Rupture Locations of Friction Stir Welded Joints of AA2017-T351 and AA6061-T6 Aluminum Alloys†

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Abstract

The tensile rupture locations of friction stir welded joints of AA2017-T351 and AA6061-T6 aluminum alloys were examined in this study. The experiments showed that the rupture locations of the joints are different for the two aluminum alloys, and they are influenced by the welding parameters. When the joints are free of welding defects, the AA2017-T351 joints are ruptured in the weld nugget adjacent to the thermo-mechanically affected zone (TMAZ) on the advancing side (AS) and the rupture surfaces appear as oval contours of the weld nugget, while the AA6061-T6 joints are ruptured in the heat affected zone (HAZ) on the retreating side (RS) and the rupture surfaces are inclined at a certain degree to the bottom surfaces of the joints. When welding defects are present in the joints, the AA2017-T351 joints are ruptured in the weld center, while the AA6061-T6 joints are ruptured on the RS near the weld center. The rupture locations of the joints are dependent on the internal structures of the joints and can be explained through them.

KEY WORDS: (Friction Stir Welding) (Aluminum Alloy) (Tensile Test) (Rupture Location) (Welding Parameter) (Welded Joint)

1. Introduction

Friction stir welding (FSW) can produce high-quality and low-cost aluminum alloy joints, and thus has been extensively and intensively studied since it was invented in 1991 [1-3]. Many studies were focused on the mechanical properties [4-10] and microstructural characterizations [8-15] of the joints. Only a few studies were more or less involved with the rupture behavior or locations of the joints [4-10], and some of the study results had a certain lack of clarity [5-7] or were contradictory to each other [8-10].

Accordingly, it is necessary for us to go further into this topic so as to comprehend the rupture behavior of the different aluminum alloy joints. In this study, two types of aluminum alloys, i.e. AA2017-T351 Al-Cu alloy and AA6061-T6 Al-Si alloy, are selected as the experimental materials for FSW, and the emphasis is placed on the rupture locations of the joints and their decisive factors.

2. Experimental Procedure

Base materials used in this study were 5-mm-thick AA2017-T351 and AA6061-T6 aluminum alloy plates. The plates were all cut and machined into rectangular welding samples, 300 mm in length and 80 mm in width, and the samples were longitudinally butt-welded using an FSW machine (Hitachi, SHK207-899). The welding tool size and welding parameters used in the experiments are shown in Table 1.

After welding, the joints were cross-sectioned perpendicular to the welding direction for metallographic examination and tensile tests using an electrical-discharge cutting machine (Brother, HSC-300). The cross sections of the metallographic specimens were polished with an alumina suspension, etched with Keller's reagent and examined by optical microscopy.

The configuration and size of the transverse

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† Received on May 31, 2003

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Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan

Table 1 Welding tool size and welding parameters used in the experiments

Aluminum alloy	Tool size			Welding parameters			
	Shoulder diameter (mm)	Pin diameter (mm)	Pin length (mm)	Tool tilt (°)	Rotation speed (rpm)	Welding speed (mm/min)	Revolutionary pitch (mm/r)
AA2017-T351	15	6	4.7	3	1500	25-800	0.02-0.53
AA6061-T6	15	6	4.7	3	1000-1500	100-1000	0.07-1.00

tensile specimens are shown in Fig. 1, in which RS and AS denote the retreating side and advancing side of the joint. Prior to the tensile tests, Vickers hardness profiles were measured along the centerlines of the cross sections of the tensile specimens under a load of 0.98 N for 10 s using an automatic microhardness tester (Akashi, AAV-502), and the Vickers indentations with a spacing of 1 mm were used to determine the rupture locations of the joints. The tensile tests were carried out at room temperature with a crosshead speed of 1 mm/min using a computer-controlled testing machine (Shimadzu, AG-10TB).

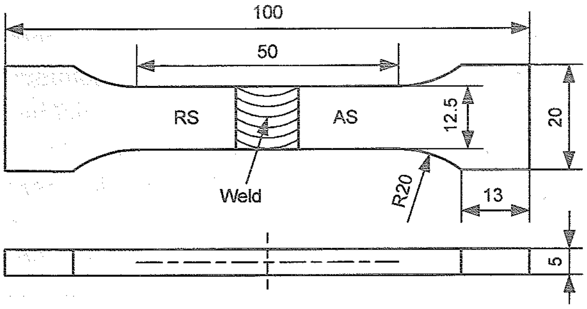

Fig. 1 Configuration and size of the tensile specimens.

3. Results and Discussion

3.1 Rupture locations of joints

Fig. 2 shows the rupture locations of the joints welded at different revolutionary pitches, including typical photographs (see **Fig. 2a** and **b**) and detailed data (see **Fig. 2c**). In this figure, the rupture location means the distance between the rupture surface and the weld center along the centerline of the joint cross-section.

Regarding AA2017-T351, some joints are ruptured on the AS, the rupture locations are not far distant from the weld center, and the rupture surfaces appear as an oval contour of the weld nugget, while other joints are ruptured in the weld center (see **Fig. 2a** and **c**).

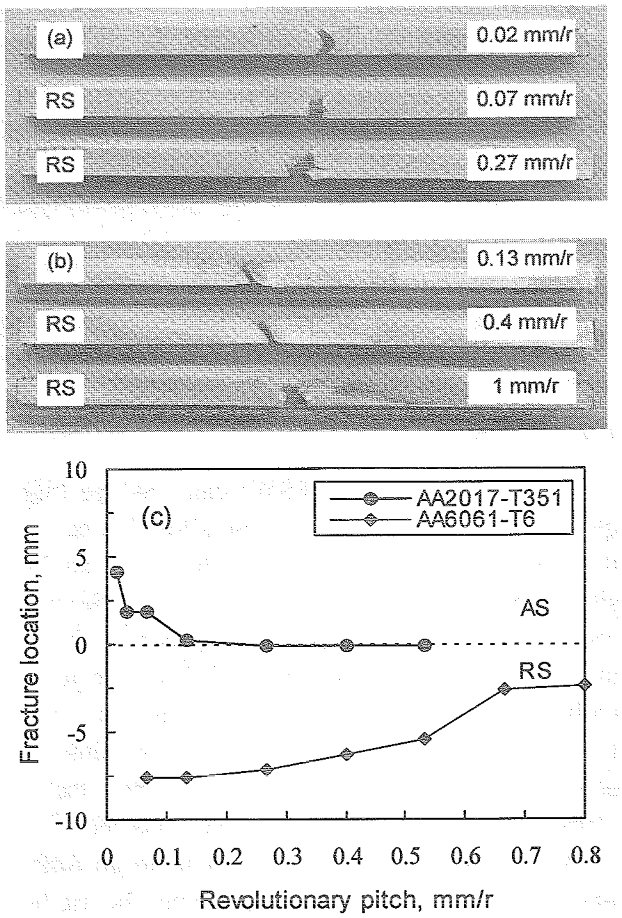

Fig. 2 Rupture locations of the joints of two aluminum alloys: (a) AA2017-T351, (b) AA6061-T6, and (c) detailed data.

With respect to AA6061-T6, all the joints are ruptured on the RS. Some rupture locations are distant from the weld center and the rupture surfaces are inclined at a certain degree to the bottom surfaces of the joints, while other rupture locations are near the weld center (see **Fig. 2b** and **c**).

It should be noted that the rupture locations of the joints change with the FSW parameters. As the revolutionary pitch increases, the rupture locations of the joints move towards the weld center, but the rupture in the weld center is only presented in the AA2017-T351 joints (see **Fig. 2c**).

These results indicate that the rupture locations of the joints are different for the different aluminum alloys, and they are influenced by the FSW parameters.

3.2 Decisive factors of rupture locations

The rupture locations of the joints are dependent on the internal structures of the joints. When the joints are free of defects, as shown in **Fig. 3**, a large number of joints are ruptured according to the microhardness distributions in the joints, e.g. AA6061-T6 joints, but a small number of joints are ruptured independently of them, e.g. AA2017-T351 joints.

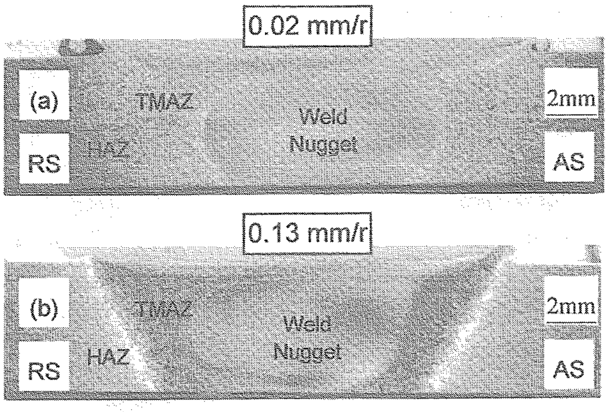

Fig. 3 Cross sections of the defect-free joints of the two aluminum alloys: (a) AA2017-T351 and (b) AA6061-T6.

In the AA2017-T351 joints, there are two low-hardness zones on both sides of the weld center (see **Fig. 4a**). However, it is strange that the joints are ruptured in neither low-hardness zone. In detail, the joints are ruptured in the weld nugget adjacent to the thermo-mechanically affected zone (TMAZ) on the RS, i.e. at or near the interface between the weld nugget and the TMAZ on the AS (see **Fig. 3a**), and the plastic deformation produced in the joints are very low. The reason for this may be that a significant difference in the microstructure exists between the weld nugget and the TMAZ, and it is necessary for us to investigate this result further.

In the AA6061-T6 joints, there are also two low-hardness zones on both sides of the weld center (see **Fig. 4b**), and they correspond to the two HAZs in the joint (see **Fig. 3b**). The minimum hardness value is present in the low-hardness zone on the RS, accordingly the joints are ruptured in the HAZ on the RS. The distance between the minimum-hardness location and the weld center decreases as the revolutionary pitch increases, consequently the rupture locations of the joints move towards the weld center.

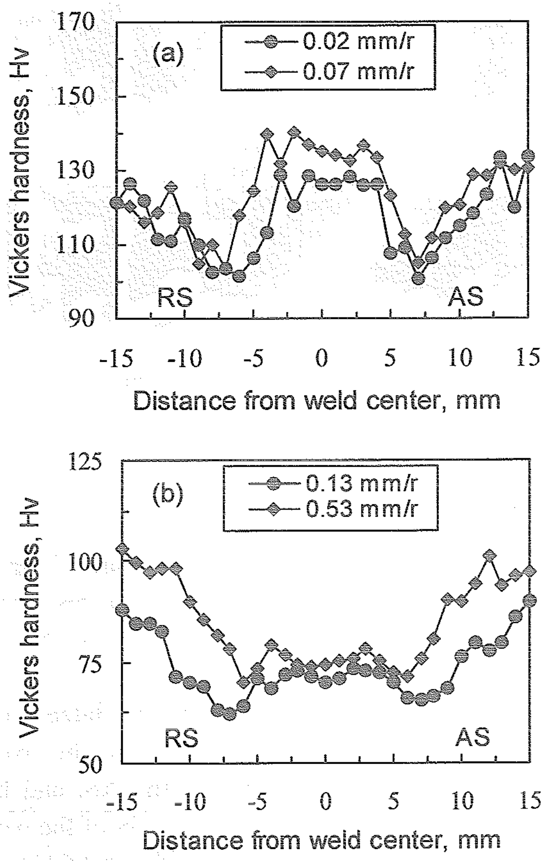

Fig. 4 Microhardness profiles in the joints of the two aluminum alloys: (a) AA2017-T351 and (b) AA6061-T6.

On the other hand, when welding defects are present in the joints, the rupture locations of the joints are significantly dependent on these defects. **Fig. 5** shows welding defects in the joints of the two aluminum alloys. In the AA2017-T351 joints, the defects are composed of many voids and distributed in the middle of the weld (see **Fig. 5a**), therefore the joints with defects are fractured in the weld center. In the AA6061-T6 joints, the defects are located in the lower parts of the joints. They are narrow and long, but smaller than the diameter of the tool pin (see **Fig. 5b**). During the tensile tests, the joints are ruptured through the tips of the defects. Because the defect length is smaller than the pin diameter, the rupture locations are not far distant from the weld center. Moreover, the defects slope slightly from the RS to the AS, therefore the joints tend to rupture on the RS.

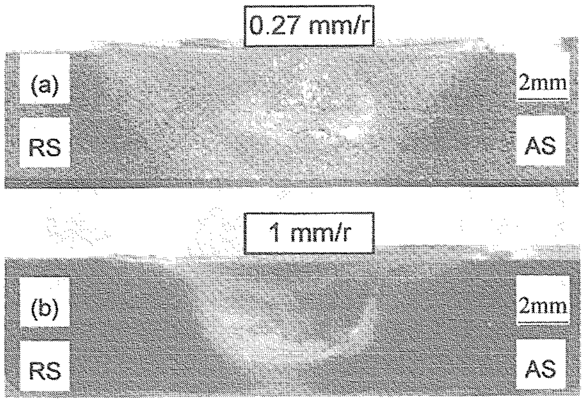

Fig. 5 Defects in the joints of the two aluminum alloys: (a) AA2017-T351 and (b) AA6061-T6.

4. Conclusions

The rupture locations of the joints are different for the two aluminum alloys selected in this study, and they are influenced by the FSW parameters or internal structures of the joints.

When the joints are free of welding defects, the AA2017-T351 joints are ruptured in the weld nugget adjacent to the TMAZ on the AS, and the rupture surfaces appear as oval contours of the weld nugget; the rupture locations of the AA6061-T6 joints are in the HAZ on the RS, and the rupture surfaces are inclined at a certain degree to the bottom surfaces of the joints.

When welding defects are present in the joints, the AA2017-T351 joints are ruptured in the weld center, while the AA6061-T6 joints are ruptured on the RS near the weld center.

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