole can be eliminated by leaving it in the allowance, but the keyhole must be eliminated in other ways for the lack of application conditions for friction stir spot welding [2]. The filling type friction stir spot welding is one of the methods. This paper uses the advanced friction stir welding equipment to carry out the aluminum alloy filled friction stir spot welding test. The influence of different process parameters on the mechanical properties of the joint is analyzed. The fracture form of the joint and the metallographic photo of the joint cross section are discussed and analyzed.

2. Test materials and testing equipment
The material used in the friction stir spot welding test is 5A06 antirust aluminum, which is organized as alpha solid solution and beta phase (Al3Mg2) at normal temperature. The alloy manganese, iron and silicon can form different impurity phases (AlMg2Zn, AlFeSi and Mg2Si). The chemical composition of the alloy is shown in Table 1.

| Alloy  | Main chemical composition (%) |
|-------|------------------------------|
|       | Mg  | Mn  | Zn  | Fe  | Si  | Ti  | Be  | Al  |
| Al-Mg | 6.8 | 0.5–0.8 | 0.2 | ≤0.4 | ≤0.4 | 0.02–0.1 | 0.001–0.005 | residue |
The equipment used in the friction stir spot welding test is RPS100, the outer diameter of the center shaft of the probe head is 9mm, and the diameter of the middle ring is 5mm.

The test parameters are as follows: the rotation speed of the stirring tool is 500 to 2750 rad/min, the welding time is 1.6 to 6.4 s, the downward displacement of the mixing ring is 0 to 0.8 mm, and the welding pressure is 21 to 30 kN.

3. Test scheme of filled friction stir spot welding
The test scheme is set as follows:

(1) Material filling stage
At this stage, the keyhole should be filled with the same material as the base material when the material heat affected zone (HAZ) near the keyhole is as small as possible. At this stage, there is no special requirement for the structure and defects of the material inside the keyhole.

(2) Repair stage of stir spot welding
The welding process is carried out at the keyhole with the friction spot welding method. The welding area should cover all the materials in the keyhole area as well as the area affected by the heat of the pre process. Finally, the welding ring welds of friction stir welding with the same structure and mechanical properties should be formed. Compared with the back weld type no keyhole friction stir welding process, the repair welding process has the advantages of no need to reduce the area of the retreat section and achieve good process location [3]. At present, because the friction spot welding process and the performance of spot welding joint are limited, the effect of the friction spot welding parameters on the performance of the solder joint and the performance characteristics of the solder joint must be fully grasped before the friction spot welding is made up. In order to facilitate the testing of spot welding performance, the test selection of 5A06 aluminum alloy plate thickness is 2 mm, the test adopts lap joint to weld, each parameter is made of 7 solder joint, 6 for mechanical properties test and 1 for section metallographic analysis. The performance of the friction spot welded joint is evaluated by solder joint performance test data, and the feasibility of using it to fill the keyhole is also discussed.

Weld performance test: For anti-shear and cross tensile specimens, as shown in Figure 1, 3 for anti-shear specimens under the same test parameters, and 3 for cross tensile specimens. Finally, the average value is used for the analysis of the test results [4].

![Figure 1. Illustration of anti shear and cross tensile specimens.](image)

Metallographic analysis of weld cross section: Metallographic specimens are obtained from the cross section along the diameter of the weld, and the cross-section is observed by Zeiss Stemi2000-C microscope.

4. Effect of process parameters on joint cross section forming
Figure 2 is a cross-sectional view of the joint of spot welding tool at different rotational speeds. As the rotation speed of the spot welding tool increases gradually, the amount of heat receiving per unit time and the material of plastic flow increase too. From the Figure 2, it can be seen that the boundary of the
solder joint and the parent material is gradually bending, and the boundary between the upper and lower parts is gradually bulged down.

![Image of solder joint under different rotational speeds](image)

**Figure 2.** Cross section of solder joints under different rotational speeds of spot welding tools.

(L=0.3 mm, t=2.4 s, F=30 kN)

Figure 3 is the joint cross section of different welding time. With the increasing of the welding time, the boundary between the welding point and the base material moves downward gradually and has a bulge trend. When the welding time is increased to 6.4 s, the surface structure of the joint appears cellular shape, which is due to the rise of the middle ring at the third stage of the welding as well as the drop of the probe, which causes the material temperature to be too high because of the friction with the probe.

![Image of solder joint under different welding time](image)

**Figure 3.** Cross section of solder joints under different welding time.

(L=0.3 mm, F=30 kN, n=2000 rad/min)

5. Mechanical properties test of joint

5.1. Influence of rotating speed (n) on friction spot welding.

In the case of other parameters unchanged, the test results of shear resistance and tensile properties obtained from different agitation speed are shown in Table 2. It can be seen from table 2 that with the increase of rotational speed n of the probe, the shear resistance of the friction stir spot welding has little change, and the tensile property is enhanced obviously.

**Table 2.** Test table for mechanical properties of solder joints at different rotational speed of probe.

| No | rotational speed (rad/min) | Time (s) | downward distance (mm) | Pressure (kN) | Shear force (N) | Tensile force (N) |
|----|---------------------------|----------|------------------------|---------------|----------------|-----------------|
| 10 | 500                       | 2.4      | 0.3                    | 30            | 8007           | 1690            |
| 11 | 1000                      | 2.4      | 0.3                    | 30            | 8380.5         | 2150            |
| 12 | 1500                      | 2.4      | 0.3                    | 30            | 8261.5         | 2400            |
| 13 | 2000                      | 2.4      | 0.3                    | 30            | 9012           | 2654.5          |
| 14 | 2500                      | 2.4      | 0.3                    | 30            | 8402           | 3028.5          |
| 15 | 2750                      | 2.4      | 0.3                    | 30            | 8273           | 3402            |
5.2. Effect of the pressure time \( (t_1) \) of the middle ring on the friction spot welding

Table 3 is the test results of the shear resistance and tensile properties of the welding seam under different pressure time. It can be seen that the shear resistance of the weld is highest when the pressure time of the middle ring is 2.4 s, and the tensile property of the weld is the highest at 1.6 s. With the reduction of the pressure time in the middle ring, the welding heat is small, and the weld material cannot reach the optimum temperature of plastic flow, the shear resistance and tensile properties of the weld decreased as a whole.

Table 3. Test table for mechanical properties of solder joints at different pressure time of the middle ring.

| No | rotational speed (rad/min) | Time (s) | downward distance (mm) | Pressure (kN) | Shear force (N) | Tensile force (N) |
|----|---------------------------|----------|------------------------|---------------|----------------|------------------|
| 20 | 2000                      | 0.8      | 0.3                    | 30            | 6390           | 1640             |
| 21 | 2000                      | 1.2      | 0.3                    | 30            | 7402           | 2320             |
| 22 | 2000                      | 1.6      | 0.3                    | 30            | 8836           | 3225             |
| 23 | 2000                      | 2.0      | 0.3                    | 30            | 8402           | 3077             |
| 24 | 2000                      | 2.4      | 0.3                    | 30            | 9012           | 2654.5           |
| 25 | 2000                      | 2.8      | 0.3                    | 30            | 8353           | 2842             |
| 26 | 2000                      | 3.2      | 0.3                    | 30            | 8787           | 2701             |

6. Feasibility analysis of friction spot welding for friction stir welding with no keyhole

The effect of the process parameters on the performance of the joint is obtained based on the above tests. It can be seen from the performance test data that the friction spot welding joint has some characteristics that the previous welded joints do not possess, such as the tensile force is far below the shear resistance performance, which is closely related to the special technology of the friction spot welding. In order to make clear the performance characteristics of the friction spot welding joint and ensure the stability and reliability of the weld performance when it is used to fill the final keyhole of friction stir welding, it is necessary to further discuss the two aspects of the fracture form of the joint and the weld structure.

6.1. Discussion on fracture form of joint.

There are two types of shear fracture forms for the friction spot welding joints, as shown in Figure 4, of which type I shear mode is self horizontal connection surface tear and type II shear method is desquamation from vertical connection surface. According to the performance data, the performance of the type I was reduced and the shear strength was not up to 7.5 kN, and the shear resistance of the type II was above 7.5 kN, and the shear strength increased with the increase of the roughness of the exfoliation interface. Therefore, the type II shear test specimen is a friction spot welding joint with reasonable technological parameters.

(a) Type I shear mode  
(b) Type II shear mode

Figure 4. Shear cracking modes of spot welding joint
The tensile test specimens of the friction spot welding joint are divided into three types, as shown in Figure 5. The type I crack mode pull apart along the horizontal connection surface, and the smooth opening of the exfoliation interface along the vertical connection surface is the type II crack mode, and the roughness opening of the exfoliation interface along the vertical connection surface is the type III crack mode. The three types of tensile test specimens correspond to the tensile strength from small to large are type II, type I and type III. Type III tensile test specimen is a friction spot welding joint with reasonable technological parameters.

(a) Type I tensile crack mode     (b) Type II tensile crack mode    (c) Type III tensile crack mode

Figure 5. Tensile cracking modes of spot welding joint

To sum up, under the optimal technological parameters, the weak surface of the friction spot welded joint is a vertical connection surface.

6.2. Analysis of metallographic photos of joint cross section.
Figure 6 is a joint metallographic photo.

Figure 6. Sub section of metallographic photo section of joint section

The joints are divided into heat affected zone (HAZ), pressure influenced zone (PIZ), thermo-mechanically affected zone (TMAZ) and base metal area from the microstructure. From the overall welding process, the joint is formed under the pressure of the stirring ring, which causes the plastic flow of the metal in the joint area [5]. The microstructure of most of the material in the solder joint and material in base metal is very different, which indicates that this part of the material is greatly affected by heat and becomes a TMAZ. There is little difference in the microstructure between the two sides of the lower end of the joint, which indicates that the material is less affected by heat and becomes the PIZ.

Because the base metal is a non heat treated aluminum alloy, there is no obvious difference between the heat affected zone and the base. In the joint, the structure of the joint is "onion like" shape. In the third stage of welding, the stir ring is moved up and the cavity is formed. At the same time, the pressure material is stirred and the material is filled with the plastic flow to the two sides. Because of the time sequence correlation, the two layers of material at the same time inevitably have the difference in the rate of flow.
7. Conclusions
The following conclusions can be drawn from the above analysis of the friction stir spot welding and the joint performance of 5A06 aluminum alloy.

(1) The experimental study of friction spot welding shows that the welding time has the greatest influence on the shear resistance and tensile properties of the friction spot welding joint; the rotation speed of the spot welding tool only enhances the tensile properties of the joint, and the welding depth and the welding pressure have a larger process range.

(2) The joints of the friction spot welding joints are "onion like" flow lines, and the joints are made up of the thermo-mechanically affected zone (TMAZ), the pressure influenced zone (PIZ) and the heat affected zone (HAZ). There are horizontal and vertical connections between the spot welding joint and the base metal, and the vertical connection interface is the weakest part of the spot welding joint.

(3) The existence of the vertical connection interface with weak performance will slacken down the mechanical properties of the repair welding of the keyhole, so a new type of friction spot welding technology needs to be developed to replace it, which is applied to the filling of the keyhole are cited in the text just by square brackets [1]. Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under heading references, see our example below.

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