A Study of Microstructural Stability of Friction Stir Welded Joints of Al-Mg Alloys during Subsequent Thermal Exposure

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Abstract

Al-Mg wrought alloys such as Al-2.6Mg, Al-4.6Mg and Al-4.6Mg- 1Si were friction stir welded and a subsequent thermal exposure was carried out in this study. The effects of elements addition and exposure temperature on the microstructural stability of welded zone were investigated. A grain refinement was found in the weld zone of each alloy and the average grain size of friction stir welded Al-2.6Mg, Al-4.6Mg and Al-4.6Mg- 1Si was 10.1μm, 7.4μm and 4.7μm, respectively. Thermal exposure caused drastic coarsening of grains in the stirred zone and abnormal grain growth initiated at some preferred sites such as upper surface and bottom. The volume fraction of coarsening grains increased with increasing exposure temperature; however an unexpected decrease in grain size was found at 550℃ in compare to 500 ℃. Besides, the addition of Mg and Si deteriorated the thermal stability of grain structure in stirred zone.

Keywords: Al-Mg, Friction stir welding, Abnormal grain growth.

1. Introduction

A solid joining process, friction stir welding (FSW), was first developed in The Welding Institute (TWI), UK in 1991[1], which was particularly suited for the hard-to-fusion-welded metal materials. It was considered to be a "green" technique to manufacture a high-quality and defect-free joints. In the past decades, since it was rapidly developed in Al alloys and successfully practiced into commercial application, many researches were motivated to the feasibility of other materials such as Mg, Cu, Ti and steel alloys, even dissimilar alloys/metals. Severe plastic deformation and frictional heating were provided by a non-consumable rotating tool, which contains a pin inserting into the edges of sheets and a shoulder keeping friction with the workpieces surface. A recrystallized fine-grained structure was continuously generated during FSW. Although the grain refining effect tends to enhance the mechanical strength and hardness, many studies[2-7] had proposed a microstructural instability problem on friction-stirred specimens at high temperature, especially easily found in stir zone.

The thermal instability of the friction stirred specimen was characterized by discontinuous abnormal grain growth, AGG (or secondary recrystallization), which had been frequently observed in FSW/FSPed AA6061[2], AA7010[3] and AA2095[4] undergoing a solution heat treatment. AGG was a microstructural phenomenon where selective grains rapidly consumed the finer matrix grains, and it generally happened when the normal grain growth (NGG) of matrix grains was suppressed. Although the majority of papers focused on heat-treatable aluminum alloys, non-heat treatable aluminum alloy, like 5083 also showed AGG. Previous studies[6-7] on 5083 showed that in post heat treatment AGG easier occurred with lower frictional heat input and the AGG phenomenon was govern by the particle pinning effect. Different kinds and contents of alloying addition will surely affect the thermal stability but still less-concerned. This study aims to investigate the effect of Mg and Si content on the AGG of post-FSW-heat treated specimens.

2. Experimental procedure

Three wrought aluminum alloys, Al-2.6Mg, Al-4.6Mg and Al-4.6Mg-1Si undergoing hot-rolling and subsequent full-annealing were used in this study. The chemical compositions were listed in Table 1. The Al specimen was sustained by a cast iron back plate and FSW was carried out by using a SKH-51 steel tool. The tool dimension was 15mm in shoulder diameter, 5.5mm in pin diameter and 3mm in pin length. The fixed parameters were 450rpm in rotational speed, 0.55mm/s in traversal speed, 1° in tool tilted angle and 70MPa in loading pressure. The FSWed specimens were heat-treated in the furnace at 300-600℃ for 1 hour to investigate the microstructural stability during thermal exposure.

The macro- and microstructural features of as-FSWed and as-heat-treated specimens were examined in cross-sectioned plane (perpendicular to the FSW path). The surface for the metallographic analysis was bath-polished with Al_2O_3 slurry, etched in modified Poulton's reagent and then observed by using optical and scanning electron microscope.

Table 1 Chemical compositions of experimental alloys.

	Mg	Si	Mn	Fe	Cr	Zn	Cu	Ti	V	Al
Al-2.6Mg	2.64	0.07	0.09	0.25	0.21	0.01	0.02	0.01	0.01	Bal.
Al-4.6Mg	4.62	0.11	0.57	0.25	0.11	0.03	0.04	0.02	0.01	Bal.
Al-4.6Mg-1Si	4.54	1.09	0.90	0.49	0.03	0.09	0.32	0.03	0.01	Bal.

3. Results and discussion

3.1 Microstructure of FSWed specimens

Fig. 1 showed that the experimental materials undergoing hot-rolling and full-annealing were characterized by stripe-like grain structure. As shown in Fig. 2(a)-2(c), there were some nearly spherical particles in the base metals and the number of particles increased with higher alloying content. The SEM-EDS analysis in Fig. 2(d)-2(g) showed that the particles of Al-Fe and Al-Mn-Fe were observed in Al-2.6Mg and Al-4.6Mg respectively. Two types of particles compositing with Al-Mn-Fe and Mg-Si were observed in Al-4.6Mg-1Si. According to the literatures [8-10] these particles were most likely Al_3Fe in Al-2.6Mg, $Al_6(Mn,Fe)$ in Al-4.6Mg, $Al_6(Mn,Fe)$ and mixture of Mg_2Si and Si in Al-4.6Mg-1Si.

Fig. 3(a)-3(f) indicated the microstructure of the friction-stirred specimens. Since all of the specimens proceeded dynamic recrystallization during FSW, they possessed a finer and equaxial grain structure in comparison to the base materials. However, the severe deformation provided by FSW insignificantly caused a variation of the particle morphology. The average grain size of FSWed Al-2.6Mg, Al-4.6Mg and Al-4.6Mg-1Si was 10.1μm, 7.4μm and 4.7μm respectively. This result exhibited that grain boundary migration during dynamic recrystallization will be easier restrained by solution atoms or precipitated obstacles while containing a higher Mg and Si addition. Finally, it resulted in a finer recrystallized structure after FSW.

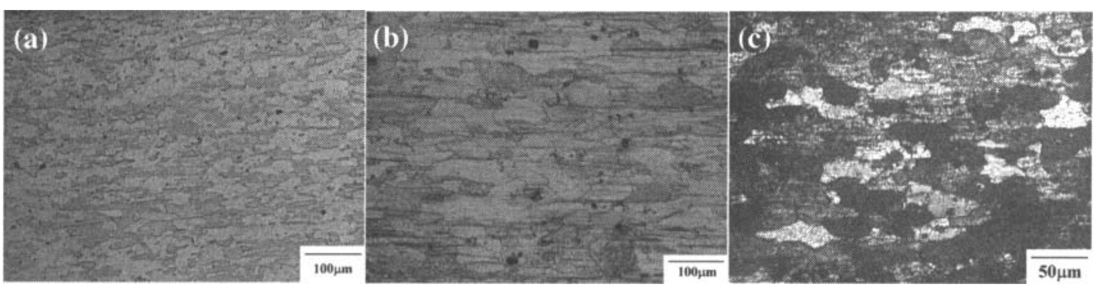
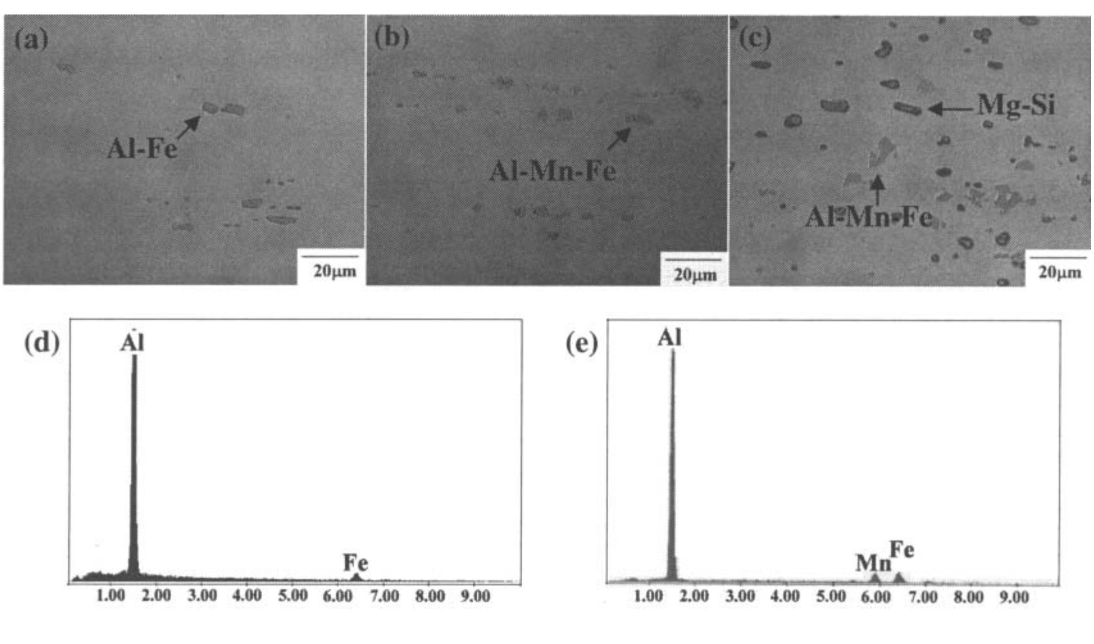


Fig. 1 The grain structure of (a)Al-2.6Mg, (b)Al-4.6Mg and (c)Al-4.6Mg-1Si.



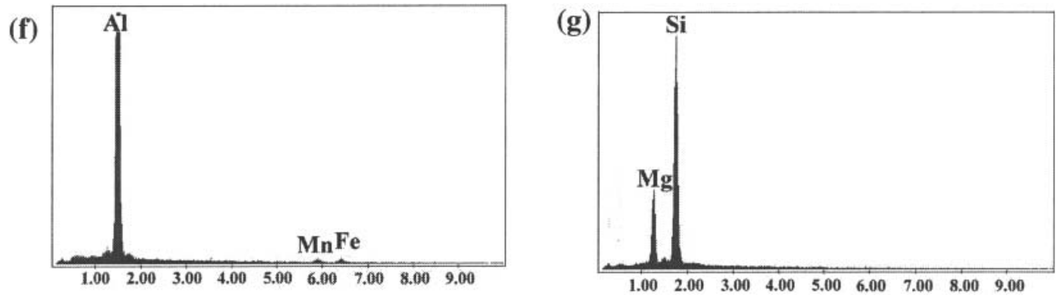


Fig. 2 The morphology of intermetallic compounds in (a)Al-2.6Mg, (b)Al-4.6Mg, (c)Al-4.6Mg-1Si, and the SEM-EDS analysis on (d)Al-Fe particles in Al-2.6Mg, (e)Al-Mn-Fe particles in Al-4.6Mg and (f)Al-Mn-Fe, (g)Mg-Si in Al-4.6Mg-1Si.

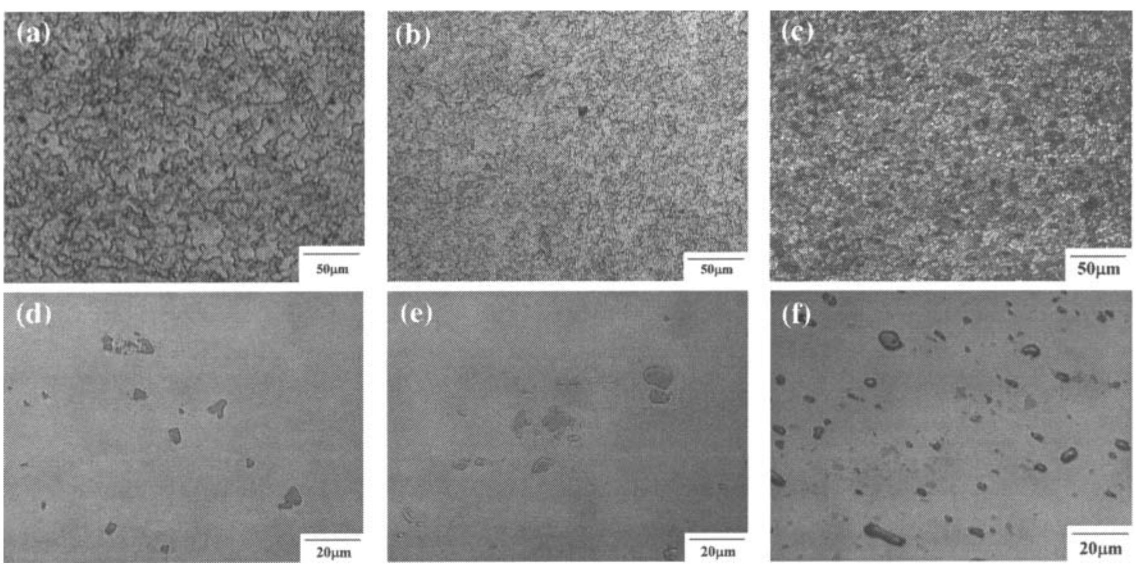


Fig. 3 The grain structure of the friction-stirred (a)Al-2.6Mg, (b)Al-4.6Mg, (c)Al-4.6Mg -1Si, and the particle morphology of the friction-stirred (d)Al-2.6Mg, (e)Al-4.6Mg, (f)Al-4.6Mg -1Si.

3.2 AGG phenomenon

For the application purpose the investigation of thermal stability was carried out by post heat treating the FSWed specimens at 300-600℃ for 1 hour. Fig. 4 showed the macrostructure of the specimens undergoing post-FSW heat treatment. All of the specimens maintained initial fine grain structure at post-heating temperature below 350℃. While heat treatment was carried out at the temperature of 400℃: the initial fine grain structure of FSWed Al-2.6Mg specimens did not become unstable; however, in the other two specimens with higher alloying contents the selective grains at upper stir zone (SZ) preferred to initiate a dramatic growth. At the temperature of 450℃: unstable coarse grains started to be found at upper SZ and thermal-mechanical-affected zone (TMAZ) in Al-2.6Mg; AGG also developed at the bottom of SZ besides upper SZ in Al-4.6Mg; AGG coarse grains occupied the overall SZ in Al-4.6Mg-1Si.

As mentioned above, higher content of Mg and Si was not only helpless to improve thermal stability but lead to a higher tendency of grain coarsening in the thermal exposure.

Furthermore, while the post-heat-treating temperature higher than 500℃, all the three kinds of FSWed specimens possessed a significant coarse grain structure at the whole SZ. In comparison to 500℃, an unexpected decrease of the grain size was found at temperature of 550℃, even 600℃. According to the literature[11], this result can be referred to the total dissolution of the effective pinning dispersoids and normal grain growth was then possible to talk place in the base material.

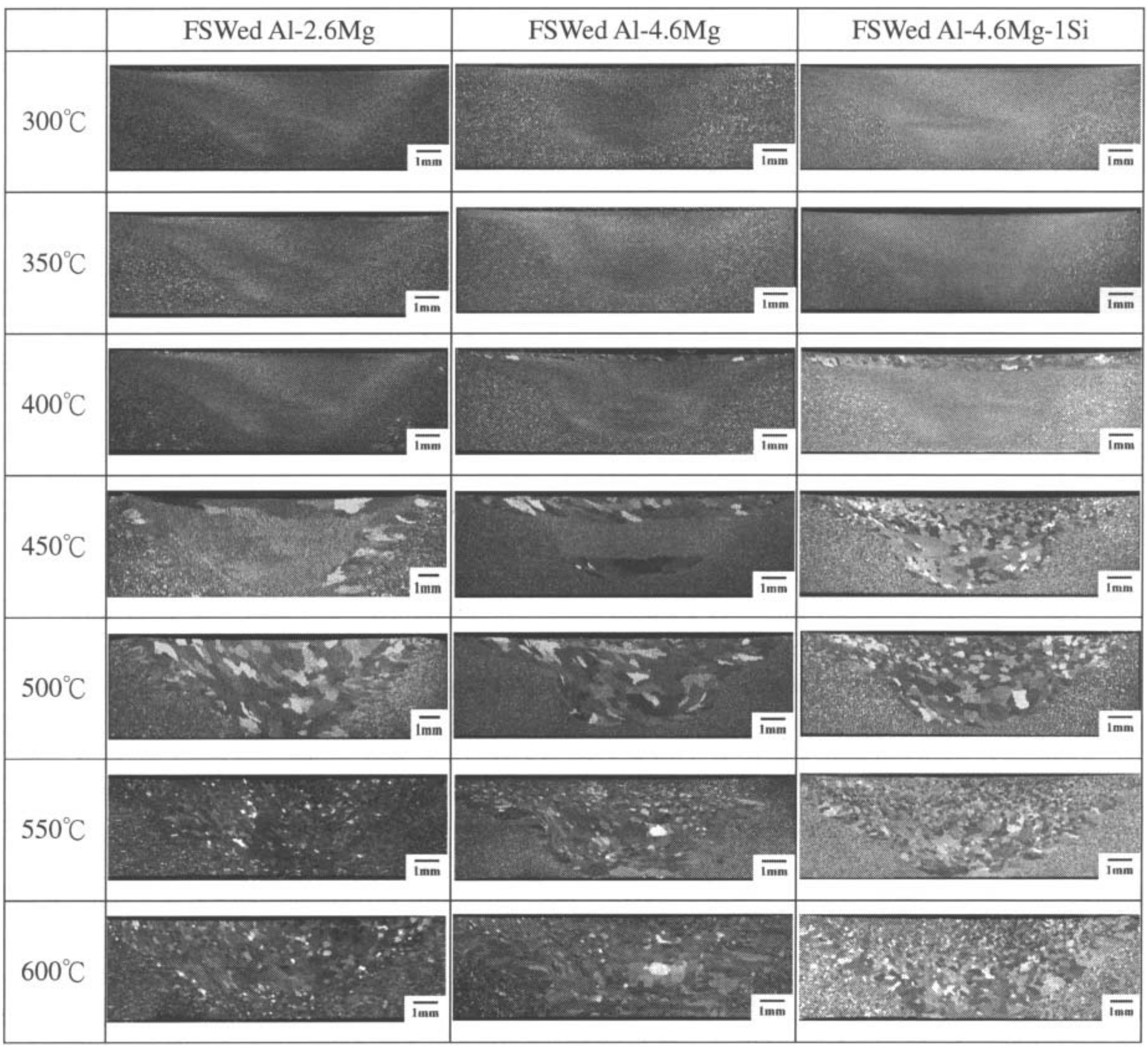


Fig. 4 The macrostructure of the FSWed specimens undergoing heat treatment at different temperature.

4. Conclusion

1. During FSW, dynamic recrystallization leads to a significant grain refinement and

lager restraining force to the grain boundary migration by solution atoms or precipitated obstacles conduced to a more significant grain refinement in the specimens with higher Mg and Si contents.

2. Grain coarsening phenomenon could be observed in the FSWed specimens undergoing heat treatment at temperature higher than 350℃ and AGG preferred to initiate in the upper surface, bottom of SZ and TMAZ region. Higher content of Mg and Si was not only helpless to improve thermal stability but lead to a higher tendency of grain coarsening in the thermal exposure.
3. In comparison to 500℃, an unexpected decrease of the grain size was found with the increasing temperature. It can be referred to total dissolution of the effective pinning dispersoids and lead to a more homogeneous grain growth behavior.

5.Acknowledgement

The authors are grateful to NSC 100-2221-E-006-093; NSC 100-2221-E-006-093 for the financial support.

Reference

1. R.S. Mishra and Z.Y. Ma: Mater. Sci. Eng., **R 50** (2005) 1-78.
2. K. N. Krishnan: J. Mater. Sci. **37** (2002) 473-480.
3. Kh. A. A. Hassan, A. F. Norman, D. A. Price and P. B. Prangnell: Acta Mater. **51** (2003) 1923-1936.
4. M. M. Attallah and H. G. Salem: Mater. Sci. Eng. A **391** (2005) 51- 59.
5. I. Charit and R. S. Mishra: Acta Mater. **53** (2005) 4211-4223.
6 K. E. Chen, W. Gan, K. Okamoto, K. Chung and R. H. Wagoner, Metall. Mater. Trans. A, **42** (2010) 488-507.
7. C. Y. Lin, T. S Lui and L. H. Chen, Mater. Trans. (JIM), **52** (2011) 1667-1673.
8. E. H. Kottcamp and E. L. Langer: ASM Handbook Vol. 3, Alloy Phase Diagram, (ASM International), USA, (1992) pp. 293.
9. E. H. Kottcamp and E. L. Langer: ASM Handbook Vol. 3, Alloy Phase Diagram, (ASM International), USA, (1992) pp. 1104.
10. E. H. Kottcamp and E. L. Langer: ASM Handbook Vol. 3, Alloy Phase Diagram, (ASM International), USA, (1992) pp. 1523-1526.
11. P. Cotterill, P. R. Mould: Recrystallization and Grain Growth in Metals, John Wiley & Sons, New York, 1976, 1980, p. 296-300.