Microstructures and Mechanical Properties of Double-Friction Stir Welded 2219 Al Alloy

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The microstructure, mechanical properties and thermal stability of double friction stir welded 2219 Al alloy were investigated. The grain size of the double friction stir zone was about 0.8 μm , which was smaller than that of the single friction stir zone. The dissolution of the very fine strengthening particles resulted in a decrease of the hardness values in the single and double friction stir zone. Following the post weld heat treatment (PWHT), the grain structure of the double-FSW joints was found to be more unstable than that of the single-FSW joints, owing to the finer grain size, higher fraction of sub-grains and lower particle density. [doi:10.2320/matertrans.MRP2007249]

(Received October 22, 2007; Accepted January 25, 2008; Published March 19, 2008)

Keywords: 2219 aluminum alloy, double friction stir welding, microstructure, thermal stability

1. Introduction

Generally, the second phases, such as the precipitates and intermetallic compounds formed by the reaction of the Al with the additives, are one of the major factors involved in the strengthening effect observed in Al alloy. However, the original properties of Al alloy are deteriorated in the fusion weld joints, owing to the coarsening and dissolution of the second phase. On the other hand, friction stir welding (FSW) enables better welds to be obtained, because the overall process is performed at temperatures below the melting temperature of the welded material.^{1,2)} FSW has been applied to high strength Al alloys, and found to result in better joint properties. More recently, in order to broaden its range of applications, FSW has been tentatively used to join various metals, such as magnesium, steel, zinc, copper alloys.³⁾

Al 2219 alloy is the typical wrought Al alloy, containing Al and Cu as the principle elements, and has been used for various aircraft components, such as external fuel tanks.⁴⁾

During the manufacturing process for products such as big cylindrical pipes for cryogenic fuel tanks using FSW, the double-FSW method has to be applied. When materials are subjected to the double-FSW process, the microstructure near the weld zone may differ from that of materials that underwent single-FSW. In general, FSW zone is more unstable than the untreated material, due to the dynamic recovery or recrystallization process, which results in a high density of dislocations within the equiaxed recrystallized grains.^{1,5-7)} Therefore, numerous studies have been performed to evaluate the microstructural, mechanical and thermal properties of the FSW zone in detail, however, almost all of these studies were focused on single-FSW

joints.⁸⁻¹⁰⁾ In contrast, to the best of our knowledge, no studies on the double-FSW zone have yet been reported.

Therefore, in this study, the microstructure, mechanical properties and thermal stability of the double-FSW zone were investigated and compared with those of the single-FSW zone and the starting material. Especially, the effect of different microstructural factors in the SZ of the single- and double-FSW joints on the thermal stability was also examined, with particular emphasis on the effect of the post weld heat treatment (PWHT).

2. Experimental Procedures

The starting material selected for this study was 2219 Al alloy sheets having a composition of Al-6.0 Cu-0.25 Mn-0.1 V-0.04 Ti-0.1 Fe-0.06 Si-0.01 Mg (mass%). The dimensions of the specimens used for the FSW process were 70 × 140 × 4.55 (mm). Figure 1 shows a schematic illustration representing the double-FSW process used for making the big cylindrical pipe (a-c). The welds were made with same welding speeds of 87 mm/min at both first welding for single FSW joint and second welding for double FSW joint, but different tool rotation speeds of 1250 and 800 rpm were applied at first and second FSW, respectively. The common features of the welding tools include a shoulder diameter of 13 mm and a pin diameter of 4 mm. The PWHT experiment was performed at the two temperatures (470°C and 510°C) for 1 hr to evaluate the thermal stability in the weld. The microstructure of the weld zone was investigated by optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and electron back scattering diffraction (EBSD). The square in Fig. 1(d) is shown the cut location of specimen for cross sectional observation. Energy dispersive spectrometry (EDS) was used for the purpose of phase identification. EBSD orientation

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Fig. 1 The schematic illustration of double-FSW procedure for manufacturing of big fuel tank (a-c) and cut location of specimen for microstructure observation (d).

maps were obtained using a JEOL JSM 7000F FE-SEM. Thin disks were cut from each weld zone using electrical discharge machine (EDM) for the TEM observation. A twin-jet electropolisher was used to produce electron-transparent thin sections in these sliced disks, using a nital solution at -50°C . These thin foils were observed at 300 kV using a JEOL TEM. The Vickers hardness profile near the weld zone was measured on a cross section and perpendicular to the single and double FSW direction, respectively, with a 100 g load for 10 s.

3. Results and Discussion

Figure 2 shows the cross-sectional macro image of the double-FSW joints (a) and the microstructures of the different weld zones (b-e). The selected surface for cross-sectional observation corresponds to the lower double line of the square in Fig. 1(d). The double FSW-joints were of good quality with no defects. The stir zone (SZ) (c) is the lighter part at the weld center containing slightly finer grains compared to that of the base metal (BM) (b) which is the SZ

Fig. 2 Optical microstructures of double-FSW joint (a) macro cross-section, (b) BM, (c) SZ, (d) TMAZ and (e) HAZ.

Fig. 3 Distribution of the intermetallic compound (a) starting material, (b) SZ of single-FSW joints, (c) SZ of double-FSW joints and (d) EDS spectrum.

of the single-FSW joint. The heat affected zone (HAZ) (e) was characterized by a coarsened grain structure compared to that of the BM. This grain coarsening was caused by the frictional heat which developed during the double-FSW process, because the HAZ was only influenced by the thermal effect. The thermally and mechanically affected zone (TMAZ) (d) was composed of plastically upset grains and the partially recrystallized grains.

Figure 3 shows the SEM results showing the distribution and EDS element spectrum of the intermetallic compounds in the weld zone. Agglomerated white particles were observed in the starting material, which were identified as Al_2Cu intermetallic compound with an atomic ratio of Al to Cu of approximately 2:1. These particles were smaller and more homogeneously distributed in the SZ of the single-FSW joints (b). The refinement of the Al_2Cu particles in the double-FSW joints was superior (c), and it is considered that this was caused by the double mechanical stirring effect of the welding tool.

To investigate the distribution and density of the particles in detail, TEM observations were conducted and the results are shown in Fig. 4. Very fine needle-like particles were observed over the entire space of the starting materials (a). In the magnified and tilted micrographs (e), they were found to be disk shaped with a size of less than 50 nm. A quantitative analysis could not be carried out owing to their small size, however, it was determined by EDS of TEM that Al and Cu were the principle elements. In the HAZ of the single-FSW joint (b), the fine particles were slightly coarsened by the frictional heat effect. Figures 4(c) and (d) show the SZs of the single- and the double-FSW joints, respectively. The very fine particles observed in the starting material and HAZ of the single-FSW joint disappeared in these regions, and it is considered that these particles were dissolved into the matrix by the simultaneous effect of the mechanical stirring and high temperature during the FSW. Bigger particles were observed in the SZ of single and double-FSW joints. The particle density in the SZ of the double-FSW joint is slightly lower than that in the SZ of the single-FSW joints. Double-FSW accelerated the dissolution of the particles into the matrix.

Fig. 4 TEM micrograph of (a) starting material, (b) HAZ of single-FSW joints, (c) SZ of single-FSW joints, (d) SZ of double-FSW joints and (e) magnified microstructure of starting material.

Fig. 5 Grain size and orientation distributions obtained from SZ of the single (a and c) and double-FSW joints (b and d).

Dislocations were still observed inside the recrystallized grains in the SZ of both the single and double FSW joints, in spite of their recrystallization, which means that the residual grain structure after the FSW process developed via the dynamic recovery and recrystallization process. The effect of the FSW number on the dislocation density in the SZ was not clear.

Figure 5 shows the grain size and boundary misorientation distribution obtained from the SZ of the single and double-FSW joints by EBSD. The SZ of the single-FSW joints was composed of grains having an average size of $2\mu\text{m}$ and the fraction of low angle grain boundaries for which the misorientation angle between neighboring grains is more than 2° and less than 15° was approximately 0.116. In the case of the double-FSW joints, the average grain size was about $0.8\mu\text{m}$ and the fraction of low angle grain boundaries was about 0.162. These results imply that the microstructures of the double-FSW joints have the more sub-grain bounda-

Fig. 6 Hardness distribution of the single and double-FSW joints.

ries, which are the accumulation of dislocations and smaller grains than those of the single-FSW joints. It is assumed from EBSD results that the microstructure of the double-FSW joints is unstable, due to the higher dislocation density and higher volume fraction of grain boundary as compared to those of the single-FSW joints.

Figure 6 shows the horizontal Vickers hardness profile of the single and double-FSW joints. The Vickers hardness value measured through the dotted line in schematic of Fig. 6 varied from 120 to 130 Hv in the starting material and decreased to approximately 80 Hv in the SZ of single-FSW joints. However, in the case of double-FSW joints, the Vickers hardness values of base metal and weld zone were almost same as approximately 80 Hv, because the base metal at the second welding was the stir zone at the first welding, as indicated by solid line in schematic of Fig. 6. Consequently, the double welding didn't induce the decrease of the Vickers hardness in the FSW joints. It is considered that these results were closely related to the microstructural characteristics. That is, the dissolution of the strengthening particles, including Cu and Al elements, reduced the Vickers hardness value in the weld joints, and even after second welding, any remarkable variation of microstructure such as re-precipitation of the strengthening particles did not occurred in the joints.

Figure 7 shows the cross-sectional macro images of the FSW joints after PWHT. No remarkable variation was observed in the single (a) and double (b) FSW joints subjected to PWHT at 470°C . However, in the joints subjected to PWHT at 510°C , abnormal grain growth (AGG) was observed in both joints. The AGG is caused by the movement of high angle grain boundary, which is usually accelerated at higher temperature.¹¹⁾ The transition temperature for AGG was assumed to be exited between two temperatures applied in this study, which was considered to be closely related to the dissolution temperature of Al_2Cu precipitates. The coarsening rate of abnormal grains was higher in the double-FSW joints (d), than in the single-FSW joints (c) at the same temperature. The three reasons could be considered for this result. Many low angle grain boundaries generally imply the stronger textured microstructure, which

Fig. 7 Grain structures in the weld nugget after PWHT (a) single, (b) double-FSW joints at 470°C, and (c) single, (d) double-FSW joints at 510°C.

develops the possibility of AGG in stead of normal grain growth. Thus, the higher fraction of low angle grain boundary preferentially introduced more active AGG in double-FSW joint.¹²⁾ Moreover, much finer grains in double-FSW joints were in more unstable state in view of energy contained in microstructure, which offered much bigger driving force for grain growth than in single FSW joints.^{13,14)} The other reason was the particle density. The relatively accelerated dissolution of fine precipitates in double-FSW joint made density of fine precipitates decreasing as shown in Fig. 4(c) and (d), which caused in the enfeeblement of pinning effect that hamper grain boundary moving.^{11,12)} Accordingly, the grain growth in double-FSW joint was more active than in single-FSW joint. As a result, it is considered that the smaller grain size, higher fraction of low angle grain boundaries and lower particle density of the double-FSW joints may be the synthetic reasons for the faster growth rate of abnormal grains.

4. Conclusion

The microstructure, mechanical properties and thermal stability of the double-FSW zone of 2219 Al alloy were investigated and compared to those of the single-FSW zone.

The Main results can be summarized as follows.

- (1) Very fine grain structures were observed in the SZ of the double-FSW joints and the grain size of the SZ in the double-FSW zone was finer than that of the SZ in the single-FSW zone.
- (2) The fine strengthening particles were dissolved into the matrix, thereby reducing the Vickers hardness value of the single and double-FSW joints.
- (3) After PWHT, a faster abnormal grain growth was observed in the double-FSW joints, because of the smaller grain size, higher fraction of the low angle grain boundaries and lower particle density.
- (4) The double-friction stirring effect introduced more dislocations and produced smaller grains in the weld zone, which resulted in an unstable grain structure in double-FSW joints.

REFERENCES

- 1) C. G. Rhodes, M. W. Mahoney, W. H. Bingel, R. A. Spurling and C. C. Bampton: *Scripta Mat.* **36** (1997) 69–75.
- 2) W. B. Lee, J. W. Kim, Y. M. Yeon and S. B. Jung: *Mater. Trans.* **44** (2003) 917–923.
- 3) C. Y. Lee, W. B. Lee, Y. M. Yeon and S. B. Jung: *Mater. Sci. Forum* **475–479** (2005) 555–558.
- 4) I. J. Polmer: *Light Alloys* (Edward Arnold, London, 1981) p. 1–12.
- 5) K. A. A. Hassan, A. F. Norman, D. A. Price and P. B. Prangnell: *Acta Mater.* **51** (2003) 1923–1936.
- 6) F. J. Humphreys and M. Hatherly: *Recrystallization and Related Annealing Phenomena* (Pergamon, Oxford, 1996) p. 363–392.
- 7) W. B. Lee, Y. M. Yeon and S. B. Jung: *Mater. Sci. and Technol.* **19** (2003) 1513–1518.
- 8) H. G. Salem: *Scripta Mat.* **49** (2003) 1103–1110.
- 9) M. M. Attallah and H. G. Salem: *Mat. Sci. Eng. A* **391** (2005) 51–59.
- 10) I. Charit, R. S. Mishra and M. W. Mahoney: *Scripta Mat.* **47** (2002) 631–636.
- 11) R. S. Mishra, R. K. Islamgaliev, T. W. Nelson and Y. Hovansky, *et al*: *Friction stir welding and processing*, (A publication of TMS, Indiana, 2001) p. 205–216.
- 12) F. J. Humphreys and M. Hatherly: *Recrystallization and Related Annealing Phenomena* (Pergamon, Oxford, 1996) p. 314–325.
- 13) Ø. Frigaard, Ø. Grong and O. T. Midling: *Metall. Mater. Trans. A* **32A** (2001) 1189–1200.
- 14) Y. S. Sato, H. Watanabe and H. Kokawa: *Sci. Technol. Weld. Joining* **12** (2007) 318–323.