Materials Science Forum Vols 539-543 (2007) pp 3814-3819 *Online: 2007-03-15*
© (2007) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/MSF.539-543.3814

Microstructural evolution and performance of friction stir welded aluminum matrix composites reinforced by SiC particles

Z.Y. Ma[1,a], A.H. Feng[1,b], B.L. Xiao[2,c], J.Z. Fan[2,d], L.K. Shi[2,e]

[1]Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China
[2] Research Institute for Nonferrous Metals, Beijing 100088, China
[a]zyma@imr.ac.cn, [b]ahfeng@imr.ac.cn, [c]xiaobolv@163.com

Keywords: Friction stir welding, composite, aluminum, SiC.

Abstract. The effect of friction stir welding (FSW) parameters on microstructure and properties of 15vol.%SiCp/2009Al composite welds was investigated at tool rotation rates of 400-1000 rpm for a constant welding speed of 50 mm/min. 8mm thick defect-free welds were produced at higher tool rotation rates of 600-1000 rpm, whereas an unwelded seam was distinctly visible at the root of plates at a lower tool rotation rate of 400 rpm. FSW resulted in generation of fine and equiaxed recrystallized grains of ~6 μm and significant improvement of SiC particle distribution in the weld nugget. Under as-FSW condition, the hardness of the weld nugget was significantly higher than that of as-extruded parent material. Furthermore, tensile and yield strengths of as-FSW composite welds in both the longitudinal and transverse directions were superior to those of as-extruded parent material. Post-weld T4 temper resulted in limited grain growth due to the pinning of SiC particles. Under the T4 condition, the tensile strength of the welds along the longitudinal and transverse directions reached 82 and 95% of the parent material, respectively.

Introduction

Metal matrix composites (MMCs) offer improved stiffness, strength, and wear resistance over monolithic matrix materials. However, the weldability of these composites is significantly reduced due to the addition of ceramic reinforcements. It is hard to achieve defect-free welds by using conventional fusion welding techniques. The drawbacks associated with the fusion welding include: (a) the incomplete mixing of the parent and filler materials, (b) the presence of porosity as big as 100 μm in the fusion zone, (c) the excess eutectic formation, and (d) the formation of undesirable deleterious phases such as Al_4C_3. Therefore, a solid state welding technique is highly desirable for joining the MMCs.

Friction stir welding (FSW), a relatively new solid state joining technique, has emerged as a promising approach for joining the MMCs [1,2]. In assessing the challenges associated with friction stir welding of the MMCs, two issues are worth noting. First, the MMCs exhibit lower plasticity than the monolithic alloys even at high temperatures [3]. Therefore, the optimum FSW parameters for producing sound welds were limited to lower tool traverse speeds [4]. Second, severe tool wear occurred during the FSW, in particular at higher tool rotation rates, due to the presence of hard ceramic reinforcements [4-6]. Such tool wear not only reduces the lifetime of the FSW tool, but also could produce some deleterious effects on the properties of the FSW welds due to the existence of the wear debris [5]. Accordingly, it is important to optimize the FSW parameters to produce sound welds without severe tool wear to achieve excellent joining efficiency. In this work, 8 mm thick 15vol.%SiCp/2009Al composite plates were subjected to FSW investigation. The purpose of this work was (a) to investigate the effect of FSW parameter on the weld quality and tool wear and (b) to understand the effect of post-weld heat treatment on the microstructure and properties of the welds.

Experimental

15vol.%SiCp/2009Al composites, fabricated by powder metallurgy and subsequent extrusion, were used for FSW. 8 mm thick composite plates were cut from the extruded bars. FSW was conducted in a friction stir welder, made by the China FSW Center, at the tool rotation rates of 400 to 1000 rpm for a constant traverse speed of 50 mm/min. The welding direction was parallel to the extrusion direction of the composites. A steel tool with a threaded, cylindrical pin of 8 mm in diameter and a dished shoulder of 24 mm in diameter was used.

Following FSW, samples were kept at room temperature for one month to naturally age. In order to study the effect of post-weld heat treatment, part of the FSW samples were subjected to T4 temper (solutionized at 500°C for 1 h, water quenched, and then aged at room temperature for one month). FSW samples were cut transverse to the welding direction, mounted, and mechanically polished. Microstructural examination was completed with optical microscopy.

The hardness profiles were produced along the mid-thickness on the cross-section of the welds by using a Vickers hardness tester at a 1kg load. Transverse and longitudinal tensile specimens with a gage length of 24 mm were machined from the FSW samples vertical and parallel to the welding direction. The longitudinal tensile specimens contain only the nugget zone. Tensile tests were conducted at room temperature at an initial strain rate of 1×10^{-3} s^{-1}.

Results and Discussion

Figure 1 shows macrographs on the cross-section of the FSW welds at various tool rotation rates. The tool rotation rate exerted a significant effect on the weld quality and the shape of the nugget zone. At a lower tool rotation rate of 400 rpm, distinctly visible voids were detected at the root of the plates (Fig.1a). This is attributed to insufficient plasticity of the composite due to lower thermal input. In this case, the welding seam at the root of the plates could not be filled out completely, resulting in generation of the unwelded voids. At higher tool rotation rates of 600-1000 rpm, 8 mm thick defect-free welds were successfully produced due to higher thermal input and more intense plastic deformation and material mixing (Fig.1b and c). At the tool rotation rate of 400-600 rpm, FSW process resulted in a slight wear of the tool. However, at higher tool rotation rate of 1000 rpm, severe tool wear occurred. After 300 mm of FSW, most of tool threads were worn out. The increasing trend of tool wear with increasing rotation rate was observed by other investigators [7].

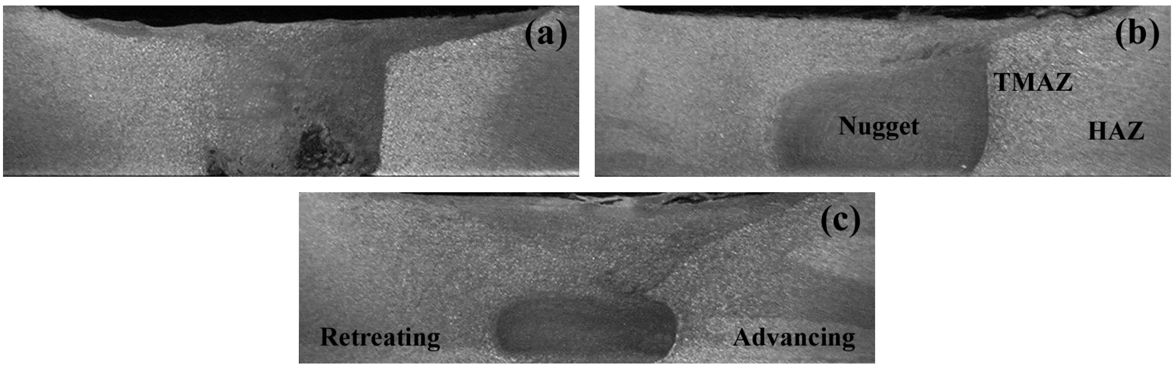

Figure1. Macrographs showing cross-sections of FSW SiCp/2009Al composite joints produced at tool rotation rate of (a) 400 rpm, (b) 600 rpm, and (c) 1000 rpm (etched by mixed acids).

As in FSW aluminum alloys, the composite welds consisted of three zones: nugget zone, thermo-mechanically-affected zone (TMAZ), and heat-affected-zone (HAZ). The nugget zone at the tool rotation rate of 400 and 600 rpm exhibited basically a cylindrical shape. Onion rings, typical structure found on the cross-sections of FSW aluminum alloys, were detected in the composite weld produced at 600 rpm (Fig.1b). With increasing the tool rotation rate to 1000 rpm, the shape of the nugget zone changed significantly. The nugget zone consisted of upper basin-shaped and lower elliptical nuggets (Fig.1c). The change in the nugget shape at 1000 rpm could be associated with two factors. First, higher tool rotation rate tends to generate elliptical nugget [2]. Second, the severe wear of tool threads changed substantially the flow characteristics of material during the FSW.

Clearly, considering both weld quality and tool wear, a moderate tool rotation rate of 600 rpm is the optimum choice of FSW parameters. Therefore, detailed microstructural examination and property evaluation were focused on the welds produced at a tool rotation rate of 600 rpm.

Figure 2 shows the distribution of the SiC particles in the parent material and the nugget zone. There are evidently visible particle clusters and particle-free regions in the as-extruded composite. After the FSW, the distribution of SiC particles in the nugget zone was significantly improved due to intense plastic deformation and materials mixing. Furthermore, the amount of finer SiC particles appears to increase after the FSW. This is attributed to the breaking effect of rotating pin. Similar observation was made by other investigators in FSW of aluminum matrix composites [4].

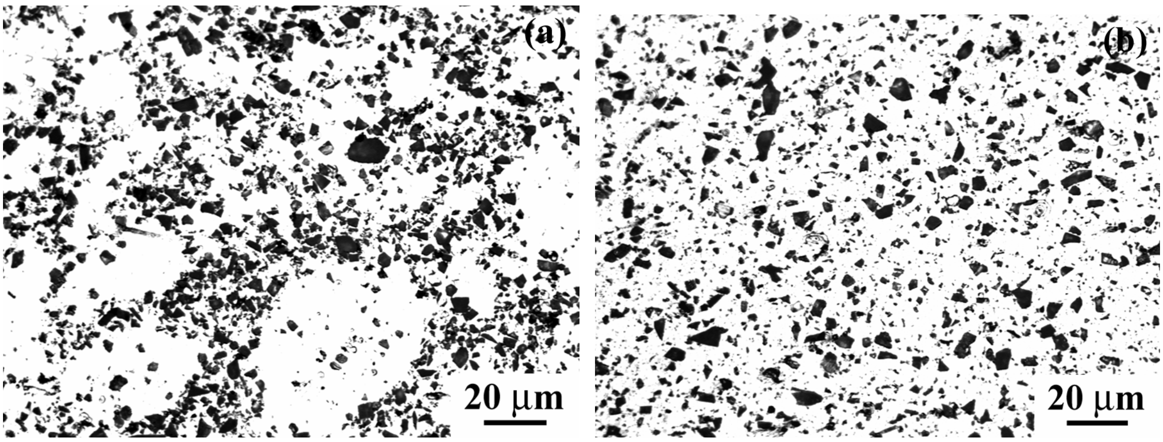

Figure 2. Optical micrographs showing the distribution of the SiC particles in the composites: (a) the parent material, (b) the nugget zone (tool rotation rate: 600rpm).

Figure 3 shows the micrographs of the nugget zone and the TMAZ under as-FSW and T4 conditions. The nugget zone is characterized by fine and equiaxed recrystallized grains of ~6 μm (Fig. 3a). The characteristic elongated grains exhibited a flow pattern around the weld nugget in the TMAZ (Fig. 3b). Clearly, recrystallization did not occur in the TMAZ. The post-weld T4 temper resulted in grain growth in both the nugget zone and the TMAZ (Fig. 3c and d). For example, the grain size in the nugget zone increased to ~8 μm after the T4 temper. The limited grain growth during the T4 temper is attributed to the effective pinning of the SiC particles. No abnormal grain growth, occurring in some FSW aluminum alloys during the post-weld heat treatment [8], was detected.

Figure 4 shows the hardness profiles along the mid-thickness on the cross section of the FSW composite at 600 rpm. The maximum hardness of ~155 Hv was observed in a zone of ~10 mm wide around the weld centerline. This hardness plateau corresponds to the width of the nugget zone. Beyond the hardness plateau, the hardness decreased gradually with increasing distance from the nugget zone. At the advancing side, the hardness decreased to the level of the parent material at ~20 mm from the weld centerline and there appears an unobvious minimum hardness zone at 24 mm from the weld centerline. At the retreating side, the hardness reached to the level of the parent material at ~17 mm from the weld centerline and there is no noticeable minimum hardness zone.

It was reported that the hardness profile greatly depends on the precipitate distribution and only slightly on the grain and dislocation structures [9]. Therefore, the increase in hardness in the nugget zone is mainly attributed to the precipitation-strengthening resulting from FSW thermal cycles. In the as-extruded SiCp/2009Al composite, the coarse precipitates resulting from slow cooling after the extrusion did not exert obvious strengthening effect on the aluminum matrix. The FSW resulted in the dissolution of all or most of the precipitates into the aluminum matrix due to high-temperature exposure. Fast cooling from FSW temperatures retained these solutes in solution. In this case, fine precipitates were generated during natural aging after FSW, resulting in an obvious increase in hardness of the nugget zone. Furthermore, the grain refinement and the uniform distribution of the SiC particles also contributed to the increase in hardness of the nugget zone.

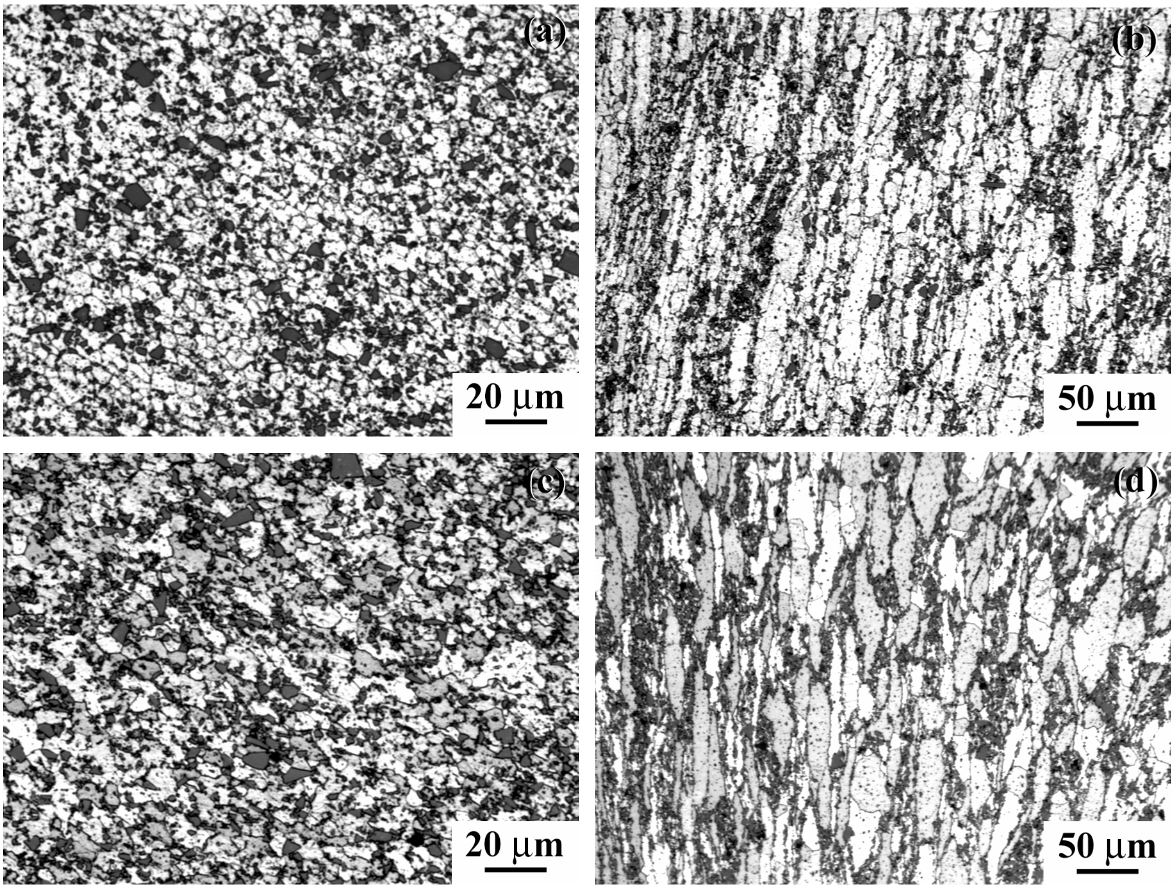

Figure 3. Microstructure of SiCp/2009Al composite welds after etching: (a) nugget zone in as-FSW condition, (b) TMAZ in as-FSW condition, (c) nugget zone in FSW-T4 condition, and (d) TMAZ in FSW-T4 condition (tool rotation rate: 600rpm).

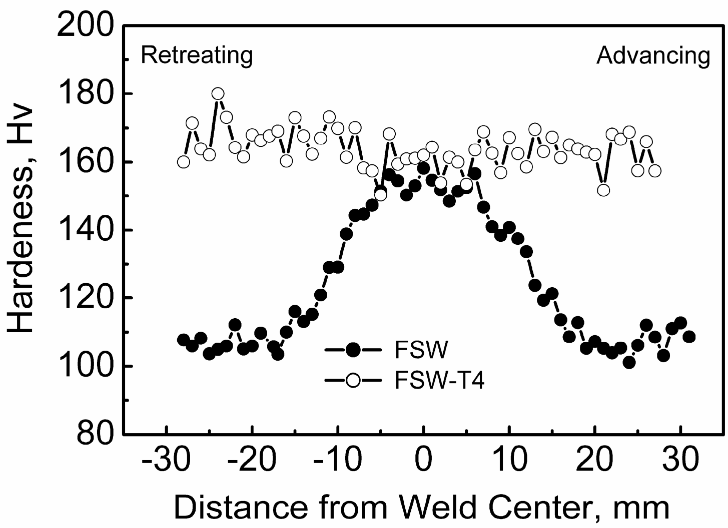

Figure 4. Microhardness profiles for SiCp/2009Al composite welds (tool rotation rate: 600 rpm).

With increasing the distance from the nugget boundaries, the amount of the precipitates dissolved into the aluminum matrix during the FSW thermal cycles decreased due to reduced process temperatures, resulting in reduced natural aging strengthening. Therefore, the hardness of the welds beyond the nugget zone decreased with increasing the distance from the nugget boundaries. The unobvious minimum hardness observed in the composite welds was attributed to the fact that FSW thermal cycles did not result in further coarsening of coarse precipitates in the as-extruded composites.

After the T4 temper, the hardness of the TMAZ and HAZ was significantly increased due to the complete dissolution of the coarse precipitates and subsequent precipitation. However, the hardness of the nugget zone exhibited only a slight increase. This appears to indicate that the precipitation-strengthening effect resulted from the FSW thermal cycles and subsequent aging nearly reached the level of the T4 temper. It is noted from Fig.4 that under the T4 condition, the hardness of the nugget zone was slightly lower than that of the TMAZ and HAZ. The reason for this difference is not clear. One of possible reasons might be associated with low dislocation density in the nugget zone [10].

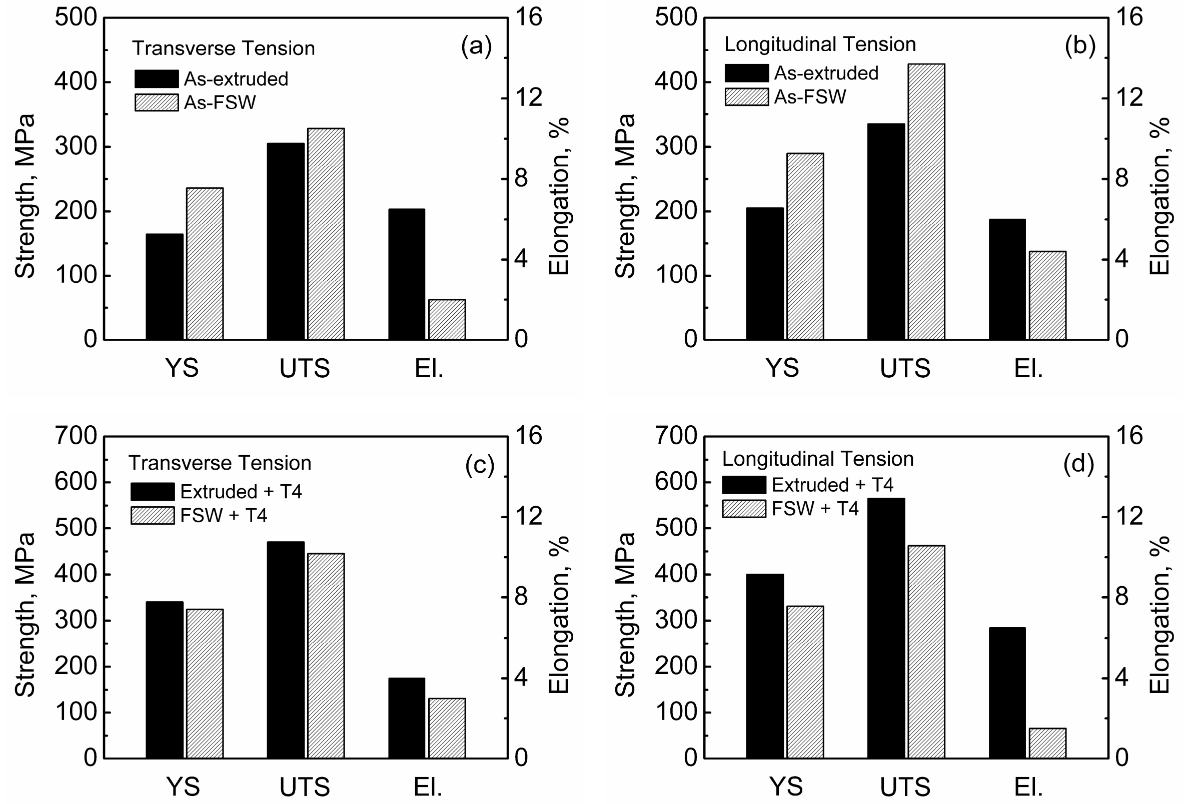

Figure 5. Tensile properties of SiCp/2009Al composites: (a) and (b) as-extruded or as-FSW, (c) and (d) T4-treated; (a) and (c) transverse tension, (b) and (d) longitudinal tension (FSW parameters: 600 rpm-50 mm/min).

Tensile tests in both the longitudinal and transverse directions showed that both tensile and yield strengths of as-FSW composite welds were superior to those of as-extruded parent material (Fig. 5a and b). As discussed about the hardness profiles above, the enhancement in strength of the FSW welds were mainly attributed to the precipitation-strengthening resulted from the FSW thermal cycles. Furthermore, fine grain size and homogeneous distribution of the SiC particles also contributed to the improvement in strength. For the transverse specimens, the gage length of 24 mm was within the zone with higher hardness than the parent material as showed in Fig. 4, therefore, the transverse strength of the FSW samples was higher than that of the extruded parent material with fracture occurring close to the transition zone between the gage length and grip section.

After the T4 temper, the strength of both parent material and the FSW samples was increased due to the complete dissolution of the precipitates and subsequent precipitation. However, the strength of the nugget zone was lower than that of the parent material in both transverse and longitudinal directions. Furthermore, the strength of the nugget zone under the T4 temper was only slightly higher than that under as-FSW condition. The variation trend for strength of the welds after the T4 temper was consistent with that for hardness (Fig. 4). The T4 temper only resulted in limited grain growth. Therefore, such variation trend might be mainly attributed to the distribution of the precipitates. Further investigation is under progress.

Summary

8 mm thick 15vol.%SiCp/2009Al composite plates were successfully joined by FSW technique at higher tool rotation rate of 600-1000 rpm. The microstructure of the nugget zone was characterized by fine and equiaxed recrystallized grains of ~6 μm and uniformly-distributed SiC particles. The hardness and strength of the nugget zone were significantly higher than those of as-extruded parent material due to precipitation-strengthening resulted from FSW thermal cycles. Post-weld T4 temper did not result in significant grain growth. Under the T4 condition, the hardness and strength of the nugget zone were lower than those of the parent material. The tensile strength of the welds along the longitudinal and transverse directions reached 82 and 95% of the parent material, respectively.

Acknowledgments

The authors gratefully acknowledge the support of (a) the Hundred Talents Project of Chinese Academy of Sciences and (b) the National Outstanding Young Scientist Foundation with grant No. 50525103.

References

[1] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Templesmith, C. J. Dawes: GB Patent Application No. 9125978.8; Dec. 1991.

[2] R.S. Mishra and Z.Y. Ma: Mater. Sci. Eng. R. Vol. 50 (2005), p. 1.

[3] D. H. Park, B. C. Ko, Y. C. Yoo: J. Mater. Sci. Vol. 37 (2002), p. 1593.

[4] M. W. Mahoney, W. H. Harrigan, J. A. Wert: in INALCO'98, vol. 2, p.231-236, Cambridge, UK, April 1998.

[5] T. W. Nelson, H. Zhang, T. Haynes: in Proc. 2nd Symp. on Friction Stir Welding, June 2000, Gothenburg, Sweden.

[6] D. J. Shindo, A. R. Rivera, L. E. Murr: J. Mater. Sci. Vol.37 (2002), p. 4999.

[7] R. A. Prado, L. E. Murr, D. J. Shindo, K. F. Sota: Scripta Mater. Vol. 45 (2001), p. 75.

[8] K.A.A. Hassan, A.F. Norman, and P.B. Prangnell: Acta Mater. Vol. 51 (2003), p. 1923.

[9] C. Genevois, A. Deschamps, A. Denquim, B. Doisneau-cottignies: Acta Mater. Vol. 53 (2005), p. 2447.

[10] C. G. Rhodes, M. W. Mahoney, W. H. Bingel, R. A. Spurling, C. C. Bampton: Scripta Mater. Vol. 36 (1997), p. 69.

THERMEC 2006
10.4028/www.scientific.net/MSF.539-543

Microstructural Evolution and Performance of Friction Stir Welded Aluminum Matrix Composites Reinforced by SiC Particles
10.4028/www.scientific.net/MSF.539-543.3814

DOI References
[3] D. H. Park, B. C. Ko, Y. C. Yoo: J. Mater. Sci. Vol. 37 (2002), p. 1593.
doi:10.1023/A:1014997625002
[6] D. J. Shindo, A. R. Rivera, L. E. Murr: J. Mater. Sci. Vol.37 (2002), p. 4999.
doi:10.1023/A:1021023329430
[7] R. A. Prado, L. E. Murr, D. J. Shindo, K. F. Sota: Scripta Mater. Vol. 45 (2001), p. 75.
doi:10.1016/S1359-6462(01)00994-0
[9] C. Genevois, A. Deschamps, A. Denquim, B. Doisneau-cottignies: Acta Mater. Vol. 53 (2005), p. 447.
doi:10.1016/j.actamat.2005.02.007
[10] C. G. Rhodes, M. W. Mahoney, W. H. Bingel, R. A. Spurling, C. C. Bampton: Scripta Mater. Vol. 6 (1997), p. 69.
doi:10.1016/S1359-6462(96)00344-2
[9] C. Genevois, A. Deschamps, A. Denquim, B. Doisneau-cottignies: Acta Mater. Vol. 53 (2005), p. 2447.
doi:10.1016/j.actamat.2005.02.007
[10] C. G. Rhodes, M. W. Mahoney, W. H. Bingel, R. A. Spurling, C. C. Bampton: Scripta Mater. Vol. 36 (1997), p. 69.
doi:10.1016/S1359-6462(96)00344-2