INTERNATIONAL JOURNAL OF RESEARCHES IN BIOSCIENCES, AGRICULTURE AND TECHNOLOGY
© VISHWASHANTI MULTIPURPOSE SOCIETY (Global Peace Multipurpose Society) R. No. MH-659/13(N)
www.vmsindia.org

EFFECT OF WELDING PARAMETERS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDED METAL MATRIX COMPOSITE

Arun Kumar Shettigar[1], Subramanya Prabhu B.[1], Rashmi Malghan L[2], Mervin A. Herbert[2] and Shrikantha S. Rao[2]

[1]Mechatronics Engineering Department, Manipal Institute of Technology, Manipal, India
[2] Mechanical Engineering Department, National Institute of Technology, Surathakal India
subramanya.prabhu@manipal.edu

Abstract:
Owing to the enhanced mechanical properties of Friction stir (FS) welded alloys are more significant than the conventional welding process. The primary study was to investigate the influence of process parameters on the mechanical properties of FS welded metal matrix composite. In order to weld the composite a threaded profile pin tool (TPP) was used. In the nugget zone numerous small particles and the uniform distribution of refined grains were obtained and this was depicted by the microstructural characterization. The higher hardness was attained at the nugget zone compared to that of the base material. A joint efficiency of 89% was accomplished in transfer direction. The ductile fractures of the Al-Cu matrix and the brittle fracture of the reinforcement particles were disclosed on fracture surface of specimens.
Keywords—Friction Stir welding, metal matrix composites, nugget zone

Introduction

The application of high strength to weight ratio materials have found more exposure in engineering field. These can be achieved by combining different constitutes of materials, like aluminum reinforced with ceramic materials, called Metal matrix composites (MMC`s). Such materials have tolerable mechanical, electrical and thermal properties [1-2]. These materials exhibited fail to serve their purpose when they are joined by conventional welding process. The braw back of conventional welding of MMC`s are segregation of ceramic particles during solidification, thermal stress generation due to variation in thermal expansion coefficients, interfacial chemical reaction resulted from high temperature and high solubility of gas in the molten state will leads to deteriorate the mechanical properties[3-4]. To overcome this problem Friction stir welding (FSW) process is adapted. This method has been used to join aluminum alloys, steel, copper, dissimilar metals and metal matrix composites [5]-[7].

FSW rotating tool is used to deform and move the material under frictional heat. The heat generated at tool and base material is depend on the welding process parameters like tool rotational speed and welding speed. Several researches have highlighted that the process parameters also affect the grain and distribution of particles [1, 8-10]. It is also found that numerous fragmented particles uniformly distributed at weld region. All these factors will assist in increasing the mechanical properties of the materials [2]. Hence, to get desired joint strength one has to study the process parameters to evaluate the process.

Experimental Setup

In this study, AA6061-4.5% copper based matrix reinforced with 10% SiC composite is used. The composite prepared by using stir casting method. The chemical composition of MMC`s is shown in Table I. These composites were sized to a dimension of 100x50x6mm by using conventional machining process. The mechanical properties of the composite is shown in Table II. A butt joint configuration was used in this study. These composites were joined by the vertical milling machine with suitable setup to convert them to friction stir welding process. The friction stir welding process is shown in Fig 1. The FSW tool was made of M2 steel and heat treated to 53HRC. A threaded profile pin had M6x1mm pitch, 16mm shoulder diameter and 5.7mm height. The process parameters used in the study is presented in the Table III. The microstructural characterization are performed by using scanning electron microscope (SEM). The grain sizes are measured by using ASTM E112-10 standard. The grains sizes were measured middle region of top, middle and bottom of the weld zone. The tensile test were conducted as per ASTM E8M having gauge length of 25mm, gauge width of 7mm and thickness of 6mm. Tensometer was used to measure the joint strength of the composite.

Results and Discussion

The stirring action of the tool at the weld region creates plastic deformation resulting in fine grains. The weld zone indicates significantly altered microstructure as compared to the base material.

The investigation of the microstructure of friction stir welded specimen was carried out using SEM. The micro image of one such sample is shown in Fig 2. It divulge gradual change in the micro structure from the initial coarse non-deformed grains of the base material to fine and equiaxed grains at the center of the weld. Based on the evolution of microstructure, Reference [6]-[7] have reported that the weld zone can be divided into four regions, namely Nugget zone (NZ), Thermomechanically affected zone (TMAZ), Heat affected zone (HAZ) and base material (BM). Fig 3 (a-e) illustrate the SEM images of MMC`s friction stir welded using TPP tool. The joining of composite was carried out with rotational speed of 710 rpm and welding speed of 50 mm/min. Fig 3 (b-d) represent the distribution of grain size at the top, middle and bottom of the NZ, respectively. The average grain size at the top, middle and bottom of the NZ is 5.4 ± 0.21, 4.9 ± 0.24 and 4.3 ± 0.23 μm, respectively. It is clear that the grain size from the top surface of the weld to the bottom of the weld joint is decreasing. The top of the NZ experiences higher centrifugal force compared to bottom NZ [11]. During recrystallization a small extrusion crushing force will be acting on metals per unit area, resulting in larger crystal nucleus. Meanwhile, the shoulder acting as heat source produces higher temperature, requiring longer cooling time due to which grain growth takes place. On the other hand, the penetration depth of the pin is less than the thickness of the weld to avoid plunging of the pin into backing plate. As a result, at the bottom of the NZ, due to lack of stirring and forging, there will be insufficient plasticization and flow of the material. At the root of the weld, base plate acts as heat sink and the heat is transferred from the top by heat conduction. The extrusion forming in the bottom is not fulfilled under maximum temperature. Therefore, extrusion at the root of the weld happens due to plastic deformation of the materials around. The entire phenomenon is responsible for the formation of fine grains at the bottom of the NZ. This is in agreement with the findings of reference [12]. Fig 3 (a-e) represent the grain structure obtained at TMAZ on either side of the NZ. A highly deformed, elongated and non-homogeneous coarser grains are found due to stirring action of the tool. The average decrease in the grain size at the NZ is 91.5%.

Fig 4 shows graphically, the average grain size distribution formed at NZ of MMC during friction stir welding. It is obvious from the plots that, the grain size at the top of the NZ is larger and gets reduced as one approaches the bottom of the weld NZ. The joint fabricated at rotational speed of 1400 rpm and welding speed of 50 mm/min exhibited largest average grain size of 5.8±0.25 μm. Higher heat conditions prevailing at lower welding speed (50 mm/min), with reduced cooling rate resulted in coarsening of grains in the NZ. On the other hand, the joint fabricated with rotational speed of 1000 rpm and welding speed of 80 mm/min exhibited smallest average grain size of 3.7±0.21 μm. This is because, the increased welding speed (80 mm/min) led to lower heat input due to shorter time available for friction in the process. It also appears that, the prevailing low heat condition also contributed towards inducement of more strain and strain rate, resulting in more dynamic re-crystallization which in turn, contributed to grain refinement. Further, the pinning effects [13] of silicon carbide particles which are mostly residing at the grain boundaries, prevent the grain growth and hence the grain size becomes smaller.

Hardness:

In FSW process, the tool rotational speed is one of the most predominant process parameter. It brings the material to plastic state by generation of frictional heat between the contact surfaces of rotating tool (pin and shoulder) and the substrate material. It is responsible for stirring and mixing of the plasticized material around the pin [9]-[10]. The nucleation sites are increased with the presence of the reinforcement particles, which lead to the reduction of grain size in the matrix [14]. Fig 5 shows the plots depicting the variation of hardness across the mid thickness of FSW joints of MMC. FS welded samples reveal highest hardness in the NZ than the parent material because of the finer grain size [2]. Stirring action of the tool causes a high plastic strain which results in rearrangement of particles from agglomerated and heterogeneous distribution in the base metal to a homogeneous distribution in the NZ [15]. This phenomenon has been observed in all the samples at different combinations of rotational speed of 710, 1000 and 1400 rpm, and welding speed of 50, 63 and 80 mm/min. Decrease in hardness was observed as the distance increases from the center, on both sides of NZ. Lower hardness value has been observed between the base composite and NZ, known as Heat affected Zone (HAZ). This is mainly due to grain softening induced by the thermal effect during stirring of the material by the tool. From Fig 5, it is observed that at a constant welding speed of 50 mm/min, as the rotational speed is increased from 1000 rpm to 1400 rpm, the hardness value was found to decrease. This is mainly due to the increase in the heat input. The higher heat input makes the weld material to experience higher temperature and higher strain rate [9]. This phenomena results in grain growth. When the welding speed increases from 50 to 80 mm/min, the hardness of the weld region also increases. This is because of the time of exposure of frictional heat between the tool and the base material interface per unit length. The more the time of frictional heat exposure, the more is the heat supplied and eventually affects the grain growth [16].

Tensile properties

Table IV presents the tensile test results of MMC`s joints friction stir welded at different combinations of rotational speeds and welding speeds. The ultimate tensile strength (UTS) of the joints increases with increase in the welding speed from 50 to 80 mm/min and reaches to a maximum value at a speed of 80 mm/min. For the samples welded at welding speed less than 80 mm/min, the specimen fracture at HAZ, near to the base material. Further increase in the welding speed beyond 80 mm/min leads to formation of pin holes, worm hole and tunnel defects. Therefore, the specimens fracture at NZ [17]. This results in the decrease in tensile strength. The forward movement of the rotating tool makes the stirred material to move from the front to the back of the tool pin. The rate of heat input depends on the welding speed [9]. The welding speed regulates the exposure time of frictional heat per unit length of the weld which impacts the heat transfer rate and consequently affects the grain growth [17]. At high welding speed, the quantity of heat input to the weld zone is less, and this results in higher cooling rate of the material. As the rotational speed is increased from 710 rpm to 1000 rpm the UTS also increases. Further increase in the rotational speed leads to reduction in UTS. Highest joint efficiency is obtained for a rotational speed of 1000 rpm and welding speed of 80 mm/min. Joint efficiency decreases with further increase in the rotational speed. Rotational speed of 1000 rpm and welding speed of 80 mm/min are found as the optimal process parameter values for FSW.

Fig 6 (a-c) shows the fracture surface of base material, friction stir welded joint across and along the direction of weld. It shows the fracture surface of composite joint FS welded at rotational speed of 1000 rpm and welding speed of 63 mm/min using TPP tool. The microscopic examination of the fracture surface, at high magnifications shows the presence of large voids, associated with particle–matrix decohesion, large dimples, tear ridges and occurrence of small dimples inside the large dimples due to the ductile failure of the matrix.

Table I. The Chemical Composition of AA6061-4.5% Cu Matrix

Cu (wt.)	Mg (wt.)	Si (wt.)	Iron (wt.)	Mn (wt.)	Al (wt.)
4.5	0.8 – 1.2	0.4 – 0.8	0.7	0.15	Remaining

Table II. Mechanical properties of composite

Composite	Vickers Hardness (Hv)	Ultimate Tensile stress (N/mm^2)	Percentage Elongation
AA6061-4.5%Cu-10%SiC	105±2	254±3.5	6.5% ± 0.1

Table. III Friction stir welding process parameters

Parameters	**Low**	**Medium**	**High**
Rotational Speed (rpm)	710	1000	1400
Welding Speed (mm/min)	50	63	80

Table IV. Tensile test resultsof AA6061-4.5%Cu-5%SiC composite joints friction stir welded using threaded profile pin tool

Rotational Speed (rpm)	**Welding Speed (mm/min)**	**Yield Strength (N/mm^2)**	**UTS (N/mm^2)**	**Elongation %**	**Joint efficiency (%)**
710	50	114±3	167±3	6.1±0.1	66
710	63	132±2	184±3	5.8±0.1	72
710	80	137±3	195±3	5.6±0.1	77
1000	50	156±2	201±3	4.9±0.1	79
1000	63	170±4	211±5	4.8±0.1	83
1000	80	172±3	226±3	4.2±0.1	89
1400	50	119±2	161±2	5.3±0.1	63
1400	63	122±2	174±2	5.1±0.1	68
1400	80	132±3	196±3	4.8±0.1	77

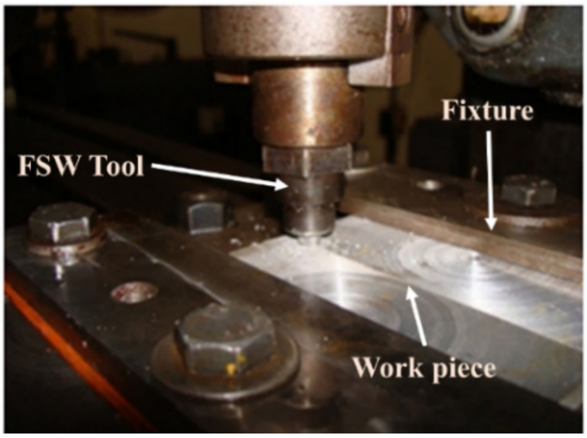

Figure 1 Friction Stir Welding Setup

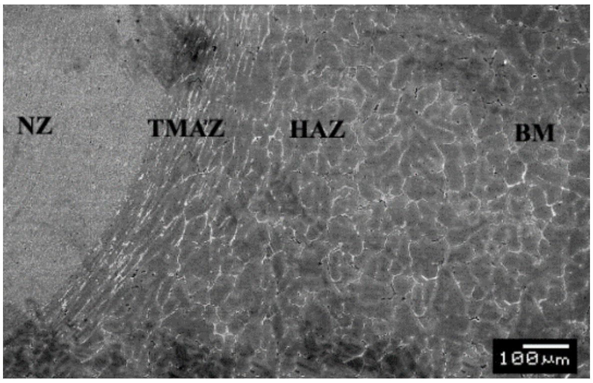

Figure 2 Scanning Electron Micrograph of FS welded composite

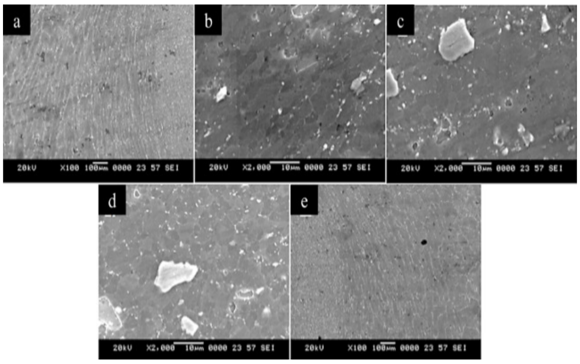

Figure 3 Scanning Electron Micrograph of grain size distribution of composite FS welded with a rotational speed of 710 rpm and welding speed 50 mm/min. a) Retreating side of TMAZ b) Top of the NZ, c) Middle of the NZ, d) bottom of the NZ and e) Advancing side of TMAZ

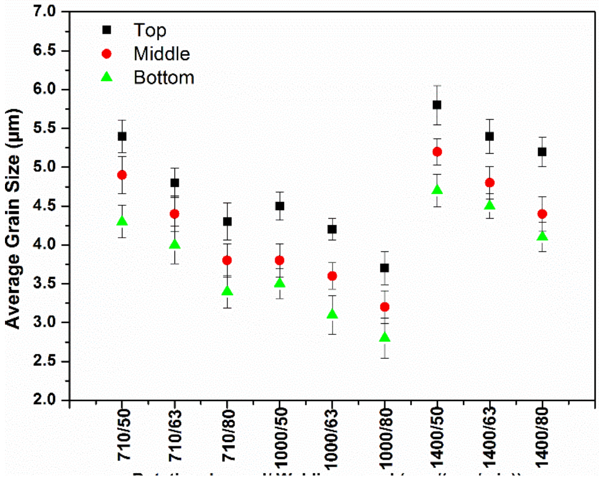

Figure 4 Average grain size distribution at NZ of FS Welded AA6061-4.5(wt%)Cu-10(wt%) SiCcomposite joint fabricated trough TPP tool

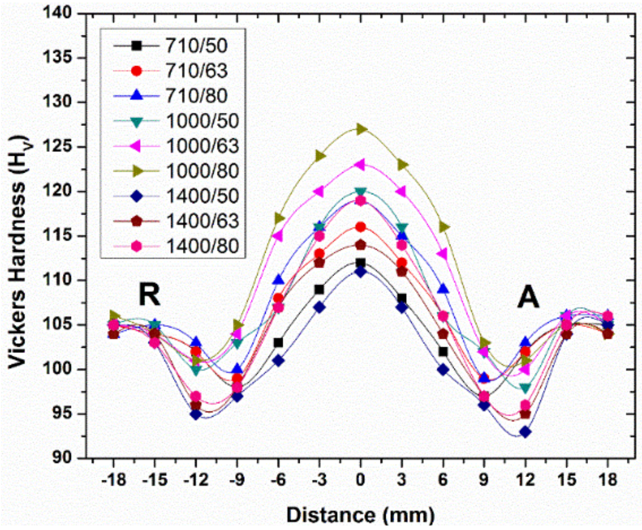

Figure 5 Hardness distribution across NZ of composite FS welded at different rotational speed and welding speed (R- Retreating side and A- Advancing side)

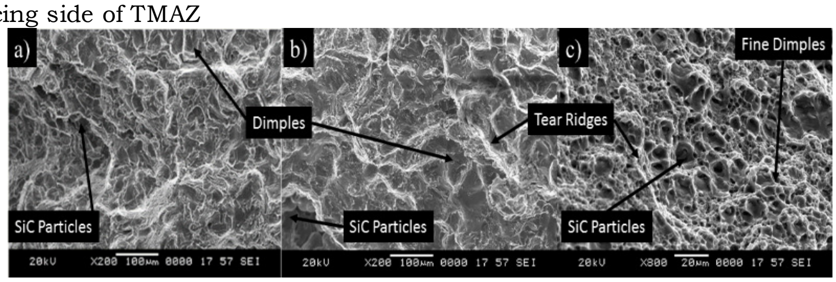

Figure 6 SEM image of the fracture surfaces. (a) Base composite, (b) friction stir welded composite across the direction of weld, tool rotational speed of 1000 rpm and welding speed of 80 mm/min. (c) friction stir welded composite in the direction of weld tool rotational speed of 1000 rpm and welding speed of 80 mm/min.

Conclusions

The AA6061-4.5Cu-10SiC composite was successfully joined by friction stir welding process. The influence of tool rotational speed and welding speed on microstructure, hardness and tensile strength of FS Welded composite is investigated. The weld region exhibited fine grain size as compared to the base material. The microstructure at the NZ exhibited fine recrystallized and equiaxed grains of size ranging from 2 to 7 µm. Homogeneous distribution of SiC particles was observed at NZ. The size of the SiC particles was reduced due to stirring action of the tool and striking of hard particles with each other. Higher hardness found at the NZ irrespective of tool rotation and welding speed due to fine grains and smaller SiC particles. The tensile test of the FS welded composite joint exhibited fracture along the HAZ zone on the advancing side, normal to the tensile stress axis, where minimum hardness was observed irrespective of rotational speed and welding speed. The microscopic examination of the fracture surfaces revealed ductile fracture. The optimal process parameter is rotational speed is 1000 rpm and welding speed is 80mm/min.

References

K.. Kalaiselvan and N. Murugan "Optimizations of Friction Stir Welding Process Parameters for the Welding of Al-B_4C Composite Plates Using Generalized Reduced Gradient Method." *Procedia Engg*, 2012. 38, pp. 49–55.

A. Kumar,C. Veeresh Nayak, Mervin A Herbert and Shrikantha S Rao, "Microstructure and hardness of friction stir welded Aluminum-copper matrix based composite reinforced with 10%SiCp."*Material Research Innovation,* 2014, 14(S-6), pp. 84-89.

D. Storjohann, Barabash O M, Babu S S, David S A, Sklad P S, and Bloom E E, "Fusion and friction stir welding of aluminum metal matrix composites."*Metallurgical and mats trans,* 2005, *36(A),* pp. 3237-47.

Uren, A, M D Escalera, and L Gil.. "In Uence of Interface Reactions on Fracture Mechanisms in TIG Arc-Welded Aluminium Matrix Composites."*Composite science and Technology,* 2000, 60, 613–22.

W. M Thomas, Nicholas E.D, Needham, J. C, Murch, M. G, Templesmith P.&Dawes. C. J. 1991, US. Patent 9125978.8.

R.S Mishra and Z.Y Ma: "Friction stir welding and processing", *J. Mater. Sci. Eng.,* 2005, R50 (12), 1–78.

A.K Shettigar, Giridhar Salian, Mervin Herbert, and Shrikantha Rao "Characterization and hardness evaluation of friction stir welded composite AA6061-4.5Cu-5SiC (wt.%)."*Defence Science Journal*, 2013, 63 (4), pp. 429-434.

P. Periyasamy, B. Mohan, V. Balasubramanian, S. Rajakumar andS Venugopal.. "Multi-objective optimization of friction stir welding parameters using desirability approach to join Al/SiCp metal matrix composites."*Trans Nonferr Metals Soci China*, 2013, 23, pp. 942–55.

N. Murugan, and B. Ashok Kumar.. "Prediction of Tensile Strength of Friction Stir Welded Stir Cast AA6061-T6/AlNp Composite." Mater. Des., 2013, 51, pp. 998–1007.

M. Jayaraman, R Sivasubramanian, and V Balasubramanian.. "Effect of Process Parameters on Tensile Strength of Friction Stir Welded Cast LM6 Aluminium Alloy Joints." *J. Mater. Sci. Technol.*, 2009, 25, pp. 655–64.

Weifeng, Xu.; Jinhe, Liu.; Guohong, Luan & Chunlin, Dong. "Temperature evolution, microstructure and mechanical properties of friction stir welded thick 2219-O aluminum alloy joint." *Mater. Des.*, 2009, 30, pp. 1886-93.

Li J. Q and H. J. Liu: "Characteristics of the reverse dual rotation friction stir welding conducted on 2219-T6 aluminum alloy."*Mater. Des.,* 2013, pp. 148-154.

Zhen-Yan Deng, Jian-Lin Shi, Yu-Feng Zhang, Dan-Yu Jiang and Jing-Kun Guo "Pinning Effect of SiC Particles on Mechanical Properties of Al2 O3±SiC Ceramic Matrix Composites". *J Eur Ceram Soc,*1998. 18, pp. 501-508.

L Ceschini, I. Boromei, G. Minak, Morri, a. And Tarterini, F., "Effect of friction stir welding on microstructure, tensile and fatigue properties of the AA7005/10 vol.%Al2O3p composite."2007,*Compo Sci Technol*, 67, pp. 605–615.

M. Guerra., Schmidt C., McClure J.C., Murr L.E. and Nunes A.C "Flow patterns during friction stir welding." *Materials Characterisation,*2003,49, pp. 95–101.

R. Palaanivel, Koshy Mathews P Murugan N and Dinaharan I "Pridection and optimization of wear resistance of friction stir welded dissimilar aluminum alloy". *Proce Eng,* 2012, 38, pp. 578-84.

Fujii Hidetoshi, Sun Yufeng, Kato Hideaki and Nakata Kazuhiro "Investigation of welding parameter dependent microstructure and mechanical properties in friction stir welded pure Ti joints." *Mater Sci Eng A.*, 2010, 527(15), pp. 3386-3391.