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Original Article

Wear and mechanical properties of 6061-T6 aluminum alloy surface hybrid composites [(SiC + Gr) and (SiC + Al_2O_3)] fabricated by friction stir processing

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ABSTRACT

In this investigation, the influence of tool rotational speed on wear and mechanical properties of aluminum alloy based surface hybrid composites fabricated via Friction stir processing (FSP) was studied. The fabricated surface hybrid composites have been examined by optical microscope for dispersion of reinforcement particles. Microstructures of all the surface hybrid composites revealed that the reinforcement particles (SiC, Gr and Al_2O_3) are uniformly dispersed in the nugget zone. It was observed that the microhardness decreases when increasing the rotational speed and showed higher microhardness value in Al–SiC/Al_2O_3 surface hybrid composite due to presence and pining effect of hard SiC and Al_2O_3 particles. It was also observed that high wear resistance exhibited in the Al–SiC/Gr surface hybrid composites due to presence of SiC and Gr acted as load bearing elements and solid lubricant respectively. The observed wear and mechanical properties have been correlated with microstructures and worn micrographs.

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1. Introduction

Aluminum alloy 6061-T6 is widely utilized in aircraft, defence, automobiles and marine areas due to its good strength, light weight and better corrosion properties. But, it exhibits inferior tribological properties in extensive usage [1,2]. In addition, aluminum based composites becomes brittle by the addition of reinforcements such as SiC and Al_2O_3 ceramic particles [3].

A proper technique can be employed to refine the microstructure and homogeneous dispersion of reinforcements on metallic surface since wear is a surface deprivation property [4]. Dispersion of reinforcement particles on metal surface and the control of its dispersal are more difficult to attain by conventional surface modification techniques [5]. Guptha et al. [6] and Mabhali et al. [7] reported that the thermal spraying and laser beam techniques were utilized to prepare surface composites, in which it degrades the properties due to formation of unfavorable phases. These techniques are operated at higher temperatures and impossible to avoid the reaction between the reinforcements and the matrix, which forms a detrimental phase. Therefore a process can be employed which is operated below melting temperature of matrix for the fabrication of surface composites which can be used to avoid the above mentioned complications.

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Table 1 – Chemical composition of aluminum 6061-T6 alloy (wt%).

Element	Mg	Si	Cu	Zn	Ti	Mn	Cr	Al
Amount (wt%)	0.85	0.68	0.22	0.07	0.05	0.32	0.06	Balance

Considering the above problems, friction stir processing (FSP) is best suited for preparation of surface composites and surface modification. In FSP a rotating tool with shoulder and pin is plunged into the surface of material, which creates frictional heat and dynamic mixing of material area underneath the tool [8], it leads to incorporation and/or dispersion of the reinforcement particles in the matrix material such as Aluminum alloys, Magnesium alloys and Copper [9–11]. Devaraju et al. [12] achieved homogeneous dispersion of SiC particles (20 μm average size) on a surface of Aluminum alloy 6061-T6 via FSP. Hybrid composites are prepared by reinforcing with a mixture of two or more different types of particles which combines the individual properties of each type of particle. Essam et al. [13] fabricated Al–1050-H24/(20% Al_2O_3 + 80% SiC) hybrid composite via FSP and exhibited high hardness and superior wear resistance than the matrix material.

Tool rotational speed is the most important process parameter in FSP which has greater influence in uniform distribution of reinforcement particles, grain refinement and heat input during the process [14,15].

However, previously no results were reported for improvement of wear and mechanical properties by the addition of mixture of SiC, Gr and Al_2O_3 particles as refinements on the surface of aluminum alloy 6061-T6 via FSP. The objective of the present investigation is to study the influence of rotational speed on wear and mechanical properties of aluminum alloy 6061-T6 based surface hybrid composites fabricated via FSP.

2. Experimental procedure

The base material employed in this study is a 4-mm thick aluminum alloy 6061-T6. The chemical composition of the base material is given in Table 1. The reinforcement particles which have effect on the wear and mechanical properties were identified as SiC, Gr (graphite) and Al_2O_3 (suppliers: The Metal Powder Company Ltd., India) [13,16–18]. The scanning electron microscope (SEM) micrographs of as received SiC, Gr and Al_2O_3 particles are shown in Fig. 1.The average size of both reinforcement particles is 20 μm.

A square groove was made with dimensions of 2 mm width and 3 mm depth tangent to the pin in the advancing side,which is 1 mm far away from the center line of the tool rotation on the aluminum alloy 6061-T6 plate. The schematic of aluminum alloy plate for FSP is shown in Fig. 2. H13 tool steel having screwed taper pin profile with shoulder diameter of 24 mm, pin diameter of 8 mm and 3.5 mm height was used.

The selected ratios of reinforcement mixtures (i.e. SiC, Gr and Al_2O_3) are presented in Table 2 and these selected particles mixture is packed in the groove. The groove opening was initially closed by means of the tool which has shoulder without pin to avoid the escapement of reinforcement particles from groove while processing. Tool traveling speed of 40 mm/min, axial force of 5 kN and tool onward tilt angle of 2.5° along the

Table 2 – Volume percentages of reinforcement particles in surface composites.

Surface composites	Reinforcements (vol.%)			Tool rotational speed (rpm)
	SiC	Al_2O_3	Gr	
Al–SiC/Gr	8	–	4	900
	8	–	4	1120
	8	–	4	1400
Al–SiC/Al_2O_3	8	4	–	900
	8	4	–	1120
	8	4	–	1400

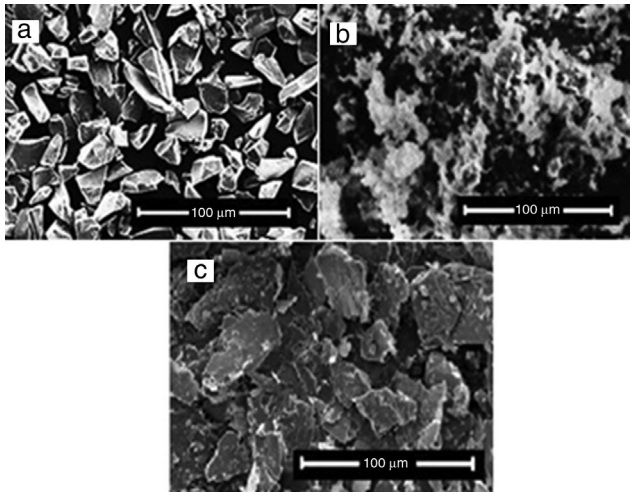

Fig. 1 – SEM micrographs of as-received: (a) SiC, (b) Al_2O_3 and (c) Gr particles.

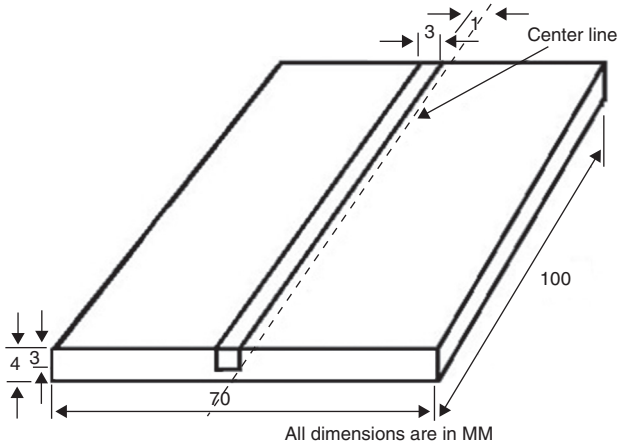

Fig. 2 – Schematic of aluminum alloy plate for FSP.

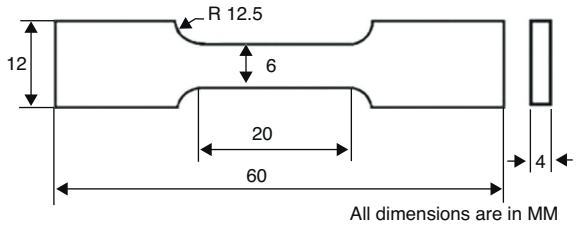

Fig. 3 – Schematic of tensile specimen.

center line were used in FSP. The experiments were carried out on a vertical milling machine (Make HMT FM-2, 10 hp, 3000 rpm).

After FSP, microstructural observations were carried out at the cross section of the nugget zone (NZ) of surface hybrid composites normal to the FSP direction, mechanically polished and etched with Keller's reagent (2 ml HF, 3 ml HCl, 20 ml HNO_3 and 175 ml H_2O) by employing optical microscope (OM). The SEM was also utilized for measuring the reinforcement particles size and worn morphology of surface hybrid composites.

Microhardness tests were carried out at the cross section of NZ of surface hybrid composites normal to the FSP direction. Samples were tested with a load of 15 g and duration of 15 s using a Vickers digital microhardness tester.

The tensile specimens were taken from the surface hybrid composites normal to the FSP direction and made as per ASTM: E8/E8M-11 standard by using Wire cut Electrical Discharge Machining to the required dimensions. The schematic sketch of tensile specimen is shown in Fig. 3. The tensile test is carried out on a computer controlled universal testing machine (make: Shimadzu, model: Autograph) at a cross head speed of 0.5 mm/min.

Wear test was carried out on a pin-on-disk tribo-meter as per ASTM: G99-05 standard. Prismatic pins of 8 mm diameter were cut from the NZ, with the axis of the pin normal to the FSP direction. The disk was made of EN31 steel with hardness of 62 HRC. The diameter of the sliding track on the disk surface was 100 mm. The wear tests were performed under dry sliding conditions with a constant load (40 N), rotational speed (650 rpm) and sliding speed (3.4 m/s). The schematic configuration of pin-on-disk is shown in Fig. 4.

Wear rate is calculated by,

$$\text{Wear rate } (\text{mm}^3/\text{m}) = \frac{\text{Volume loss}}{\text{Sliding distance}}$$

3. Results and discussions

3.1. *Microstructure*

The size of the nugget zone (NZ) is normally about equal to the size of the rotating pin, width and depth of 8 mm and 3.5 mm, respectively. The optical micrographs of Al–SiC/Gr at 900 rpm, Al–SiC/Gr at 1120 rpm, Al–SiC/Gr at 1400 rpm, Al–SiC/Al_2O_3 at 900 rpm, Al–SiC/Al_2O_3 at 1120 rpm, Al–SiC/Al_2O_3 at 1400 rpm surface hybrid composites and as-received aluminum alloy are shown in Fig. 5. The particles of SiC, Gr and Al_2O_3 were

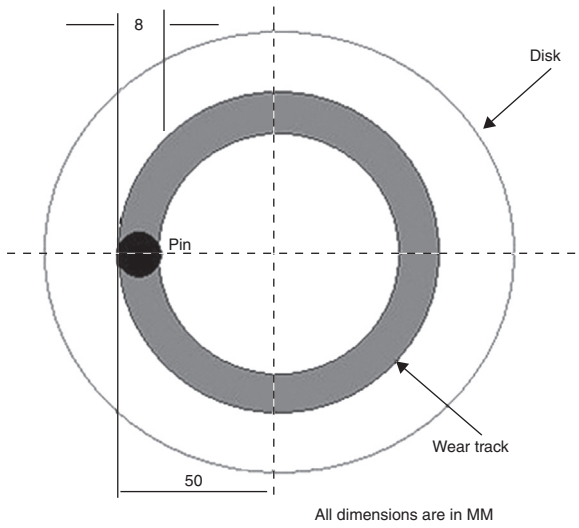

Fig. 4 – Schematic configuration of pin-on-disk tribo-meter.

observed to be dispersed uniformly in the NZ for all the conditions of composites made by FSP as the rotating tool gives sufficient heat generation and a circumferential force to distribute the reinforcement particles to flow in a wider area [12,13]. Earlier researches noticed that microstructural modifications were observed due to FSP [8,9,11–13] and the similar observations were identified in this investigation.

3.2. *Effect of rotational speed on microhardness*

Microhardness survey of Al–SiC/Gr at 900 rpm, Al–SiC/Gr at 1120 rpm, Al–SiC/Gr at 1400 rpm, Al–SiC/Al_2O_3 at 900 rpm, Al–SiC/Al_2O_3 at 1120 rpm, Al–SiC/Al_2O_3 at 1400 rpm surface hybrid composites and as-received aluminum alloy is shown in Fig. 6. It was revealed that, as the rotational speed increases, the microhardness decreases. This is due to the high heat generation that causes matrix softening which decreases the microhardness. This softening of the NZ resulted in coarsening and/or dissolution of strengthening precipitates in the aluminum matrix which occurs especially in heat treatable aluminum alloys [19,20].

Mainly, the microhardness value depends on the presence and uniform distribution of SiC and Al_2O_3 particles. The optimum microhardness value was obtained at the rotational speed of 900 rpm, 8 volume percentage of SiC and 4 volume percentage of Al_2O_3. This was due to fact that at 900 rpm, the tool shoulder supplied enough heat input and shear force to make the reinforcement particles more easily wrapped by the softening metal and rotated with FSP tool, which results in well separation and distribution in the nugget zone. The presence of SiC particles was considered for effective grain refinement due to the restrain of grain boundary and the enhancement of the induced strain [21]. However the higher hardness was achieved by the SiC and Al_2O_3 particles.

3.3. *Effect of rotational speed on wear rate*

The wear rate with respect to the sliding distance of Al–SiC/Gr at 900 rpm, Al–SiC/Gr at 1120 rpm, Al–SiC/Gr at

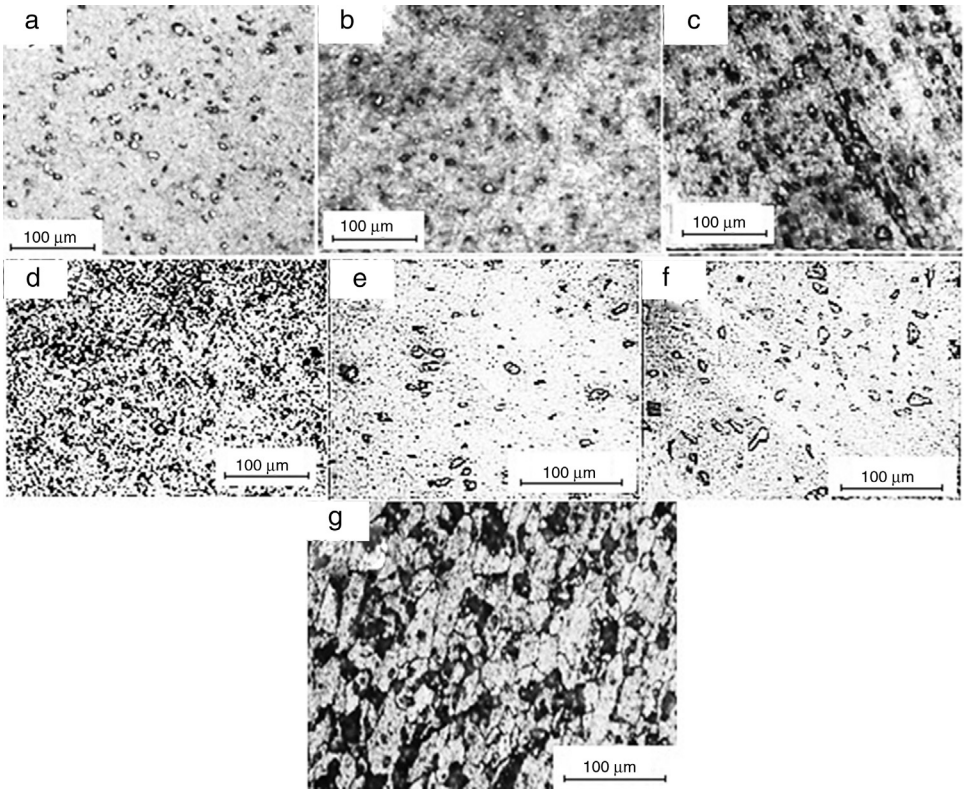

Fig. 5 – Optical microstructures of the surface hybrid composites: (a) Al–SiC/Gr at 900 rpm, (b) Al–SiC/Gr at 1120 rpm, (c) Al–SiC/Gr at 1400 rpm, (d) Al–SiC/Al_2O_3 at 900 rpm, (e) Al–SiC/Al_2O_3 at 1120 rpm, (f) Al–SiC/Al_2O_3 at 1400 rpm and (g) as-received aluminum alloy.

1400 rpm, Al–SiC/Al_2O_3 at 900 rpm, Al–SiC/Al_2O_3 at 1120 rpm, Al–SiC/Al_2O_3 at 1400 rpm surface hybrid composites and as-received aluminum alloy are shown in Fig. 7. It was revealed that the increase in the rotational speed increases the wear rate. It is a well-known fact that increasing the rotation speed, increases the heat generation in the nugget zone which leads to more softening of the matrix due to the over aging [19,20]. The high heat generation causes matrix softening which results in increased wear rate.

The wear rate increases in the Al–SiC/Al_2O_3 surface composites compared to Al–SiC/Gr surface hybrid composites. The presence of SiC and Al_2O_3 particles increases the wear rate due to pulled out of hard SiC particles from the composite pin during the wear process. These particles formed on the steel disk which acts as barrier and further converts the adhesive wear to abrasive wear, resulting in greater amount of material worn-out from the composite pin.

The lower wear rate was obtained at the optimum condition of rotational speed of 900 rpm, 8 volume percentage of SiC and 4 volume percentage of Al_2O_3 in the Al–SiC/Al_2O_3 surface hybrid composites. This is due to the enhanced hardness by the dispersion SiC and Al_2O_3 particles that acted as load-supporting elements [13], and the presence of Al_2O_3, which acted as sold lubricant [22]. The Al_2O_3 particles released on the wear surface during wear process avoids the direct metal to metal contact and served as a solid lubricant and thereby

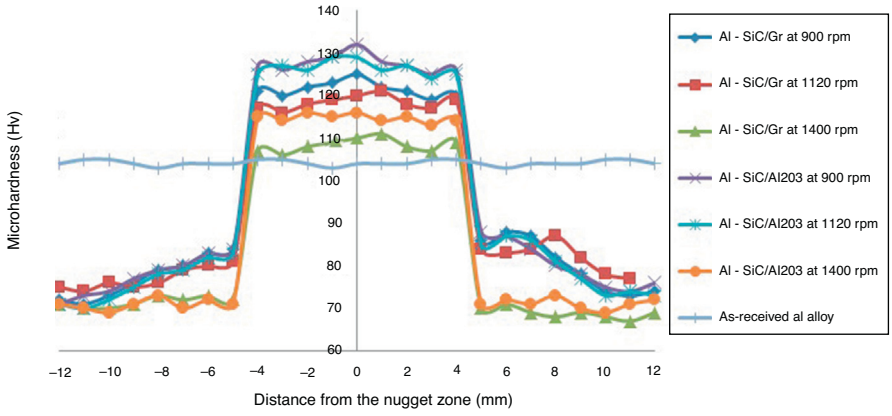

Fig. 6 – Microhardness survey of aluminum alloy surface hybrid composites.

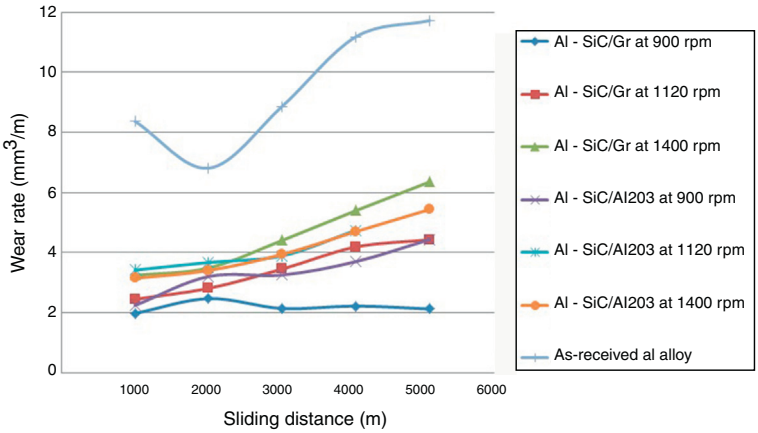

Fig. 7 – Variation of wear rate with respect to the sliding of aluminum alloy surface composites.

reduces the coefficient of friction between the composite pin and the steel disk. Essam et al. [13] and Tjong et al. [22] showed that Al_2O_3 and BN particles acted as solid lubricant similar to Gr during wear that produces a tinny layer between the deformed surfaces. This decreases the coefficient of friction and enhances the wear resistance.

The wear rate decreases in the Al–SiC/Gr surface hybrid composites compared to Al–SiC/Al_2O_3 surface hybrid composites and as-received aluminum alloy. The presence of SiC and Gr particles decreases. The lower wear rate was obtained at the optimum condition of rotational speed of 900 rpm, 8 volume percentage of SiC and 4 volume percentage of Gr. This is due to the enhanced hardness by the dispersion SiC, which acted as load-supporting elements [13], and the presence of Gr, which acted as sold lubricant [23].

The SEM micrographs of the worn morphology of Al–SiC/Gr at 900 rpm, Al–SiC/Gr at 1120 rpm, Al–SiC/Gr at 1400 rpm, Al–SiC/Al_2O_3 at 900 rpm, Al–SiC/Al_2O_3 at 1120 rpm, Al–SiC/Al_2O_3 at 1400 rpm surface hybrid composites and as-received aluminum alloy are shown in Fig. 8. The presence of tribo mechanically mixed layers converts the wear manner into a two body to three body wear and acts as solid lubricant that decreases the wear rate and minimizes the coefficient of friction [13,24,25]. This resulted in decrease of metal removal

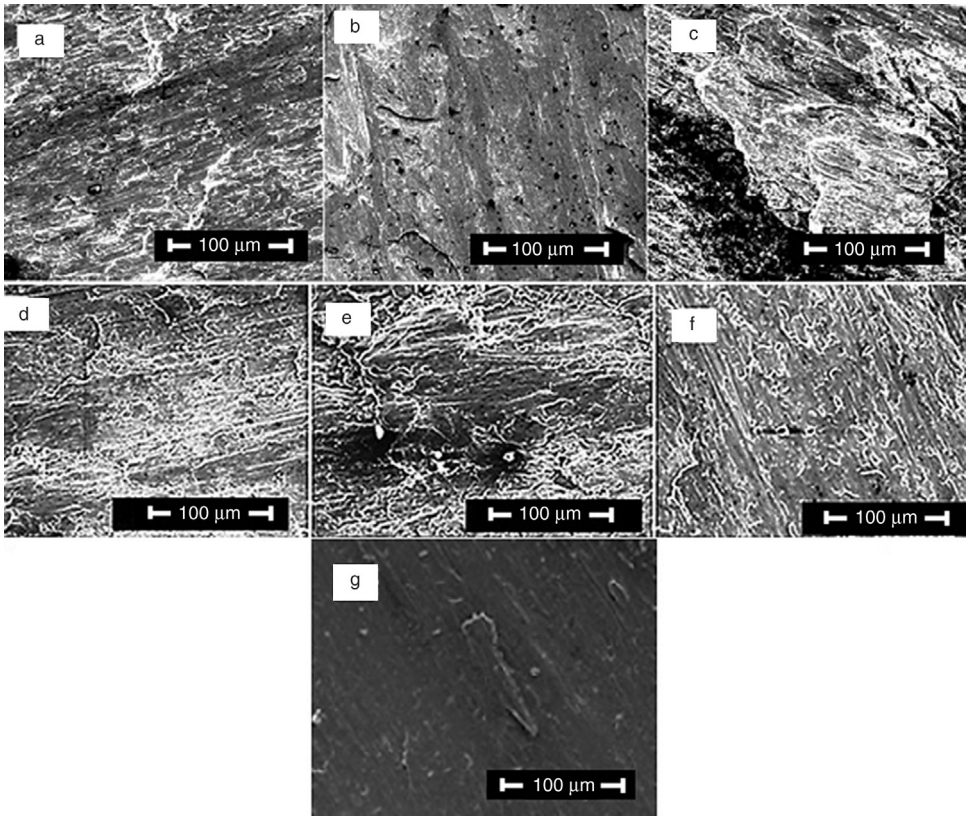

Fig. 8 – Worn morphology of the surface hybrid composites: (a) Al–SiC/Gr at 900 rpm, (b) Al–SiC/Gr at 1120 rpm, (c) Al–SiC/Gr at 1400 rpm, (d) Al–SiC/Al_2O_3 at 900 rpm, (e) Al–SiC/Al_2O_3 at 1120 rpm, (f) Al–SiC/Al_2O_3 at 1400 rpm and (g) as-received aluminum alloy.

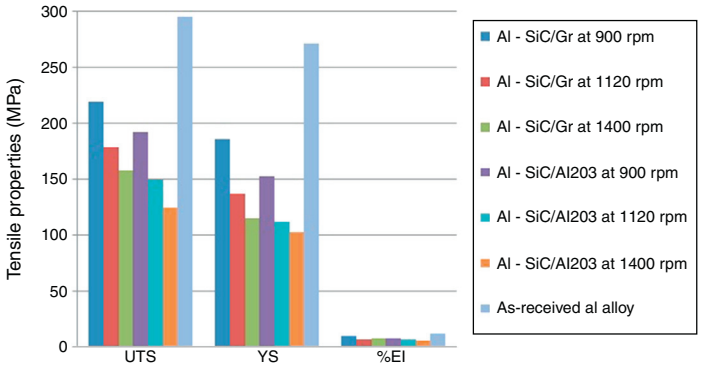

Fig. 9 – Comparison of tensile properties of aluminum alloy surface composites.

during wear test. It was observed that the worn debris formation was more at the Al–SiC/Al_2O_3 surface hybrid composites and less at the Al–SiC/Gr surface hybrid composites. In other words, the presence of hard pulled out SiC and Al_2O_3 particles formed on the steel disk acts as a barrier and further it converts the adhesive wear mode into abrasive mode.

3.4. *Effect of rotational speed on tensile properties*

The tensile properties such as UTS, YS and %EL of all Al–SiC/Gr at 900 rpm, Al–SiC/Gr at 1120 rpm, Al–SiC/Gr at 1400 rpm, Al–SiC/Al_2O_3 at 900 rpm, Al–SiC/Al_2O_3 at 1120 rpm, Al–SiC/Al_2O_3 at 1400 rpm surface hybrid composites and as-received Al alloy are presented in Table 3. Comparison of all the tensile properties is shown in Fig. 9. It was revealed that, as

Table 3 – Tensile properties of aluminum alloy surface composites.

Surface composite	UTS[a] (MPa)	YS[a] (MPa)	%EL[a]
Al–SiC/Gr at			
900 rpm	219	185	9.1
1120 rpm	178	137	6.4
1400 rpm	157	115	7.2
Al–SiC/Al_2O_3 at			
900 rpm	192	152	7.8
1120 rpm	149	112	5.9
1400 rpm	124	102	4.8
As-received alloy	295	271	12

[a] Average of three values.

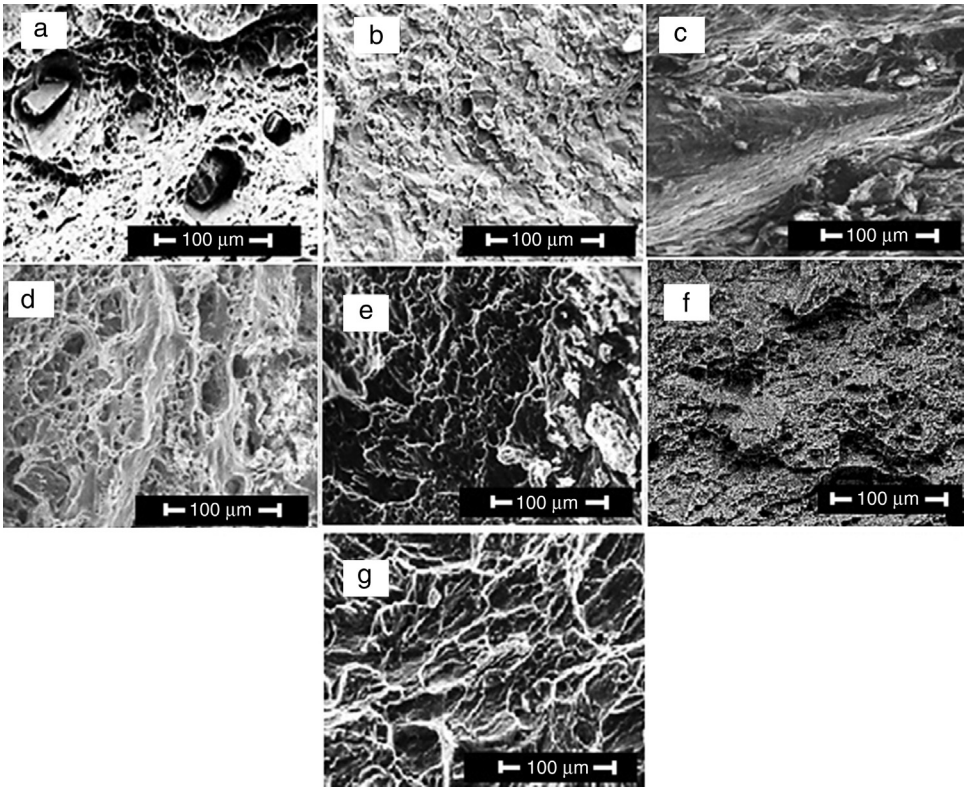

Fig. 10 – Fracture features of (a) Al–SiC/Gr at 900 rpm, (b) Al–SiC/Gr at 1120 rpm, (c) Al–SiC/Gr at 1400 rpm, (d) Al–SiC/Al_2O_3 at 900 rpm, (e) Al–SiC/Al_2O_3 at 1120 rpm, (f) Al–SiC/Al_2O_3 at 1400 rpm and (g) as-received aluminum alloy.

the rotational speed increases, the UTS, YS and %EL decreases. Moreover, as earlier mentioned, the heat input increases with increase of rotational speed [19,20] which resulted in matrix softening. Actually, the softening of the material would be expected to improve the %EL. However, contrary to this, the %EL in Table 3 decreases slightly as the rotational speed increases due to the loss in strength of the matrix.

The presence of reinforcement particles such as SiC, Gr and Al_2O_3 could restrict the grain boundary sliding and dislocation motion. Also, together with weak interfacial bond between the reinforcement particles and the matrix, finally leads to deterioration of the tensile properties [26,27]. In other words, composite has incompatible deformation between the plastically deformed matrix and the rigid reinforcement particles causing the generation of geometrically necessary dislocation. Besides, the presence of reinforcement particles increases the effective slip distance of dislocations during deformation, which leads to reduced elongation [28].

The SEM fractographs of Al–SiC/Gr at 900 rpm, Al–SiC/Gr at 1120 rpm, Al–SiC/Gr at 1400 rpm, Al–SiC/Al_2O_3 at 900 rpm, Al–SiC/Al_2O_3 at 1120 rpm, Al–SiC/Al_2O_3 at 1400 rpm surface hybrid composites and as-received Al alloy are shown in Fig. 10. The appearance of the as-received aluminum alloy fracture surface, which includes dimples and voids, demonstrates a ductile fracture (Fig. 10g). It is also observed the pulling out of reinforcement particles and small dimples in the fracture surface of the Al–SiC/Gr at 900 rpm, Al–SiC/Gr at 1120 rpm, Al–SiC/Gr at 1400 rpm, Al–SiC/Al_2O_3 at 900 rpm, Al–SiC/Al_2O_3 at 1120 rpm, Al–SiC/Al_2O_3 at 1400 rpm surface hybrid composites. These observations further confirms the mentioned reasons for low UTS, YS and %EL of all the surface composites.

4. Conclusions

The influence of tool rotational speed on wear and mechanical properties of aluminum alloy 6061-T6 surface hybrid composites fabricated via friction stir processing were investigated and the following conclusions were obtained.

Microhardness increases due to presence and pining effect of hard SiC and Al_2O_3 particles.

Low wear rate was exhibited in the Al–SiC/Gr surface hybrid composite due to mechanically mixed layer generated between the composite pin and steel disk surfaces which contained fractured SiC and Gr. The presence of SiC particles serves as load bearing elements and Gr particles acted as solid lubricant.

Tensile properties are decreased as compared to the base material due to the presence of reinforcement particles which make the matrix brittle.

Conflicts of Interest

The authors declare no conflicts of interest.

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