Materials Science Forum Vols. 426-432 (2003) pp. 2873-2878
online at http://www.scientific.net
© 2003 Trans Tech Publications, Switzerland

Friction Stir Welding of Al_2O_3 Particulate 6061 Al Alloy Composite

K. Nakata[1], S. Inoki[1], Y. Nagano[2] and M. Ushio[1]
[1] Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047 Japan
[2] Showa Denko K.K., Oyama Research Lab., Inuzuka, Oyama, Tochigi 323-678, Japan

Keywords: Friction Stir Welding, Metal Matrix Composite, Mechanical property

Abstract. 10 and 20 vol% Al_2O_3 particulate 6061 Al alloy composite sheets have been successfully joined by friction stir welding. Al_2O_3 particles were uniformly distributed in the stirred zone. Tensile test results showed good mechanical properties. Effect of the FSW conditions of tool rotation speed and welding speed on the formation of the good FSW joint was investigated in comparison with 6061 Al alloy. The optimum FSW condition range became narrower with increasing volume fraction of Al_2O_3 particles.

Introduction

Aluminum Metal Matrix Composites (MMCs) reinforced with ceramic particles such as Al_2O_3 ceramics have been applied for light structural materials in aerospace, automobile, and other industries because of their good performances for specific tensile strength, stiffness, and wear resistance. It is expected that the demand for MMCs will increase in these applications. However, adequate joining technique, which is important for structural materials, has not been established for MMCs yet. Conventional fusion weldings are difficult because of the irregular redistribution of reinforcement particles. Also, the reaction between reinforcement particles and matrix aluminum as well as weld defects such as porosity in the fusion zone make fusion welding more difficult [1].

Friction Stir Welding (FSW), developed by TWI [2], is a solid state joining process which joints using the friction heat generated between a base metal and a special tool at a temperature lower than a melting point. A good joint that has no defects such as a blowhole and a weld crack can be obtained. This process also enables joining cast materials and composites [3,4].

In this paper the applicability of FSW to joining aluminum metal-matrix composites with ceramic particle reinforcement have been examined in comparison with those of 6061 as a matrix material.

Experimental Procedures

Table 1 Chemical composition of MMCs and Al alloy used

	Chemical composition (mass%)									
Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Al
6061	0.57	0.16	0.18	0.04	0.89	0.09	0.10	0.02	-	Bal.
6061/10%Al_2O_3	0.59	0.10	0.27	0.005	1.02	0.09	0.003	0.006	0.002	Bal.
6061/20%Al_2O_3	0.60	0.10	0.27	0.01	1.00	0.20	0.01	0.01	-	Bal.

Material Used. The materials used are 6061-T6 metal-matrix composites reinforced with 10 and 20 percent volumes Al_2O_3 particles (6061/10%Al_2O_3 and 6061/20%Al_2O_3, respectively) together with 6061-T6 as the matrix material for comparison. The compositions of each alloy are shown in Table 1. 6061/10%Al_2O_3 is a forged plate in 4mm thickness and 6061/20%Al_2O_3 and 6061 Al alloy are rolled plates in 2mm and 4mm thickness, respectively. Each alloy was heat treated by the same T6 condition with solution heat treatment at 808K for 1h and aging treatment at 448K for 8h.

FSW Condition. The FSW tool dimensions were 15 mm in shoulder diameter, 5 mm in pin (probe) diameter with a screw pin, and a pin length equivalent to the thickness of each material. The tool rotation speed Rt and the welding speed V were varied from 500 to 3000 rpm and 100 to 2500 mm/min, respectively. In 6061/20%Al_2O_3, only welding speed was varied because of excessive wear of the pin. A square butt joint with 50 x 100 mm rectangular plates was used, and in advance, groove surfaces were machined and degreased with acetone.

Weldability and Mechanical Property Evaluations. Visual and X-ray radiography inspections of each FSW joint were carried out in order to find weld defects on the surface and the inner zones. Metallurgical inspections were done on a cross section of the joint after polishing and etching with a diluted Keller's reagent.

The tensile test and the hardness measurement were done at an as-welded condition, namely naturally aged for 20days at room temperature and a post-welded artificially aged condition at 448K for 8 h.

Results and Discussions

Effect of FSW Parameter on Formation of FSW Joint. Fig.1 shows the appearance and the X-ray radiograph of the FSW joints of each alloy at a constant welding speed of 500 mm/min. Good FSW joints, which had no defect, were obtained in each material at the condition of 1500 rpm, though some flashes occurred on the surface and then relatively rough surface appearance was observed in MMCs. The condition of 500 rpm caused a decrease in the heat input compared to the condition of 1500 rpm and 500 mm/min, thus X-ray radiographs revealed inner defects in the weld in both materials, 6061 and 6061/10%Al_2O_3. It appeared on the surface in 6061/10%Al_2O_3.

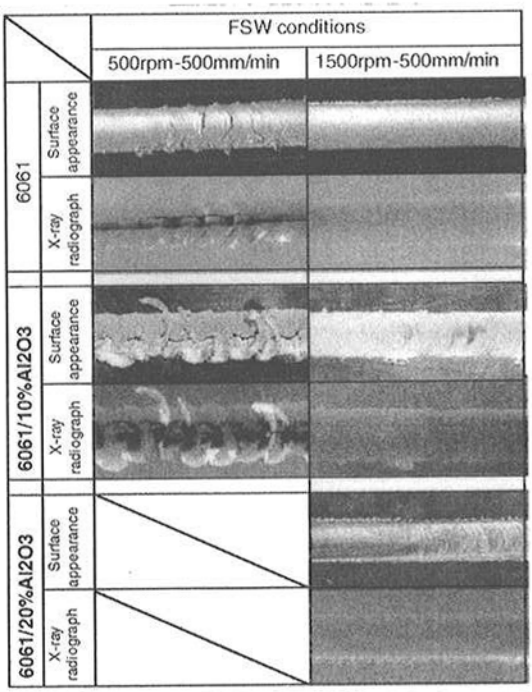

Fig.1 Appearance and X-ray radiography of FSW joint.

Fig.2 summarizes the effects of tool rotation speed and welding speed on the weldability. In 6061 and 6061/10%Al_2O_3, the optimum FSW conditions showing no defect with smooth surface are shown by each arrow, and results of

6061/20%Al_2O_3 are shown by open circle marks due to limited data. In unreinforced 6061, a wide zone of optimum FSW conditions and good weld joints were obtained even at high welding speed of 2000mm/min. In contrast, 6061/10%Al_2O_3 was limited to a slower speed in order to produce good weld joints. It is estimated from Fig.2 that the optimum zone of 6061/20%Al_2O_3 became narrower than that of 6061/10%Al_2O_3. This was caused by the inherent poor formability of MMCs due to containing reinforcement particles.

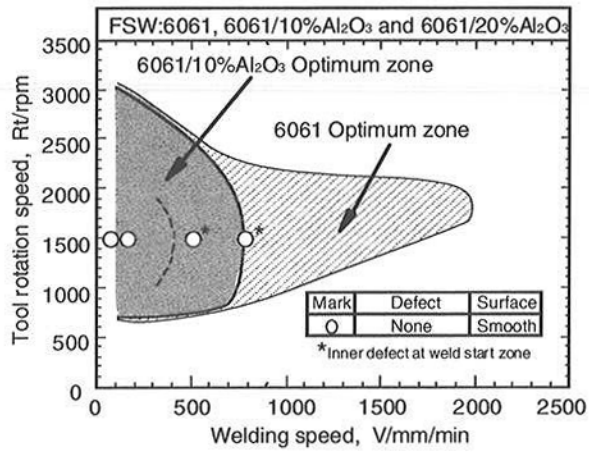

Fig.2 Optimum FSW condition zone of each material.

Structure of The Welds. Fig.3 shows macrostructures in the cross section of the FS weld of each alloy. Quite similar structures were observed in each alloy, which consisted of the four following zones: (1) the stirred zone (SZ), which is fully recrystallized by rotation of the tool and has equiaxed

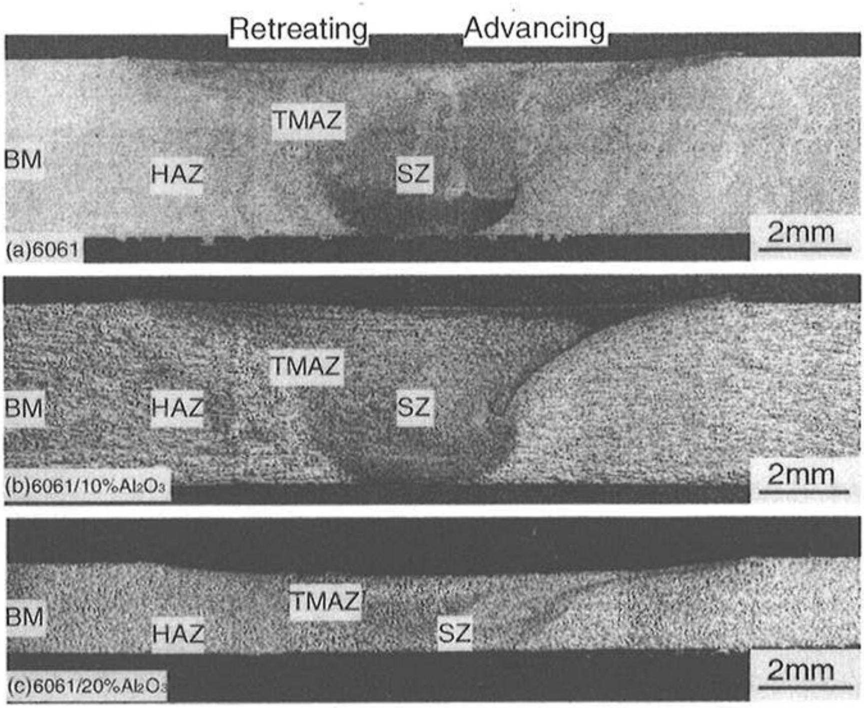

Fig.3 Macrostructures of cross-section of FSW joint, (a)6061, (b)6061/10%Al_2O_3, (c)6061/20%Al_2O_3.

grains by a dynamic recrystallization, (2) the thermo-mechanically affected zone (TMAZ), (3) the heat affected zone (HAZ) and (4) the base metal (BM). Fig.4 shows microstructures of 6061/10%Al_2O_3 and 6061/20%Al_2O_3. The black particles show Al_2O_3 particles. The regular orientations of Al_2O_3 particles distribution are clearly seen in base metal of 6061/10%Al_2O_3 and 6061/20%Al_2O_3 made by the forging and rolling , respectively (Fig.4 (a) and (e)). Also, in the HAZ, which is not mechanically affected, the distribution of Al_2O_3 does not changed (Fig.4 (b) and (f)). In the TMAZ, it is affected by a plastic flow as well as heat affection so that the distribution of Al_2O_3 slightly changes in comparison with that of the base metal. In the SZ the regular orientation of Al_2O_3 particles distribution, which was seen in the base metal, completely disappeared and then the Al_2O_3 particles redistributed uniformly by the stirring action of the tool.This suggests that an adequate FSW condition enables a sufficient metal flow even with Al_2O_3 reinforcement particles. In addition quite a fine Al_2O_3 particles in sub-micron size, which were not observed in the base metal, were observed in the SZ. Investigation of comparing the aspect ratio of Al_2O_3 particles in the base metal and the SZ suggested that the original particles were partly brokened by colliding with a rotating pin and resulted in these fine particles, because the aspect ratio of Al_2O_3 particles in the SZ decreased in comparison with those in the base metal of MMCs.

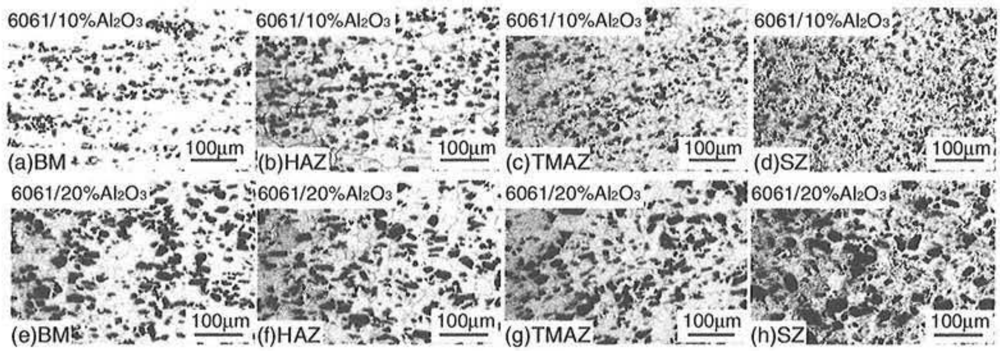

Fig.4 Microstructures of cross-section of FSW joint of 6061/10%Al_2O_3 in (a)-(d), 6061/20%Al_2O_3 in (e)-(h).

Hardness. The hardness traverses of FSW joints measured at an as-welded and a post-weld artificially aged conditions are presented in Fig.5 collectively for each alloy. The as-welded welds are softened throughout the weld zone because of heat affection during the FSW. The hardness in the HAZ indicated a lower value than that in the SZ, and an increase of Al_2O_3 vol% increased the difference between the hardnesses in the SZ and in the HAZ. A post-weld artificially aged condition raised the hardness in the weld of each alloy. In particular the hardness in the SZ indicated high values almost equal to that of the base metal. However, the recovery of the hardness in the HAZ was less than that in the SZ. Thus, the difference in the SZ and in the HAZ hardnesses became larger than those at an as-welded condition. These differences may cause the decrease of joint elongation because of the stress concentration at the HAZ.

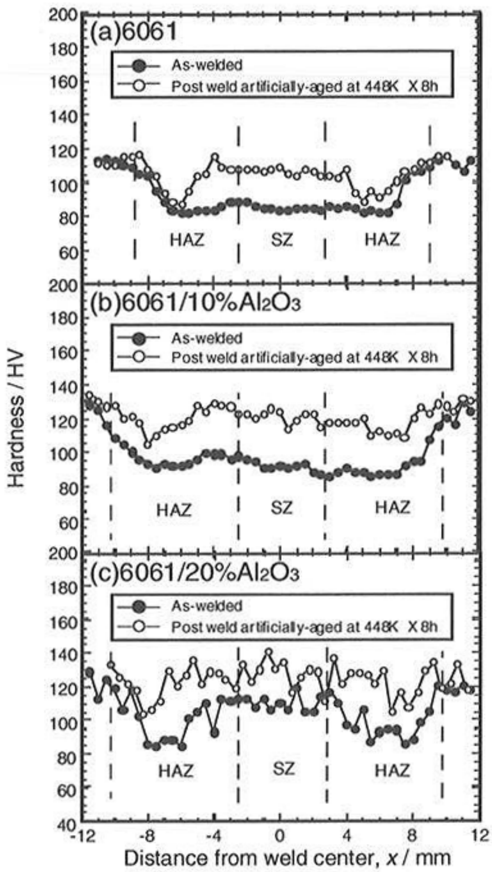

Fig.5 Hardness profiles of FSW joints of (a)6061, (b)6061/10%Al_2O_3 and (c)6061/10%Al_2O_3 at as-welded condition and postwelded artificially-aged condition(448K x 8h).

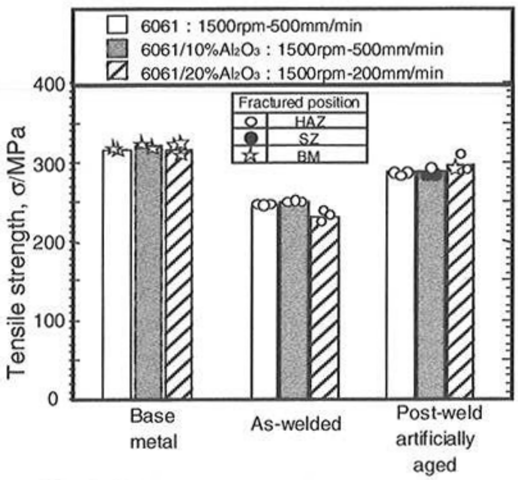

Fig.6 Tensile strength of FSW joints of 6061, 6061/10%Al_2O_3 and 6061/10%Al_2O_3 at as-welded condition and postwelded artificially-aged condition(448K x 8h).

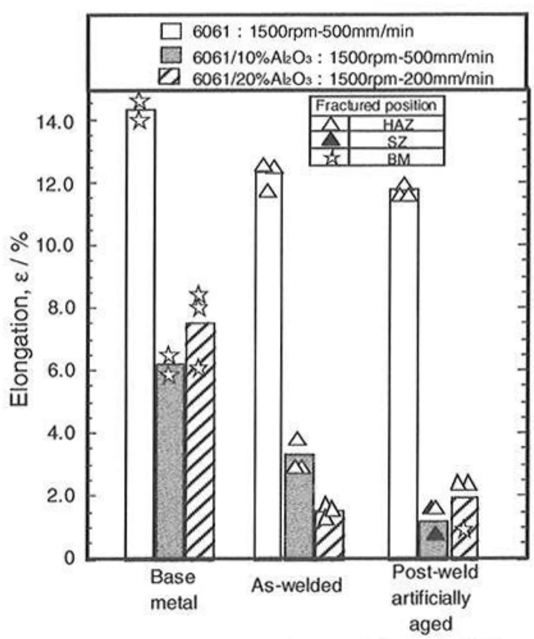

Fig.7 Elongation of FSW joints of 6061, 6061/10%Al_2O_3 and 6061/10%Al_2O_3 at as-welded condition and postwelded artificially-aged condition(448K x 8h).

Tensile Properties. Fig.6 shows the comparison of the tensile strength of each alloy at both an as-welded and a post-weld artificially aged conditions. From Fig.6 it can be stated that the same tensile behaviors are obtained in each alloy. In other words, the lowest tensile strength in an as-welded condition was restored to the strength equivalent to 90% of the base metal by post-weld artificially aging. As shown in Fig.7, the elongation of 6061 joint in both conditions indicated a slightly lower value than that of the base metal, 12% in elongation. While, MMCs joints indicated poor elongation, 1.5-3.5%, though those of the base metal had inherently low elongation, 6-8%.

The failure in most of the tensile specimen occurred in the HAZ, which was associated with minimum hardness in the joint. The resulting large difference in the hardnesses of the SZ and the HAZ is one explanation of the large decrease in the joint elongation of MMCs.

Conclusion

In this study, the effect of welding parameter on the weld formation and the mechanical properties of FSW joints correlated with microstructural aspect have been evaluated for 6061-T6 metal-matrix composites reinforced with 10 and 20 percent volumes Al_2O_3 particles in comparison with 6061 Al alloy. The following conclusions can be summarized

(1) A square butt joining by friction stir welding (FSW) of 6061-T6 metal-matrix composites reinforced with 10 and 20 percent volumes Al_2O_3 particles were successfully done at the optimum conditions of 1000 to 3000 rpm of the tool rotation speed and lower welding speed than 500 mm/min. In contrast, a wide zone of the optimum FSW condition and good weld joint was obtained for 6061 Al alloy even at a high welding speed of 2000mm/min.

(2) The regular orientation of Al_2O_3 particles distribution in base metal was completely disappeared and redistributed uniformly in the stirred zone.

(3) The as-welded joints were softened throughout the weld zone owing to heat affection during the FSW. The post-weld artificially aging treatment raised the hardness in the weld of each alloy. In particular, the hardness in the stirred zone restored almost to that of the base metal.

(4) The tensile strength of the welded joints for each alloy indicated good results, which were 73-78 % of the base metal strength, and post-weld artificially aging treatment restored them to 84-93 % of the base metal strength. The elongation of the welded joint of MMCs indicated lower value, 20-50 % of the MMCs base metal elongation, in comparison with that of 6061, approximately 85 % of the base metal elongation.

Acknowledgment

This work was partly supported by Grant-in-Aid for Scientific Research (B).

References

[1] M.B.D.Ellis: Int. Mater. Rev. vol.41, 2 (1996), p.41

[2] W.M.Thomas et al: International Patent Application No. PCT/GB92/02203 and GB Patent Application No. 9125978.8,6 Dec.1991, U.S. Patent No.5,460,317.

[3] Yoshitaka Nagano et al, "Mechanical properties of aluminium die castings joined by friction stir welding", 3rd Int. Symp. On Friction Stir Welding, TWI, (2001).

[4] Tracy W. Nelson, Han Zhang and T. Haynes, "Friction Stir Welding of Aluminum MMC 6061-Boron Carbide", 2nd Int. Symp. On Friction Stir Welding, TWI, (2000).