Effect of post-weld heat treatment on the mechanical properties of 2219-O friction stir welded joints

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As a solid-state process, friction stir welding (FSW) can avoid the formation of solidification cracking and porosity associated with fusion welding processes and significantly improve the weld properties of aluminum alloys [1]. However, many studies on the mechanical properties of FSW joints of heat-treatable aluminum alloys such as 2017-T351 [2], 2024-T6 [3], 2195-T8 [4], 2519-T87 [5], 6061-T6 [6, 7], 6063-T5 [8] and 7075-T651 [9] have indicated that FSW gives rise to softening of the joints and results in the significant degradation of the mechanical properties. In order to restore the mechanical properties of the FSW joints, a post-weld ageing heat treatment to 6082 aluminum alloy joints has been performed [10]. When the base material was in T6 condition, the micro-hardness in the weld zone increased, but the one in the heat-affected zone decreased; while the base material is in T4 condition, the micro-hardness in the entire joints increased. Another post-weld solution and ageing heat treatment to 6061-O aluminum alloy joints indicated that the micro-hardness values across the joint significantly increased, while the toughness of the joints deteriorated [11]. These results imply that the effects of the post-weld heat treatment (PWHT) on the mechanical properties of the joints are related not only to the base material conditions, but also to the PWHT processes. The present letter demonstrates the effect of the post-weld solution-ageing heat treatment on the mechanical properties of 2219-O aluminum alloy FSW joints. The emphasis is placed on the tensile properties and fracture locations of the joints.

The base material used in this study was a 5-mm-thick 2219-O aluminum alloy plate, with the chemical compositions and mechanical properties listed in Table I. The welding samples, 260 mm by 50 mm, were longitudinally butt-welded using an FSW machine. The welding tool size and welding parameters are listed in Table II. After welding, the samples were cut into two parts, one part for the PWHT and the other part for the as-welded examinations. The PWHT process includes solid solution at 535 °C for 32 min, quenching in water at 25 °C, and ageing at 165 °C for 18 hr. After the heat treatment, all the joints, including as-welded joints, were cross-sectioned perpendicular to the welding direction for metallographic analyses and tensile tests. The cross-sections of the metallographic specimens were polished with a diamond paste, etched with Tucker's reagent and observed by optical microscopy. Vickers hardness distributions in the joints were measured along the centerlines of the cross sections under a load of 4.9 N for 10 s, and the distance between the adjacent measured points was 1 mm. The room-temperature tensile test was carried out at a crosshead speed of 1 mm/min using an Instron-1186 testing machine. The marked length of each specimen was 50 mm, and the tensile properties of each joint were evaluated using three tensile specimens cut from the same joint.

Fig. 1 shows the tensile properties of the joints welded at different welding speeds before and after the heat treatment. The tensile properties of the as-welded joints almost do not change with the welding speed (see Fig. 1a). The tensile strength is equivalent to that of the base material, and the elongation is changed between 10 and 12%. However, the tensile properties of the heat-treated joints increase with increasing welding speed (see Fig. 1b). The tensile strength is up to 385 MPa, equivalent to 2.4 times that of the base material, and the maximum elongation is 3.2%. These results indicate that the heat-treated joints possess a higher tensile strength and a lower elongation than the as-welded joints.

Fig. 2 shows the fracture locations of the joints before and after the heat treatment. As seen from this figure, the as-welded joints fracture in the base material zone (BMZ) (see Fig. 2a), while the heat-treated joints fracture in the weld zone (WZ) (see Fig. 2b). This implies that the PWHT process has a significant effect on the fracture locations of the joints. That is to say, the BMZ is a weak part of the joints before the heat treatment, while the WZ becomes the weak part of the joints after the heat treatment is performed.

In most cases, the tensile properties and fracture locations of the joints are related to the hardness

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TABLE I Chemical compositions and mechanical properties of 2219-O aluminum alloy plate

Chemical compositions (wt%)									Mechanical properties		
Al	Cu	Mn	Fe	Ti	V	Zn	Si	Zr	Tensile strength	0.2% proof strength	Elongation
Bal.	6.48	0.32	0.23	0.06	0.08	0.04	0.49	0.2	159 MPa	114 MPa	17.5%

TABLE II Tool size and welding process parameters used in the experiments

Tool size (mm)			Welding parameters		
Shoulder diameter	Pin diameter	Pin length	Rotation speed	Travel speed	Tool tilt
15	6	4.8	800 rpm	100–400 mm/min	2.5°

distributions in the joints [2, 6, 12, 13]. Fig. 3 shows the micro-hardness profiles in the joints before and after the heat treatment. Before the heat treatment, the micro-hardness values in the WZ are higher than those in the BMZ (see Fig. 3a), indicating that the WZ is strengthened by the FSW process. Therefore, the joints fracture in the BMZ and the tensile strength of the joints equals that of the base material, but the elongation of the joints decreases. After the heat treatment, the micro-hardness in the joints significantly increases (see Fig. 3b), thus resulting in the significant increase of the tensile strength.

However, the tensile properties of the heat-treated joints increase with increasing welding speed and the fracture locations tend to occur in the WZ (see Figs 1b and 2b)

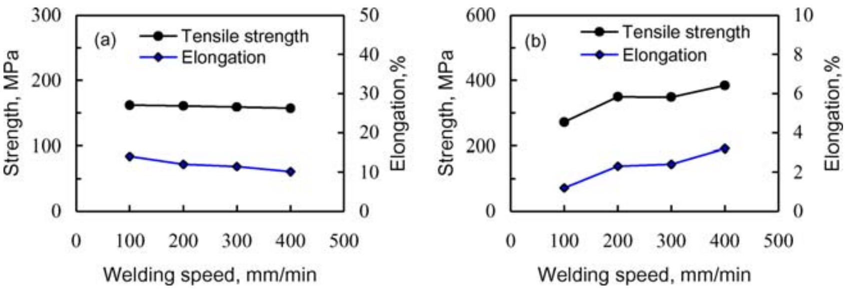

Figure 1 Tensile properties of the joints: (a) before heat treatment and (b) after heat treatment.

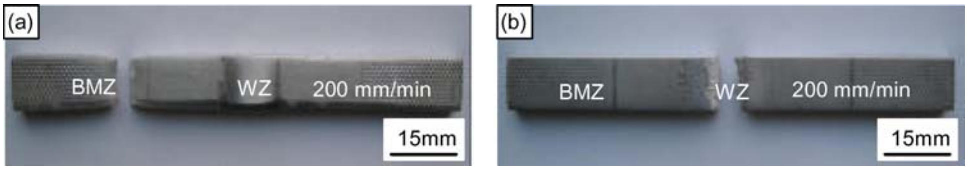

Figure 2 Typical fracture locations of the joints: (a) before heat treatment and (b) after heat treatment.

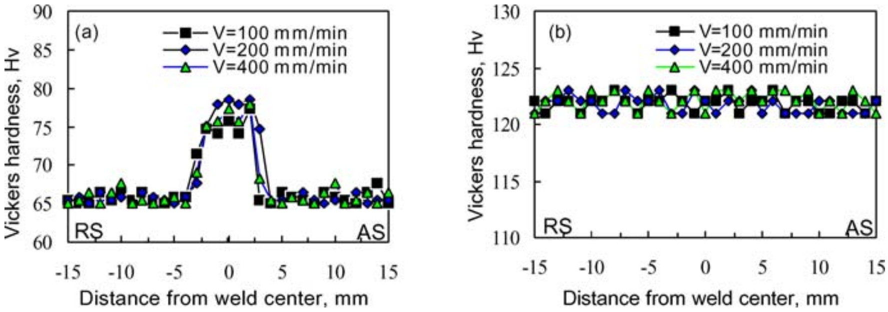

Figure 3 Micro-hardness profiles in the joints: (a) before heat treatment and (b) after heat treatment.

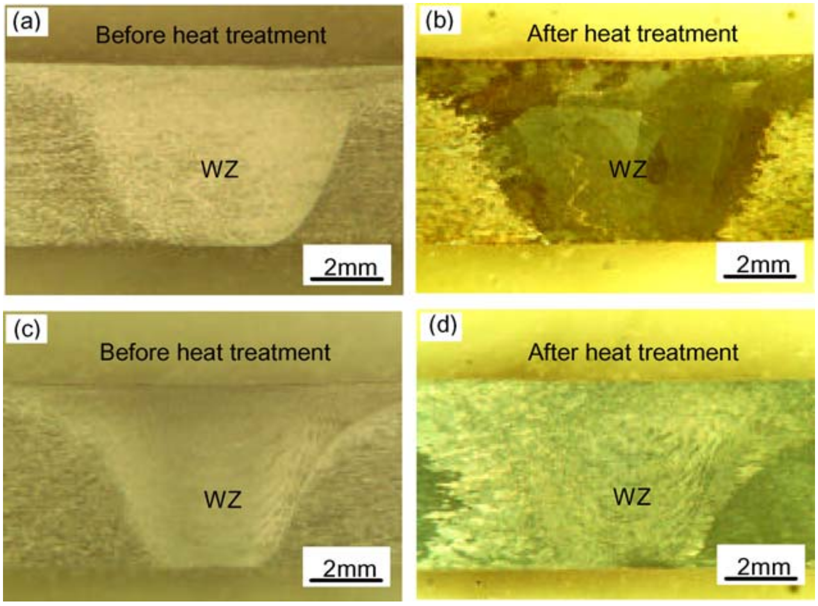

Figure 4 Cross sections of the joints welded at different welding speeds before and after heat treatment: (a) and (b) 100 mm/min; (c) and (d) 200 mm/min.

although the micro-hardness profiles in the joints are flat (see Fig. 3b). This can be explained by the inner structure of the joints. Fig. 4 shows the cross sections of the joints welded at different welding speeds before and after the heat treatment. It can be seen from the figure that the serious grain coarsening is produced in the WZ of the heat-treated joints (see Fig. 4a and b), therefore the WZ becomes a weak part of the joints and the fracture occurs in the WZ. Moreover, the greater the welding speed, the smaller the grain size (see Fig. 4b and d), accordingly the tensile properties of the joints, including strength and elongation, increase with increasing welding speed.

To sum up, the tensile strength of the FSW joints of 2219-O aluminum alloy can be significantly improved by the PWHT process, and the strength increases with increasing welding speed. The PWHT process also influences the fracture locations of the joints, and all the heat-treated joints fracture in the WZ. These results can be explained by the micro-hardness profiles and the inner structure of the joints.

References

1. C. J. DAWES and W. M. THOMAS, *Weld. J.* **75** (1996) 41.
2. H. J. LIU, H. FUJII, M. MAEDA and K. NOGI, *J. Mater. Process. Technol.* **142** (2003) 692.
3. S. BENAVIDES, Y. LI, E. MURR, D. BROWN and J. C. MCCLURE, *Scripta Mater.* **41** (1999) 809.
4. T. U. SEIDEL and A. P. REYNOLDS, *Metall. Mater. Trans. A* **32** (2001) 2879.
5. P. S. PAO, E. LEE, C. R. FENG, H. N. JONES and D. W. MOON, Proceedings of the Fourth International Symposium on Friction Stir Welding (Utah, USA, May 2003) Paper No. Post-8.
6. H. J. LIU, H. FUJII, M. MAEDA and K. NOGI, *J. Mater. Sci. Lett.* **22** (2003) 1061.
7. G. LIU, L. E. MURR, C. S. NIOU, J. C. MCCLURE and F. R. VEGA, *Scripta Mater.* **37** (1997) 355.
8. Y. S. SATO, H. KOKAWA, M. ENOMOTO and S. JOGAN, *Metall. Mater. Trans.* A **30** (1999) 2429.
9. M. W. MAHONEY, C. G. RHODES, J. G. FLINTOFF, R. A. SPURLING and W. H. BINGEL, *ibid.* A **29** (1998) 1955.
10. J. BACKLUND, Proceedings of NALCO-7 (Cambridge, UK, April 1998) p. 171.
11. K. N. KRISHNAN, *J. Mater. Sci.* **37** (2002) 473.
12. Y. S. SATO and H. KOKAWA, *Metall. Mater. Trans.* A **32** (2001) 3023.
13. H. J. LIU, H. FUJII, M. MAEDA and K. NOGI, *J. Mater. Sci. Lett.* **22** (2003) 441.

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