International Journal of Applied Research in Mechanical Engineering

Volume 1 | Issue 3 Article 7

January 2012

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Recommended Citation

Aruri, Devaraju and Kumar, Adepu (2012) "Dry Sliding Wear And Static Immersion Corrosion Resistance of Aluminum Alloy 6061-T6/SiCp Metal Matrix Composite Prepared Via Friction Stir Processing," *International Journal of Applied Research in Mechanical Engineering*: Vol. 1 : Iss. 3 , Article 7.
DOI: 10.47893/IJARME.2012.1033
Available at: https://www.interscience.in/ijarme/vol1/iss3/7

Dry Sliding Wear And Static Immersion Corrosion Resistance of Aluminum Alloy 6061-T6/SiC$_p$ Metal Matrix Composite Prepared Via Friction Stir Processing

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Abstract - In this experiment, SiC particles 20μm in average size were incorporated into the commercially Aluminum alloy 6061-T6 to form particulate metal matrix composite produced by using Friction Stir Processing (FSP). After the preparation of composite, the homogeneity of the particles distribution inside Al matrix has been observed by optical microscope (OM) and scanning electron microscope (SEM). Dry sliding wear test was conducted by using pin on disk equipment and Static immersion corrosion (SIC) resistance was evaluated in 3.5% NaCl aqueous solution at various regimes. From the results, it observed that the SiC particles are well distributed homogenously inside the nugget zone without any defects, obtained good bonding between the SiC particles and Al matrix alloy. The micro hardness of nugget zone with SiC particles is more compare to the as-received Al alloy due to the dispersion of SiC particles. It found that, exhibited superior dry sliding wear resistance and significant improvement SIC resistance of FSPed Aluminum alloy 6061-T6/SiC$_p$ composite is compare with as-received Al alloy.

Keywords- *Friction stir processing, Aluminum alloy 6061-T6, SiC particles, Micro hardness, Dry sliding wear resistance, Static immersion corrosion*

I. INTRODUCTION

Metal-matrix composites (MMCs) are represent a new class of structural materials as conventional metals and alloys approach their developmental limits and with proper processing, the reinforcement of a metal matrix with various particulate reinforcements can yield MMC with significantly improved properties (e.g. lower density, higher specific modulus and higher specific yield strength) ideal for many potential automotive and aerospace applications [1]. The addition of ceramic reinforcements (SiC) raised performance limits of the Aluminum alloy 6061[2] and however the presence of reinforcements in matrix, makes it brittle [3]. In this regard, it may however be noted that wear is a surface dependent degradation mode, which may be improved by a suitable surface modification and/or composition. Hence, instead of bulk reinforcement, if the ceramic particles would be added, it could improve the wear resistance [4]. The discontinuously reinforced aluminum composites (DRA) are especially used for electronic packages and thermal-management applications because of their combination of high thermal conductivity and low density. Several SiC$_p$/Al MMCs have been also used in drive shafts, brake rotors and brake drums in automobile applications and however the addition of reinforcements could significantly alter the corrosion behavior of the material [3].

Increase in the corrosion resistance of Aluminum alloy based composites due to the formation of a film of a hydrated Al oxide/hydroxide and this layer is formed by hydrolysis to produce an Al hydroxide layer adjacent to the metal and these layers acted as barrier and hampered the ionic transport across the corrosion product. On the addition of reinforcement could lead to further discontinuities in the film, increasing the number of sites where corrosion can be initiated and rendering the composite liable to sever attack. Depending on the type of SiC reinforcement may be cause for conflicting results in the corrosion of aluminum MMCs reported in literature [3].In aqueous solutions silicon carbide can serve as an inert electrode for proton or oxygen reduction. Depending on the SiC type, galvanic corrosion with aluminum is possible. The degree of galvanic corrosion is strongly dependent on the type of SiC reinforcement. The electrical resistivity of SiC depends on its purity. It ranges from approximately 10-5 to 1013Ωcm. Pitting attack is reported to be the major form of corrosion in SiC$_p$/aluminum MMCs [3]. Stress-corrosion cracking studies for alternate exposure and immersion in NaCl solutions have been conducted on aluminum alloy 6061 composites and results were shown that it was not susceptible to stress-corrosion cracking [4-7]. For long -term use of aluminum alloys based MMCs components in service, effective corrosion protection must be considered. In contrast to aluminum alloys protection methods, relatively little are known about the corrosion protection of aluminum alloys based MMCs and the effectiveness of standard corrosion protection methods [8]. One of the main advantages in the use MMC is the influence of reinforcement on the corrosion rate and this is particularly important in aluminum alloy based composites, where a protective oxide film imparts corrosion resistance [9]. The addition of reinforcing phase could lead discontinuities in the film, thereby increasing the number of sites for corrosion can be initiated and making the composites more susceptible for corrosion [10].

TABLE I. TYPICAL CHEMICAL COMPOSITION OF ALUMINUM ALLOY 6061-T6

Element	Al	Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Others
Amount (Wt %)	Bal	0.8-1.2	0.4-0.8	Max. 0.7	0.15-0.40	Max. 0.25	Max. 0.15	Max. 0.15	0.04-0.35	0.05

Friction stir processing is a new technology for surface modification and developing surface and bulk reinforcement MMCs and it's an adaptation of friction stir welding and based on the concept of friction stirring. The stirring action and frictional heat generated by the FSP tool can be used to distribute ceramic particles as reinforcement on the surface of light metals like aluminum, copper and magnesium alloys. Therefore, the friction stir process can be used as a generic process to modify the microstructure and change the composition, at selective locations. At this time, FSP is the only solid-state processing technique that has these unique capabilities. The SiC particles were uniformly distributed and excellent bonding obtained between SiC_p and base metal. The composite exhibited high microhardness compared to untreated material [11]. The reinforcement particles (SiC, Al_2O_3 or their mixture) were distributed almost homogenously over the nugget zone by FSP without any defects except small some voids forming around the Al_2O_3 particles. The hybrid composites containing 20% Al_2O_3 + 80% SiC exhibited superior wear resistance was reported by Essam R.I. et al [12]. Initial coarse microstructure of the cast NAB (NiAl bronze alloy) was transformed to a fine structure and defect free and FSProsessed NAB static immersion corrosion resistance was increased compared with the cast counterpart [13]. The SiC may react with molten aluminum to form brittle Al_4C_3 carbide [14, 15] and bonding problem between the SiC_p and base metal in normal fusion process. Considering this problem, friction stir processing (FSP) seems to be a good technique for successful fabrication of MMCs. In the present work, SiC particles were dispersed in to Aluminum alloy 6061-T6 via FSP and in order to reveal properties like microstructure, micro hardness, dry sliding wear and static immersion corrosion resistance and compare with as-received Al alloy.

II. EXPERIMENTAL PROCEDURE

In this experiment, commercial SiC particles (average size: 20μm) and Aluminum alloy 6061-T6 rolled plate (thickness: 4mm) were used and the chemical constitution of Al6061-T6 is shown in Table 1. The SEM image of as-received SiC_p is shows in Fig.7. A groove was prepared at the edge of pin in the advancing side, which were 3mm width and 3mm depth. The groove was 2mm away from the center line and plate with groove as shown in Fig.1. The FSP tool was made of H13 tool steel and had a cylindrical shape shoulder (Ø24mm) and a screwed taper pin profile (Ø8 mm) as shown in Fig.2. In the beginning of the FSP, the groove was covered with a modified FSP tool that only had a shoulder and no probe to prevent the SiC particles from being displaced out of the groove during process. Then the tool penetrated into the plate until the shoulder's head face reached 0.25mm under upper surface. The rotational speed of tool was 1400rpm and the travelling speed was 40mm/min along the center line. The tool tilt forward angle of 2.5^0 was used. The process is carried out on a vertical milling machine (VMM) (Make HMT FM-2, 10hp, 3000rpm) and tool arbor as shown in Fig.3 & 4 respectively. Specimen was cut from the region under the tool shoulder (stir zone), picture of FSPed plate as shown on Fig.5. The distribution of the dispersed SiC_p was observed by SEM and OM. The micro hardness was measured as per IS: 1501-2002 test method.

Wear test was conducted with a pin-on-disc equipment setup and the picture of equipment setup as shown in Fig.6. Most requirements of the ASTM standard G99-04 were followed. Nevertheless, several modifications were introduced, mainly regarding the pin shape.

Fig.1 Picture of as-received Al alloy with groove

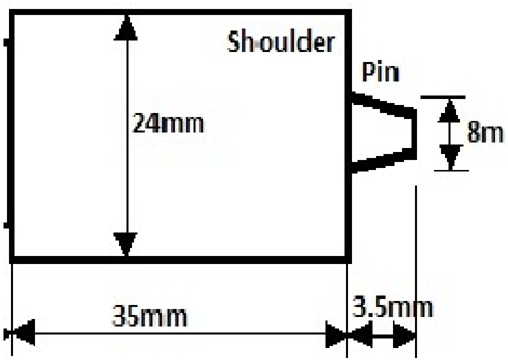


Fig.2 Schematic diagrame of FSP tool

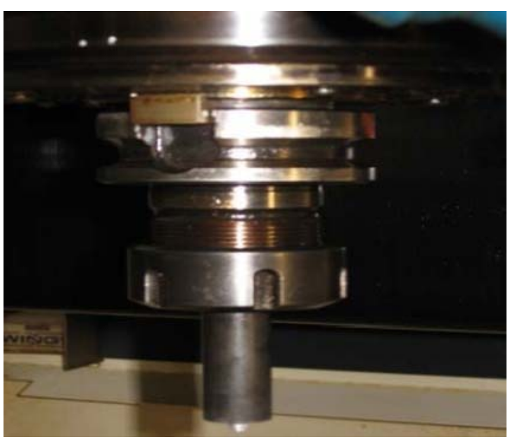


Fig.3 Picture of VMM arbor

Fig.4 Picture of Vertical milling machine

Prismatic pins were made of the materials under study (Aluminum alloy 6061 and its surface composite produced by FSP) with rectangular cross section of 10mm×3.5mm. With this geometry, the nominal contact area was maintained constant during the tests in spite of the wear process. The counterpart discs were made of EN31 steel, hardness of 62 HRC. The diameter of the sliding track on the disc surface was 100mm. Before the wear test, each pin specimen was ground down to 1000 grit abrasive paper. The wear tests were performed under dry sliding condition with a constant load (50 N), rotational speed (650rpm) and sliding speed (3.4m/s). The coefficient of friction between the pin specimen and the disk was determined by measuring the frictional force with a LVDT sensor.

Static immersion samples were machined from the stir zone with a dimension of 10mm x 10mm x 3.5mm and were ground with 1000SiC abrasive paper to provide a uniform surface finish. Prior to test, the samples were degreased in acetone and blow dried and weighed carefully. Samples were immersed into a glass beaker containing of 500ml of a 3.5wt% NaCl solution at room temperature. The solution was prepared from distilled water and reagents grade chemicals. The corroded samples were taken out after 48, 96, 192 and 384hrs respectively. The corroded samples were flushed with water and immersed in the solution of 500ml HCl (density, 1.19) + 1000ml of H_2O for 2 min to clean off the corrosion products, then completely rinsed out using a toothbrush and flushed with water and immersed in ethanol and blow-dried, and finally weighed. The gravimetric measurements were made by using a weighing balance. The weight loss for each condition was obtained by average of two results. For the purpose comparison, the base material samples with the same size were tested under the same conditions.

III. RESULTS AND DISCUSSIONS

1). Microstructure:

After the Aluminum alloy 6061-T6/SiC_p was fabricated by FSP, microstructure at cross-section of stir zone was observed by OM and SEM (the parameters are 1400rpm and 40mm/min) and microstructures are shown in Fig.8 & 9. In such higher rotational speed and lower travel speed enough heat input was produced and the tool also supplied shear force to make the SiCp flow and disperse in stir zone. It is seen that the reinforcement particles distributed more widely and uniformly in the nugget zone and good interface bonding between SiC_p and base metal without any defect by applying single pass FSP. This was due to the stirring action generated in pass by the rotated tool. There is no reaction between SiC_p and the base metal because of FSP is a solid-state process, and peak temperature during process was below the melting point of base materials [16]. E.R.I. Mahmoud et al [12] were reported that there are no new phases except the added reinforcement powders (SiC, Al_2O_3) and the aluminum matrix. This suggests that no reaction occurred between the SiC and Al_2O_3 powders or between the aluminum matrix and the powders during three FSP passes, which can be considered to be a merit of the FSP technique over other traditional fusion techniques such as stir-casting. The reinforced particles were easily wrapped by softening metal and rotated with the FSP tool; it is difficult to travel like the same move with softening base metal. So the particles are not easy to disperse in larger region [17].

2). Microhardness:

Microhardness behavior of the composite metal over the length of FSPed zone as shown in Fig.10 and the microhardness of the FSPed Aluminum alloy 6061-T6/SiC_p of the nugget zone is higher than that of the as-received Al alloy. It is considered that higher value was obtained not only by the grain refinement but also the pinning effect and presence of hard SiC particles. At lower traverse speed SiC particles were separated well and consequently an intense pinning effect occurs in stir zone leading to a further enhancement of microhardness values.

3) Dry sliding wear behavior:

Fig.11 & 12 shows wear loss graphs with respect to the sliding time using the specimen as the pin and EN31 steel (HRC: 62) as the disk material. It is seen that the wear loss increased with sliding distance. For the as-received Al alloy wear loss low during the initial period after which it increased, height of 2.5mm was lose within 15min may be due to Al become more ductile because of frictional heat generation during test. But FSPed Aluminum alloy 6061-T6/SiC_p wear rate was linearly increased with respective to sliding time but it took 45min to height lose of 2.5mm. In other words, FSPed Aluminum alloy 6061-T6/SiC_p is travelled a distance of 9km whereas as-received Al alloy is 3km with a constant speed of 3.4m/s. It reveals that both the extent of wear and the rate of wear are very lower in the FSPed specimen as compared to the as-received substrate. The improved wear resistance of FSPed Aluminum alloy 6061-T6/SiC_p is attributed to improved hardness achieved by dispersion of ceramic particles.

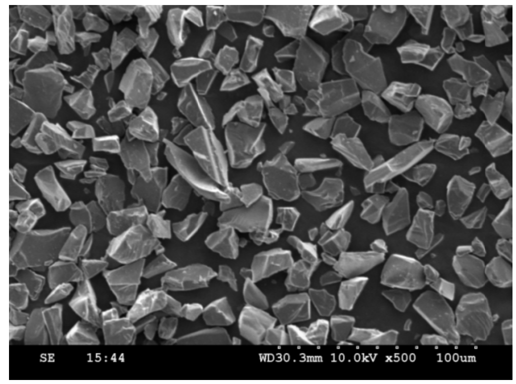


Fig.7 SEM image of as-received SiC particles

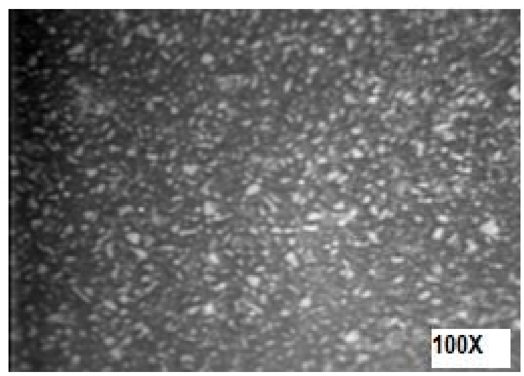


Fig.8 Optical microstructure of FSPed composite

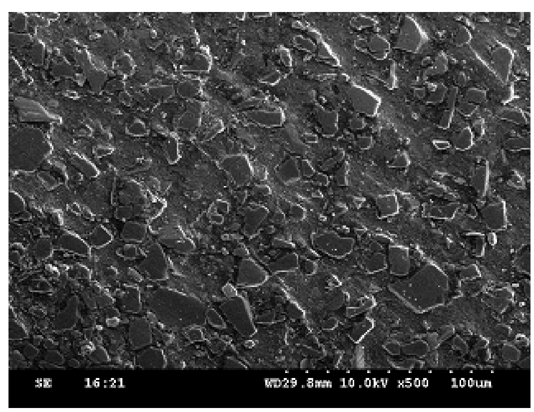
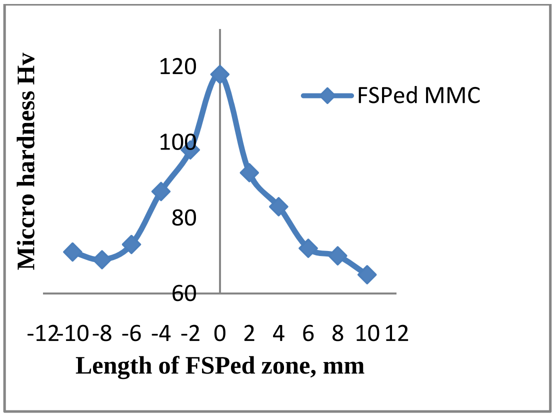


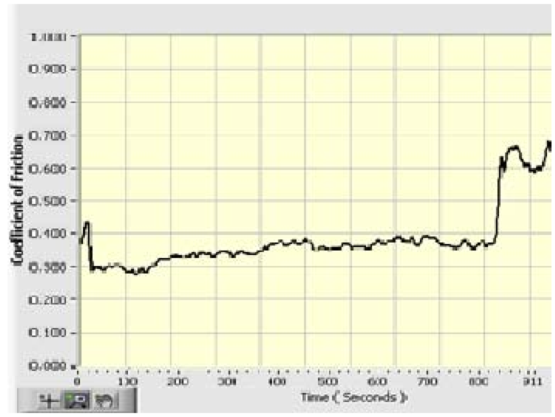
Fig.9 SEM microstructure of FSPed composite



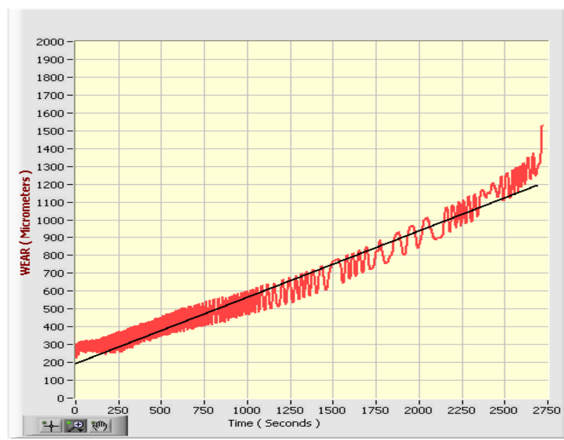
Scanning electron micrographs are shown in Fig.13 & 14 of the worn surfaces. From graphs it observed that the variation of the coefficient of friction with sliding time for FSPed Aluminum alloy 6061-T6/ SiC$_p$ is fairly low (with an average of 0.35) and does not change with sliding distance. The lower coefficient of friction implies that the mechanism of wear is predominantly abrasive in nature due to the harder (steel disk) surface scratching over the softer (pin) surface. During wear of as-received Aluminum alloy the coefficient of friction was found to high. The increased coefficient of friction is attributed to a localized welding of the worn debris to the as-received Al alloy and it may be concluded that wear mechanism in as-received Al alloy is abrasive as the predominant wear initiation mechanism, which converts to adhesive at a much latter stage [18].

a)

b)



c)



d)

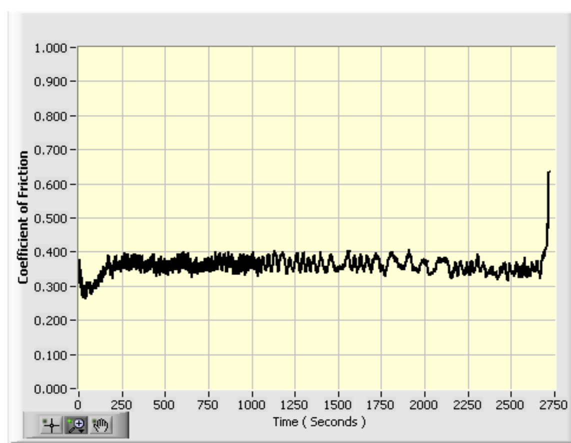


Fig.11 a) & b) as-received Al alloy & Fig. 12 c) & d) FSPed composite, Graphs of wear loss (µm) and coefficient of friction with respect to time (sec

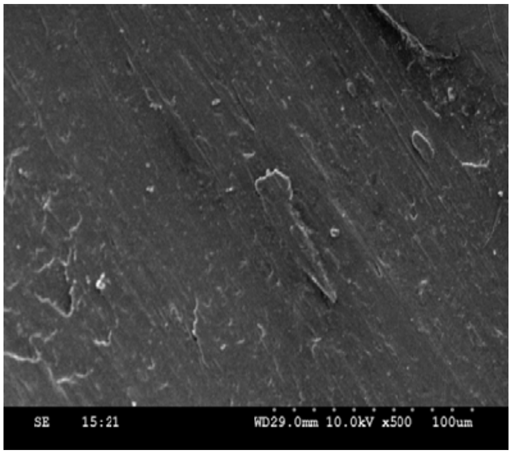


Fig.13 Worn surface SEM image of as-received Al alloy

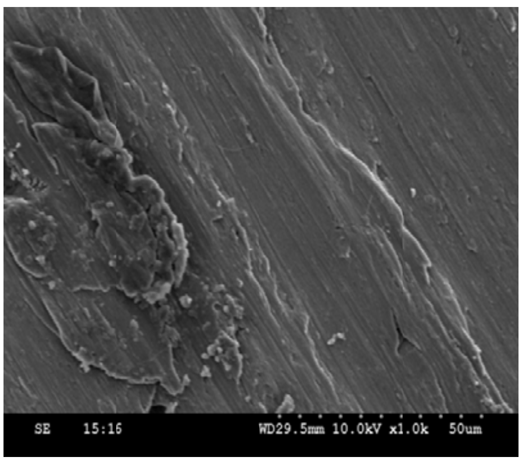


Fig.14 Worn surface SEM image of FSPed composite

Fig. 13 and 14 shows the worn tracks observed in as-received Al alloy and FSPed Aluminum alloy 6061-T6/SiC_p against a steel disk. It is seen that adhesion dominates sliding wear for as-received Al alloy by wear scar. In contrast, worn FSPed Aluminum alloy 6061-T6/SiC_p surface shows much less sever adhesive wear but instead if dominated by abrasive wear and plastic deformation. The presence of worn out particles convert the wear mode from two body to three body wear and reduces the rate of wear further by acting as a lubricant, which is also evident from the lower coefficient of friction in FSPed Aluminum alloy 6061-T6/SiC_p. On the other hand, in FSPed Aluminum alloy 6061-T6/SiC_p layer due to a comparatively lower coefficient of friction, wear due to decrease in adhesive mode and furthermore, the abrasive mode of wear is lower in the FSPed Aluminum alloy 6061-T6/SiC_p because of a higher hardness.

4). Static immersion corrosion behavior:

The weight loss of the base metal and FSPed Aluminum alloy 6061-T6/SiC_p MMC are shown in Fig.13. It observed that the base metal exhibited apparently higher weight loss than the FSPed MMC during the test and the weight loss of both base metal and FSPed MMC samples decreases with increasing time. The weight loss can be divided into two stages: higher weight loss before 192 hr and lower loss after 192 hr. D.R.Ni [13] reported that the microstructure modification changed the corrosion behavior of the NAB is a 3.5% NaCl solution. In static immersion corrosion test, the FSP NAB exhibited significantly greater corrosion resistance compare to the cast counterpart. Corrosion of as-received Al alloy exhibited apparently higher than compared the FSPed Aluminum alloy 6061-T6/SiC_p may be due to good bonding between the reinforcement and Al matrix, grain refinement and also type of SiC reinforcement.

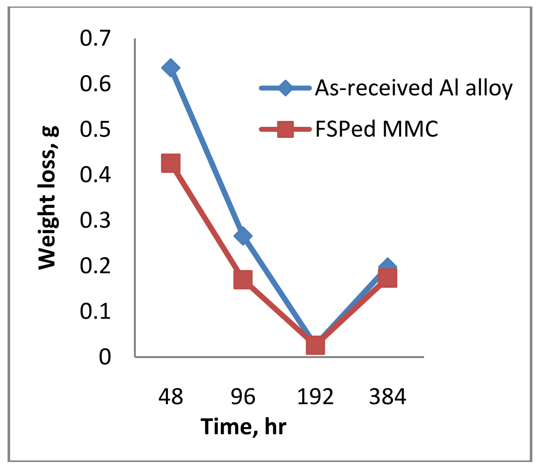


Fig.15 Weight loss of FSPed composite and as-received Al alloy

V. CONCLUSIONS

The SiC particles dispersed Aluminum alloy 6061-T6 was successfully fabricated by the FSP. The micro structure, micro hardness, dry sliding wear and SIC resistance was evaluated by the dispersion of the SiC particles. The SiC particles were distributed homogenously inside the nugget zone without any defect and also it observed that the excellent bonding of SiC particles with matrix metal obtained by FSP process. The micro hardness of nugget zone with SiC particles is more compare to as-received Al alloy. Exhibited superior dry sliding wear resistance of FSPed Aluminum alloy 6061-T6/SiC_p composite as compare to as-received Al alloy. In static immersion corrosion test the FSP Aluminum alloy 6061- T6/SiC_p exhibited significantly greater corrosion resistance than compare to as-received Al alloy.

ACKNOWLEDGEMENT

The authors thank the authorities of DIAT pune, India for providing the facilities to carry out this research study.

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