Repair Welding of Tunnel Defect in Friction Stir Weld of Al-Zn-Mg Alloys

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Abstract. The tunnel defect formed in friction stir welding dramatically, which deteriorated mechanical properties of joints owing to its larger size in lack of fusion. By welding the Al-Zn-Mg aluminum plates with specific process parameters, the defective joints with tunnel defect were obtained. Then, the repair welding and twice repair welding were carried out to use friction stir welding on the defective joint. Experiment results showed that the joint with tunnel defect could be repaired by the friction stir repair welding. Microstructure of repaired joints showed that grain size in the nugget zone decreased slightly while inhomogeneity of grain size was increased, and grain presented recrystallization phenomenon in the retreating side of thermo-mechanically affected zone; Mechanical properties testing results showed that the yield strength and tensile strength increased obviously. The tensile fracture scanning results showed that repaired joints presented layered in different positions. Compared with the repair welding joint, the mechanical properties of twice repair welding joint lowered slightly, and the thickness of welding reduced gradually with the repair welding.

Introduction

As a new developing promising solid state welding process in recent years [1], friction stir welding (FSW) is characterized by the high welding quality, low production cost and low welding distortion, which can be utilized to weld some materials that are difficult to fuse weld [2,3]. Joints welded by FSW is achieved without melting material, which is performed by stirring the interface and facilitated by heating due to plastic dissipation as well as friction between tool and work pieces.

For FSW welding, material which formed the joint underwent different thermodynamic histories [4,5]. The top of weld underwent dual function as stirring and friction, and it was sound. The middle of joint was stirred by rotation tool, in which joint was eligible due to the least heat dissipation. The bottom of weld underwent the least thermodynamic histories, however, where most heat dissipation appeared. Defects formed in bottom of FSW welds easily [6,7]. In the fast development and application of FSW process, it has been known that welding defects may be formed during FSW when improper welding parameters were used[7-9].

Defects play a major role in the determining mechanical strength of the joint wickedly. About the volume defects in FSW welds, Liu et al. [10] considered that the groove defect could be removed by friction stir repair welding, but different repair welding processes present different repair results. Rosen et al. [11] used FSW to repair voids in aluminum alloy and then obtained sturdy repaired joint. But there are not researches about narrow tunnel defects in the FSW joints.

In this study, in order to remove narrow tunnel defects in the bottom of FSW welds, proper welding parameters and technological conditions were chosen. Microstructures and mechanical
properties of repaired and un repaired were studied, which could offer some referenced opinions for the FSW repair welding of tunnel defects.

**Experiment**

The base metal used in this study was a Al-Zn-Mg aluminum plate of 6 mm in thickness, whose chemical compositions were listed in Table 1. The plate was cut and machined into rectangular welding samples of 1000 mm in length and 150 mm in width.

| Table 1. Chemical Composition of Matrix (wt.%). |
|-----------------------------------------------|
| w(Zn) | w(Mg) | w(Cu) | w(Cr) | w(Mn) | w(Si) | w(Fe) | w(Al) |
|-------|-------|-------|-------|-------|-------|-------|-------|
| 4.60  | 1.20  | 0.20  | 0.20  | 0.15  | 0.35  | 0.40  | Bal.   |

Oxidation film was removed near the welding area by mechanical cleaning methods before welding. During the FSW process, the samples were fixed by pneumatic clamping and were welded by machine of MTI which made in America, whose stir-pin is 5.8 mm in length, and diameter of rotation tool is 6 mm in width, inclination of rotation tool is 0.5° in angle and with three-section dextral thread contrarotating. Al-Zn-Mg aluminum alloys were welded by using specific welding technological parameters to get the joint with tunnel defects. The welding parameters are showed in Table 2.

| Table 2. Welding Technological Parameters for Original Joints and Repair Joints. |
|-----------------------------------------------|
| sort             | Rotation speed/(r/min) | Welding speed/(mm/min) | Pressure (/kN) | Press amount (/mm) |
| Original welding | 600                | 400                  | 0              | 0.1            |
| Repair welding   | 800                | 300                  | 9              | 0              |

Microstructure of weld joint in nugget zone, thermo-mechanically affected zone and heat affected zone were researched with Zeiss metallographic microscope; the tensile property of joints were tested with Zwick/Roell Z600E tensile testing machine; the tensile fracture morphology was observed by Ultra 55 scanning electron microscope.

**Results and Discussion**

**Macro and Microstructures of Joints**

Welding heat input was not enough, which was caused by low rotational velocity or high welding speed. This phenomenon would lead to insufficient driving of the material by welding tool. As the tool was moving, a continuous longitudinal tunnel following the weld line developed at the back of welding line. The defective joint was repaired by using friction stir welding again with a reasonable processing parameter. With higher welding heat input could materialize in welding area and plastified thorough-paced and with the compressing of stirring shaft, in which material flows anywhere in the joint. The tunnel defect in the bottom of joint disappeared.

Fig.1 indicated the schematic diagram of defective and repaired joints. The diameter of the tunnel defect was more than 2 mm, which was shown that a distance about 2 mm from the bottom of joint in advancing side of nugget zone. In the repair welding processes, the width of nugget zone increased obviously, and tunnel defects disappeared completely, but the thickness of welding
reduced gradually with 0.1mm decline of the repair welding and 0.4 mm decline of twice repair welding, meanwhile flash defect showed seriously in both sides of the repair weld.

Fig.2 showed microstructure photographs of defective joint and repaired joint. Fig.2 a-c indicated that the average size of equiaxed grain decreased with repair welding, which was finded in the joint of twice repair welding where grain decreased remarkably. But the size of grain changed from two to twelve µm nonuniform. This phenomenon is due to that slight grain was stirred compressed or heated by the high-speed spinning stir pin. Part of grains presented deformation or recrystallization and produced smaller grain than before. Another part of gains changed little because it was not stirred overmuch. Therefore, the average size of whole welding line declined gradually.

Fig.2 d-f showed that microstructure photographs in the retreating side of thermo-mechanically affected zone. It could be seen that vimeineous grains did not altered in size obviously. However, recrystallization could be seen clearly in Fig.2 d-f. This phenomenon was due to that the original grains got lots of thermal effect again in the repair welding. The recrystallization was presented at
the grain boundary, which was more serious with repair welding. Experiments showed that grains in
the advance side did not change conspicuously.

Tensile Properties of Joints

Tensile experimental results were shown in Table 3. Three tensile specimens in group selected
from the original or repaired joints were chosen for tensile test. The Rp0.2 and tensile strength
original joint were only 158.6 MPa and 207.4 MPa respectively, because of the tunnel defects. But
after FSW repaired and twice repaired welding, the yield strength of repaired joint increased to
240.3 MPa and 234.5 MPa respectively by comparison, meanwhile the tensile strength increase to
373.8 MPa and 354.7 MPa respectively by comparison. The tensile properties of joints by twice
repair welding decreased more than the repair welding slightly.

| number       | yield strength Rp0.2/MPa | tensile strength Rm/MPa | elongation A/(%) | Location of break |
|--------------|--------------------------|-------------------------|-----------------|------------------|
| defect-1     | 147.6                    | 204.5                   | 2.0             | nugget zone(middle) |
| defect-2     | 161.3                    | 208.8                   | 2.1             | nugget zone(middle) |
| defect-3     | 166.9                    | 209.0                   | 1.7             | nugget zone(middle) |
| average      | 158.6                    | 207.4                   | 1.9             | ------          |
| repair-1     | 243.1                    | 373.5                   | 11.6            | nugget zone(AS)  |
| repair-2     | 246.9                    | 372.9                   | 12.2            | nugget zone(AS)  |
| repair-3     | 230.9                    | 357.1                   | 12.2            | nugget zone(AS)  |
| average      | 240.3                    | 373.8                   | 12.0            | ------          |
| twice-1      | 236.9                    | 353.8                   | 10.8            | nugget zone(AS)  |
| twice -2     | 240.1                    | 346.1                   | 12.4            | nugget zone(AS)  |
| twice -3     | 234.5                    | 354.7                   | 11.8            | nugget zone(AS)  |
| average      | 237.2                    | 351.5                   | 11.7            | ------          |

Fracture Features of Joints

As shown in Fig.3, fracture morphology of the ununited surface of tunnel in the original FSW
joints presented a feature of "heliciform", which were caused by rotation tool rotated and the
plasticizing viscous fluid flowed. The spiral stuff presented periodic distribution, whose distance
between each other was equal to that the welding speed divided the rotational speed ratio of friction
stir tool. Since welding heat input was not enough, and lots of heat was lost in the bottom through
fixture, thus, where plastic fluid flowed unevenly and material was insufficient. As rotate tool was
moving, a continuous longitudinal tunnel followed along the weld line and developed at the back of
welding line. Material in the advance side of nugget zone obtained much thermal effect where
tunnel defects appeared in all probability.

The tunnel defects were eliminated after repair welding, which could be reflected clearly in Table
3. After repair welding, the yield strength and tensile strength of the joints increased more than 78
Mpa and 144 MPa respectively. The facture features of repaired joint were mixed mode fracture of
the intergranular fracture and shear fracture, and material was layered seriously. Since the metal in
welds got lots of thermal effect again in the repair welding, plastic liquid were layered in different
positions. Different positions of welding presented stratification in the plastic flow process, joints of
repair welding were layered in the tensile tests because of different strength after curing. While
twice repair welding joint was layered worse than the and whose yield strength and tensile strength
lower 3 MPa and 22 MPa than the . The mechanical property of friction stir welding repair welding
decreases after more than once.
Conclusions

(a) The tunnel defects appeared in Al-Zn-Mg aluminum FSW joint can be eliminated by FSW repair welding. In repair welding, the width of welding area increased significantly. Meanwhile, the thickness of welding reduced gradually in the repair welding.

(b) The grain size changed from two to twelve $\mu$m in diameter in nugget zone decreased slightly as the grain size inhomogeneity increased and also the grain presented recrystallization phenomenon in the retreating side of thermo-mechanically affected zone.

(c) Tensile properties of joint obtained greatly increased by the repair welding, but the tensile properties of twice repaired joint decreased slightly than the once repaired. The tensile fracture morphology presents a development trend that the fracture layered serious gradually. Therefore, the times of repair welding should limited.

Acknowledgements

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