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Microstructural Characterization and Hardness Evaluation of Friction Stir Welded Composite AA6061-4.5Cu-5SiC (Wt.%)

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ABSTRACT

Recent developments in advanced materials research have led to the emergence of new materials having features like low density, high strength to weight ratio, excellent mechanical properties, heat and corrosion resistance. In friction stir welding (FSW), a non-consumable rotating welding tool is used to generate the frictional heat and plastic deformation of the material in the welding zone, which is in the solid state. The advantages of FSW as compared to the fusion welding are high joint strength, less defect weld, uniform distribution of grain structure in the weld zone and low power consumption. AA6061with 4.5 % weight of copper and 5 % weight of *SiC* composite material has been prepared to conduct experiment and carry out characterization, evaluation of the mechanical properties. Micro-structural characterization of the weld zone is carried out by scanning electron microscope (SEM). Evaluation of hardness was also carried out across the weld zone. A successful method for FSW of AA6061-4.5(wt.%) *Cu*-5(wt.%) *SiC* has been developed.

Keywords: Friction stir welding process, Aluminum matrix composites, ceramic particles, hardness, microstructure

1. INTRODUCTION

Aluminum matrix composites (AMC) are continuously finding their application in the field of aerospace, marine and automotive industries. For important applications, metal matrix composites (MMCs) have functional properties such as increased strength to weight ratio, higher elastic modulus, higher service temperature, improved wear resistance, attractive electrical and thermal conductivity and low coefficient of thermal expansion compared to the conventional metals and alloys[1,2]. Joining AMC by fusion welding techniques such as laser beam welding or MIG/TIG welding leads to general non–optimal microstructures, especially in the case of aluminum alloys reinforced with *SiC* particle[3]. Therefore, fusion welding of above composite is found to be very difficult for fabricators primarily due to:

(i) Segregation of *SiC* particles in liquid state.
(ii) Deleterious reactions between reinforcing hard particles and liquid aluminum
(iii) Presence of copper content causing hot cracking, poor solidification microstructure and porosity in the fusion zone which intern leads to poor weldability[4,5,6].

These problems can be resolved satisfactorily by employing energy efficient and environmental friendly welding process known as friction stir welding (FSW)[7]. The FSW is a solid state joining process developed and patented by the welding institute of Cambridge (UK) during 1991[8]. This novel technique acts as an inhibitor to the defects and property deteriorations associated with the fusion welding such as melting and coarsening of strengthening phases[9,10]. In addition, the extensive thermo-mechanical deformation induces dynamic recrystallisation and recovery that refine the microstructure of the stir region[11]. The FSW tool consists of a shoulder and a pin. Pin profile plays an important role in material flow and in turn regulates the welding speed of the FSW process[12]. Tool geometry such as pin length, pin shape and shoulder size are also a key parameters; because they would affect the heat generation and the plastic material flow[6,10,13,14]. The primary function of the non-consumable rotating tool pin is to shear and stir the material. The probe is slightly shorter than the thickness of the work piece and its diameter is marginally larger than the thickness of the work piece[8,15,16]. The severe plastic deformation is due to flow of material around the rotating and advancing tool. The material flow depends on the welding parameters. Frictional heat is generated due to friction developed by the tool shoulder and weld material surface and by deformation. The material softens and flows around the tool as the tool advances[7,9,17-19].

The present work focuses on the various process parameters viz. tool probe profile, tool rotational speed and welding speed and correlates the process parameters and tool parameters on weld nugget microstructure and hardness of friction stir welded AA6061-4.5Cu(Wt.%)-5SiC(wt.%) AMC.

2. EXPERIMENTAL DETAILS

The chemical composition of composite is provided in Table 1. AA6061-4.5*Cu* reinforced with 5(wt.%) *SiC* composite was produced by stir casting process with bottom pouring arrangement. Plates of size 100 mm x 50 mm x 6 mm were prepared from cast composite using machining process. The butted plates were placed on a rigid backing plate and

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firmly held by means of a specially designed fixture. A non-consumable rotating tool made of HSS M2, heat treated to HRC 53 with square profile pin, consisting of concave shaped shoulder of diameter 16 mm and having pin length of 5.8 mm is shown in Fig. 1.

The welding process was carried out on a 5.5 KW capacity BFW vertical milling machine. The tool was inclined at an angle of 1° backward with respect to normal of the workpiece. The rotating tool was plunged into the abutting edges of the plate until the shoulder touches the surface with sufficient thrust force. After a dwell period of 15 seconds, the machine table was moved at a predetermined welding speed. When the plunged tool reaches the other end, the tool was retracted. This process was repeated for various combinations of welding parameters as depicted in Table 2. Figure 2 represents the friction stir welding setup. The welded specimens were cross-sectioned perpendicular to the welding direction from joints. These specimens were polished with a diamond paste and finally etched with Keller`s reagent. Scanning electron microscope (SEM) images were taken to characterize the following surfaces for change in grain structure along various regions of the welded plate:

(a) center of the nugget zone at 1mm below the top surface
(b) 3 mm below the top surface
(c) 5 mm below the top surface
(d) advancing side TMAZ, and
(e) retreating side TMAZ.

Vicker`s hardness tester (VM-50) was used to measure the hardness of the welded specimen at different zones of the weld. The hardness tests were performed at mid thickness region across the weld at 3 mm intervals on the either sides of the center of the nugget zone using a load of 5 kgf for a dwell period of 15 sec.

3. RESULTS AND DISCUSSIONS

Macrostructure features can reveal typical FSW defects such as pin hole, tunnel, worm hole, kissing bond, zigzag and piping due to the improper flow of the metal and insufficient consolidation of the metal in the stir zone[9]. The macrostructure of the welded composite are illustrated in Table 3. It is clear that a defect free weld was obtained at

(1) low speed and medium welding speed,
(2) low speed and high welding speed,
(3) medium speed and medium welding speed, and
(4) high speed and medium welding speed.

The tool is responsible for generating frictional heat throughout the welding process, which leads to plastic deformation in the base composite. In addition, welding occurs owing to the hot forging of plastic material into the rear hole of the tool from retreating side (RS) to advancing side (AS). Insufficient temperature is generated at low rotational speed or very high welding speed leading to insufficient absorption of heat with in the deformed material, thereby preventing the material from undergoing hot forging process induced by the tool. Due to this, defect may be observed on the cross-section of the weld region. High rotational speed would induce

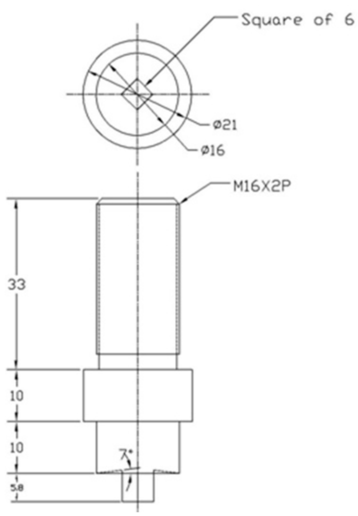


Figure 1. Friction stir tool of square profile pin.

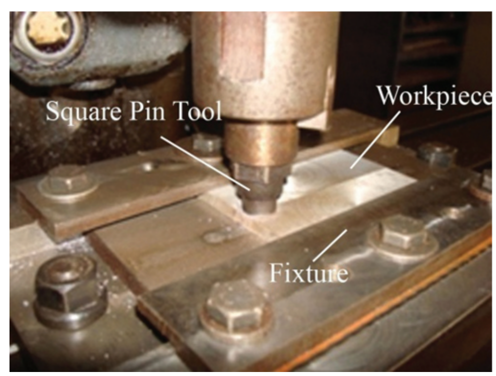


Figure 2. Friction stir welding experiment setup.

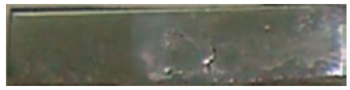
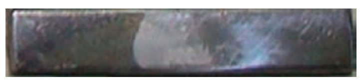
Table 1. Chemical composition of AMC used in the present study

Cu	*Mg*	*Si*	*Fe*	*Mn*	*SiC*	*Al*
4.5	0.8 – 1.2	0.4 – 0.8	0.7	0.15	5	**Remaining**

Table 2. Friction stir welding parameters

Material	**Process parameters**	
	Rotational speed (rpm)	**Welding speed (mm/min)**
AA6061-4.5Cu-5 SiC composite	710, 1000, 1400	50, 63, 80

Table 3. Macrostructure observations

Process parameters		Macrostructure	Type of defect	Probable cause
Rotational speed (rpm)	Welding speed (mm/min)	AS RS		
710	50		Pin hole	Inadequate heat generation
	63		Defect free	Sufficient heat generated
	80		Defect free	Sufficient heat generated
1000	50		Piping defect	Insufficient metal transforation
	63		Defect free	Sufficient heat generated
	80		Worm hole	Insufficient heat generation and insufficient metal transportation
1400	50		Pin hole	Inadequate heat generation
	63		Defect free	Sufficient heat generated
	80		Tunnel defect	Turbulence of metal flow due to high speed

turbulence in the metal flow which results in the tunnel defect in the RS of the nugget region[19].

4. MICROSTRUCTURE OBSERVATION

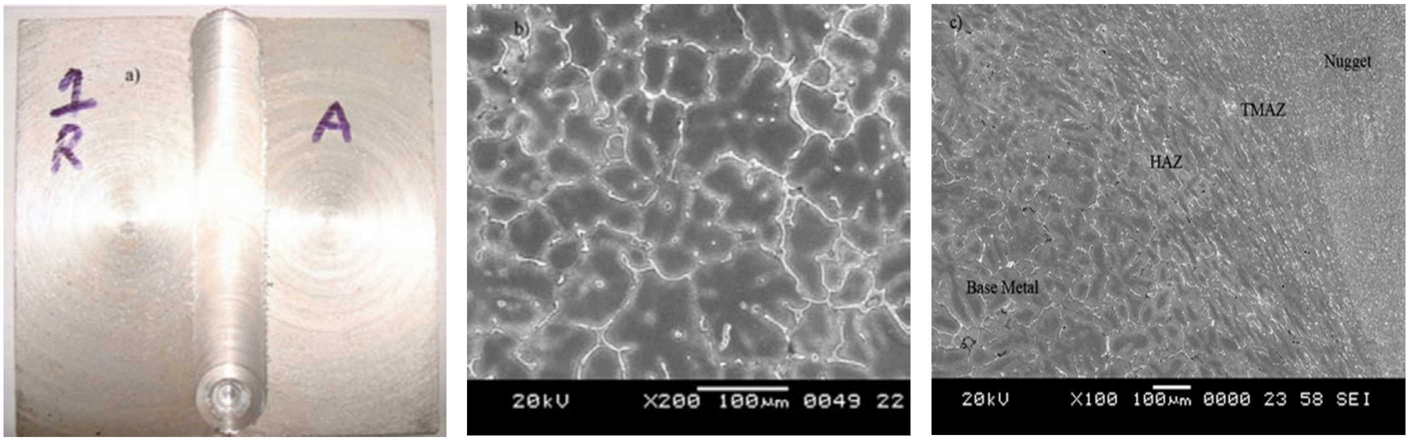
Figure 3(a) is the butt joint produced using friction stir welding. SEM image of AMC parent material is shown in Fig. 3(b) and AMC after welding is shown in Fig. 3(c). The parent AMC has a dendritic structure, as it is produced by using stir casting process. The dendritic structure of the parent metal shows dispersion of *SiC* particles in the AMC. The microstructure of FSW is classified into mainly three regions namely, heat affected zone (HAZ), thermomechanical affected zone (TMAZ), and weld nugget zone as shown in Fig. 3 (c)[4,20,21]. It clearly reveals the different grain sizes in the interfacial boundary between the TMAZ and weld nugget.

The nugget zone was slightly larger than the size of the rotating pin, irrespective of width and height of the pin. However, the size of the zone will vary with frictional pressure, forging force and friction time. As the friction time is decreased, the large amount of thermal energy is propagated in the direction of work piece which will increase in the size of the nugget zone[4]. The weld nugget surrounded by TMAZ, having highly deformed and elongated coarser grain due to the stirring by tool. However, in this region plastic deformation and recrystallisation is somewhat lesser than weld nugget region.

In this study, square pin FSW tool is being used which provides pulsating stirring action in the flowing material due to flat faces which results in formation of finer grains[16]. The average grain size which is 63 μm in base AMC reduces to 2.11 μm at top of nugget region, 2.04 μm at middle and 1.99 μm at bottom of nugget. The bottom of the nugget metal was in contact with base plate, which acts as heat sink. As a result, temperature will be low at the bottom of the nugget and grains will cool faster resulting in lower grain size[14]. The percentage of reduction in grain size at nugget region was approximately 96 %. Table 4 shows the SEM image of welded zone pertaining to rotational speed 1000 rpm and welding speed of 63 mm/min. It is observed that the *SiC* particles were homogenously distributed in the weld zone[20].

5. HARDNESS

To characterize the hardness of the weld region of the FSW, Vicker`s hardness testing machine VM50 was used. The Vicker`s hardness values on either side of the weld region, from the center of the weld (nugget region), at different rotational speeds and welding speeds are shown in Table 5. The base composite recorded a hardness of 95±0.35 H_V. The hardness of the nugget zone is found to be higher than that of the base composite irrespective of the tool rotation and weld traverse speed. The breakage of *SiC* particles and refinement of



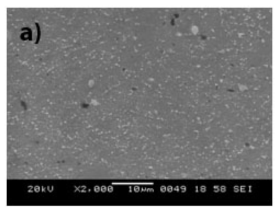
(a) (b) (c)

Figure 3. (a) Welded AMCs specimen, (b) Microstructure image of parent AMCs, (c) Microstructure image of welded region.

Table 4. SEM image of different regions of welded zone

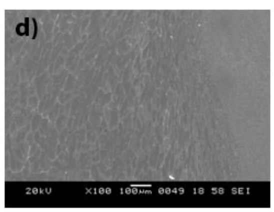
Rotational speed = 1000 rpm
Welding speed = 63 mm/min

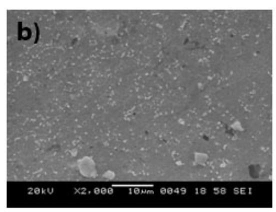
(a) Top weld nugget region
grain size approx. = 2.11 µm

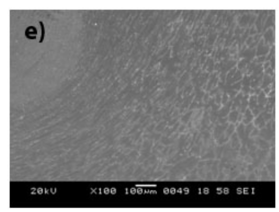


(b) Middle weld nugget region
grain size approx. = 2.04 µm

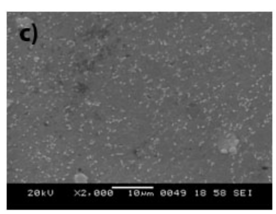
(c) Bottom weld nugget region
grain size approx. = 1.99 µm







(d) Advancing side of nugget
region and transition region
(TMAZ and HAZ)



(e) Retreating side of nugget
region and transition region
(TMAZ and HAZ)

Table 5. Vicker's hardness values on either side of the weld region from center of the weld

Rotational speed (rpm)	Welding speed (mm/min)	Distance (mm) from the center of the weld (butt surface)										
		-15	-12	-9	-6	-3	0	3	6	9	12	15
	50	95±0.3	112±1	104±1	100±1.5	109±1.25	120±2	107±2	100±2	113±1	112±1	95±0.5
710	63	95±0.6	112±1	106±1	107±1	108±2	111±1.5	103±2	94±1.75	102±1	112±1	95±0.2
	80	95±0.3	92±1.5	87±2	93±1.5	99±1	102±2	92±1	89+2	90±1.5	85±1	95±0.4
	50	95±0.8	82±0.5	80±2	88±1.5	96±1	100±2	91±1.5	85±1	87±1	105±1	95±0.1
1000	63	95±0.2	103±1	96±1	105±1	109±1.5	118±1	103±2	84±1.5	94±1.5	107±1.5	95±0.3
	80	95±0.4	84±1	86±1.5	89±2	106±1	116±1.5	92±1	87±1	85±1	84±0.5	95±0.5
	50	95±0.6	108±1	95±2	88±1	103±1.5	114±1	102±1	90±1.5	91±1	110±1.25	95±0.3
1400	63	95±0.4	99±1	96±1.5	94±1.5	105±1	121±2	99±2	101±1	108±1.5	108±1.5	95±0.2
	80	95±0.5	109±1	97±1	108±1	121±1.5	136±1	119±1.5	111±1	108±2	116±1	95±0.3

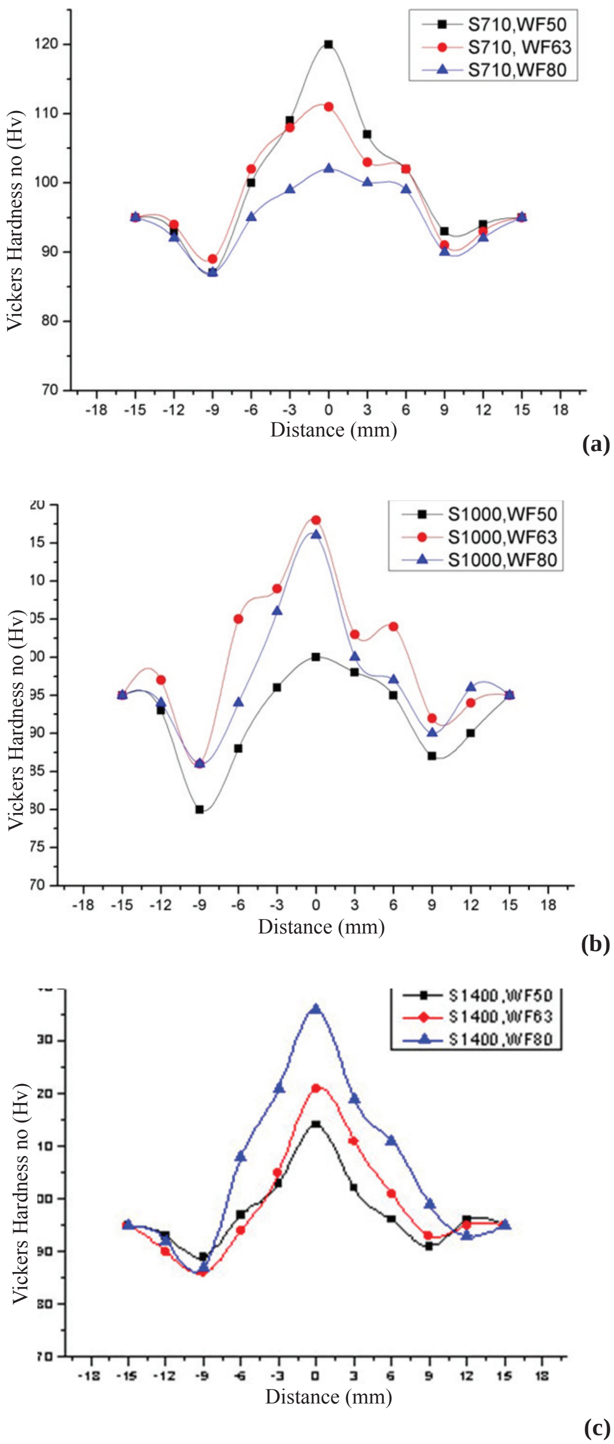


Figure 4. Vicker's hardness profile of welded region at a speed of (a) 710 rpm (b) 1000 rpm, (c) 1400 rpm and welding speed of 50 mm/min, 63 mm/min and 80 mm/min.

grains induced by the tool contributed to increase the hardness in the nugget region[7,10,20]. It was suggested that the particle damage occurred mainly by knocking of corners and sharp edges of large particles[24]. Figure 4 shows the variations of the hardness along the center line on a cross-section of the welds at predetermined rotational and traverse speeds.

In TMAZ, the material undergoes plastic deformation and recrystallisation usually does not occur, due to insufficient deformation strain[19]. Thus hardness values were found to be lower than nugget zone. The difference in hardness between the HAZ and SZ is attributed to the grain refinement in the stir zone and annealing process in the HAZ[21]. Advancing side recorded appreciably lower hardness values compared to retreating side (RS) irrespective of the tool rotational speed used. This is mainly due to the slightly higher shear force and friction force resulting in high temperature in AS as compared to RS[10,22]. From Fig. 4(a) it is observed that, at a constant speed of 710 rpm, as the welding speed is increased the hardness value is found to decrease. This is mainly due to decrease in the friction time and hence the weld material experiences low heat input and high strain causing the recrystallised zone to be narrowed[23]. As the speed is increased to 1000 rpm, the hardness values are increased up to a certain limit and then it starts to decrease as shown in Fig. 4(b). When rotational speed is 1000 rpm and welding speed is 50 mm/min, the hardness value was considerably low. This is because, high rotational speed and low welding speed led to increased heat and redued cooling rate, which results in larger grain size. When welding speed was increased from 50 mm/min to 63 mm/min, the hardness value was found to increase considerably. Further increase in the welding speed, will cause accumulation of *SiC* particles leading to lower hardness. At a constant high speed of 1400 rpm, as the welding speed increases, the hardness value was also found to increase. This is due to the non unifrom dispersion of *SiC* particles at higher rotational speed and welding speed as shown in Fig. 4(c), in the measurement region which would give rise to unsatisfactory results.

6. CONCLUSION

The study demonstrates that, friction stir welding can be successfully adapted for joining aluminum matrix composite. The microstructure at the nugget zone was characterized by fine and equiaxed grain with average grain size reduction from top nugget zone to bottom nugget zone. The weld zone can display homogeneous distribution of *SiC* particles. The clusters present in the parent composite were fragmented by stirring action of the tool. The weld zone can exhibit higher hardness than parent material due to fragmentation, homogeneous distribution of *SiC* particles and grain refinement. Highest hardness value for defect free weld (nugget region 121H_V and HAZ 94H_V) was obtained for a rotational speed of 1400 rpm and welding speed of 63 mm/min.

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