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Tribological characterization of eco-designed aluminium hybrid metal matrix composites

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In present experimental investigation, wear characteristics of Al 7075-T6/Eggshell/SiC/Al_2O_3 hybrid composites (Al 7075-T6 as base metal with eggshell particles wt. % 0.5, 1and 1.5, average particle size ~ 60 µm, SiC particles wt. % 1, 1.5 and 2, average particle size ~ 65 µm and Al_2O_3 particles wt. % 1.5, 2 and 2.5, average particle size ~90 µm) synthesized through electromagnetic stir casting route have been studied at various specimen temperatures under dry and lubricated test conditions. Wear investigations have been conducted on pin-on-disk rotary tribometer at a constant load of 20 N for a sliding speed of 2m/s and sliding distance of 2 km. Tribological attributes of synthesized composites have been evaluated as the function of reinforcements content and mechanical stirring time, as per the design of experiment according to Taguchi L9 orthogonal array. Experimental study has shown that at 30 °C pin temperature under dry wear condition, among the developed hybrid composites, specimen S8 demonstrated a maximum relative decrease of 60% in wear loss while with lubrication the wear loss has been relatively decreased by 89% as compared to the base metal (specimen S0). At elevated pin temperature of 70 °C under dry wear condition, the hybrid composite specimen S8 exhibited maximum relative reduction of 82% in wear loss whereas under lubricated condition the wear loss has been relatively reduced by 82% in comparison of their unreinforced counterpart (specimen S0). With exceedingly augmented tribological attributes, the current study strongly rationalizes high temperature wear resistant applications of synthesized aluminium hybrid composites with a total reinforcement weight percentage of 4.5% only (specimen S8).

Key words: Stir casting, Hybrid composites, Reinforcements, Wear properties, Friction

1 Introduction

Aluminium composites with their remarkable attributes are superseding the conventional materials in advanced engineering applications. Uvaraja *et al.*[1] studied that characteristics of aluminium composites can be modified by altering base metal, types of reinforcement, reinforcement content and synthesis method. Particulate reinforced composites are preferred over continuous fibre reinforced or laminate composites due to their isotropic structure and capability to undergo various secondary forming operations. In general, bare aluminium alloys are not considered as much acclaimed materials for high performance wear resistant applications because of lower hardness. However, hard particulate reinforcements infused into aluminium alloys produce composites with enhance wear resistance by restricting the plastic deformations, hence, advocating their application in automobile and aerospace sectors. Metal matrix AlSi18CuNi mixed with Al_2O_3 particles through stir casting shows improved wear resistance as observed by Baradeswaran *et al.*[2].

Devaraju *et al.*[3] analyzed that aluminium composites synthesized by infusing Boron carbide particles into Al 7075 have enhanced wear resistance as compared to the base metal.

Schultz *et al.*[4] investigated that Al2219 / MoS_2 composites prepared through liquid metallurgy route display decreased ductility and increased wear resistance. Silicon carbide mixed with Al 6061 alloy shows improved tensile strength and wear resistance in comparison of the base metal matrix as per Moona *et al.*[5]. Experimental investigations conducted by Bharath *et al.*[6] and Uthayakumar *et al.* [7] demonstrated that Al 6061/ Al_2O_3 and Al2124/SiC composites synthesized through stir casting demonstrate increased hardness and enhanced wear properties. It was notice by Panneerselvam *et al.* [8] that composites fabricated by mixing Al_2O_3 with A6082 through friction stir casting exhibit increased wear

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resistance. It has been observed by many material science researchers (Sangeethkumar *et al.*[9] and Shafiei *et al.*[10]) that aluminium as a base metal infused with single reinforcement shows improved mechanical and physical properties in comparison of the base metal but at the cost of other essential characteristics desired to avert premature failure of different engineering components undergoing mechanical stresses. To overcome this issue, development of aluminium hybrid composites as reliable and modifiable materials has been endorsed to fulfill desired design conceptions. Depending upon type and size of reinforcements and their chemical compatibilities with base metal, aluminium metal matrix composites can be synthesized by many different techniques such stir casting, diffusion bonding, powder blending and consolidation, powder metallurgy, physical vapour diffusion, low pressure plasma deposition, liquid infiltration, squeeze casting and compocasting etc. as per Mahadevan *et al.*[11]. Additionally, these materials should be developed on the basis of new standards for designing environmental friendly composite products as discussed by Franck[12]. It was observed by Wang *et al.*[13] that recycled waste materials could be used as reinforcements to substitute synthetic fibers, such as glass fibers. The current study was conducted to synthesize Al 7075-T6/ eggshell/ SiC/ Al_2O_3 hybrid composites through electromagnetic stir casting route. In order to avoid non uniform dispersion and inferior interfacial bonding of reinforcement particles during stir casting, a three phase motor with alternating current was used as electromagnetic stirrer. Nine aluminium hybrid composite castings were prepared as per the design of experiment and were investigated extensively for their enhanced tribological attributes in comparison to the unreinforced base metal (as-cast Al7075-T6), posing them as cost effective alternatives for wider spectrum of light weight wear resistant applications.

2 Experimental Details

2.1 Base metal and reinforcements

Aluminium 7XXX series alloy Al 7075-T6 acquiring superior physical properties with elemental composition given in Table 1 as per Kucharikova *et al.* [14] was used as metal matrix for this experiment.

Three particulate reinforcements, including one natural reinforcement in form of eggshell powder were infused into the base metal in order to prepare environmental friendly cost effective hybrid composites. Particulars of reinforcements are given in Table 2.

2.2 Experimental set-up

In current investigation, synthesis of aluminium hybrid metal matrix composites was conducted by combining conventional mechanical stir casting system with an electromagnetic stirrer as shown in Fig. 1. Mechanical stirrer of traditional stir casting setup rotating at 150 rpm exerted centrifugal force on particulate reinforcements during mixing in molten metal, hence repelling them away and resulting into agglomeration and non uniform distribution of particles into metal melt. Electromagnetic stirrer in form of an electric motor (10 hp, three phase, rotating at 960 rpm) with the help of alternating current was rotated due to electromagnetic force developed by moving electromagnetic field of coil, applying rotational force on particle reinforcements causing their uniform dispersion into metal matrix.

2.3 Composite synthesis and sample preparation

Present experimental study involved synthesis of nine aluminium hybrid composites as shown in Table 3 with Al 7075-T6 as base metal and variable content of three particle reinforcements along with variable mechanical stirring times. Hybrid composites were developed in accordance with L9 orthogonal array as per Taguchi optimization technique, assuming that there was no cross talk between any two control factors as given in Table 4. Weighed and cleaned ingot of Al 7075-T6 was melted upto 900 °C in electric furnace. To obtain improved wettability

Table 2 — Reinforcement particulars

Particulate reinforcement	Mean particle size (µm)
Egg Shell Powder (Cleaned and sun dried hen eggshells, ball milled at 200 rpm, with ball to powder ratio 5:1 and carburized in muffle furnace at 500 °C for 2 hours)	60
Silicon Carbide Powder	65
Aluminium Oxide Powder	90

Table 1 — Al 7075-T6 elemental composition by weight percentage

Elements	Al	Mg	Cu	Cr	Fe	Mn	Si	Ti	Zn	Others
Content (Weight %)	87-91	2.1-2.9	1.2-2	0.18-0.28	>0.5	>0.3	>0.4	>0.2	6	Balance

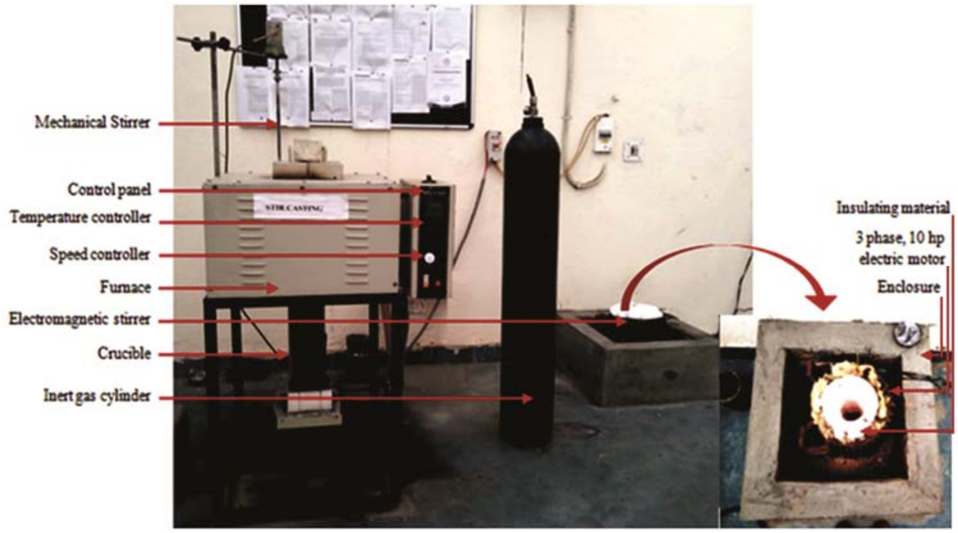

Fig. 1 — Stir casting setup with electromagnetic stirrer.

Table 3 — Design of experiment as per L9 orthogonal array

Aluminium hybrid composite specimen number	Reinforcements			Mechanical stirring time (minutes)
	Eggshell particles Weight %	Silicon Carbide particles Weight %	Aluminium Oxide particles Weight %	
S1	0.5	1	1.5	2
S2	0.5	1.5	2	4
S3	0.5	2	2.5	6
S4	1	1	2	6
S5	1	1.5	2.5	2
S6	1	2	1.5	4
S7	1.5	1	2.5	4
S8	1.5	1.5	1.5	6
S9	1.5	2	2	2
S0	As-cast Al 7075-T6			
Mechanical stirring speed	150 rpm			
Stirring temperature	850°C			
Reinforcement preheat temperature	500 ° C			
Electromagnetic stirring speed	960 rpm			
Electromagnetic stirring time	0.5 minutes			

and remove gases from reinforcement surfaces, calculated and weighed amounts of reinforcements were preheated in a muffle furnace at 500 °C for 1 hour. The temperature of molten metal was reduced and reinforcements were mixed into steps. Mechanical stirrer of conventional stir casting setup rotating at 150 rpm was also preheated to avoid any temperature drop during infusion of reinforcements into base metal. Molten mixture was mechanically stirred for variable time durations as per the design of experiment, further the graphite crucible containing molten mixture was place on electromagnetic stirrer (3 phase, 10 hp electric motor rotating at 960 rpm) for next 30 seconds in inert atmosphere. Composite castings were allowed to solidify in the crucible itself. After solidification, ten standard wear test specimens (one as-cast Al 7075-T6 and nine Al 7075-T6/ Eggshell/ SiC/ Al_2O_3 hybrid composites, in three replications) were prepared as per ASTM G99-17 to be tested for tribological characteristics against an EN 31 rotating disk as shown in Fig. 2 on a pin-on-disk rotary tribometer (Ducom, Atlas; TR-20L-PHM 800-DHM 850) as shown in Fig. 3.

3 Observations and Discussion

To investigate wear characteristics of aluminium hybrid composites on pin-on-disk rotary tribometer as shown in Fig. 4, each pin specimen of length 50 mm, diameter 10 mm with polished hemispherical tip of diameter 10 mm was slid over EN 31 disk (HRC 62) of diameter 100 mm and thickness 8 mm with a wear track diameter of 50 mm. A constant normal load of 20 N was applied on specimens with fixed sliding speed of 2 m/s and sliding distance of 2 km. All specimens (one as-cast Al7075-T6 and nine Al 7075-T6/ egg shell/ SiC/ Al_2O_3 hybrid composites, in three replications) were first tested at pin temperature 30 °C under dry wear and lubricated condition (using SAE10W30 as lubricant) for wear, coefficient of friction and frictional force. A comparison of wear

Table 4 — Various control parameters with levels

Control parameters	Parameter nominations	Level I	Level II	Level III
Eggshell particles weight %	A	0.5	1	1.5
Silicon carbide particles weight %	B	1	1.5	2
Aluminium oxide particles weight %	C	1.5	2	2.5
Mechanical Stirring time (minutes)	D	2	4	6

Fig. 2 — Standard wear specimens as per ASTM G99-17 and EN 31 disk

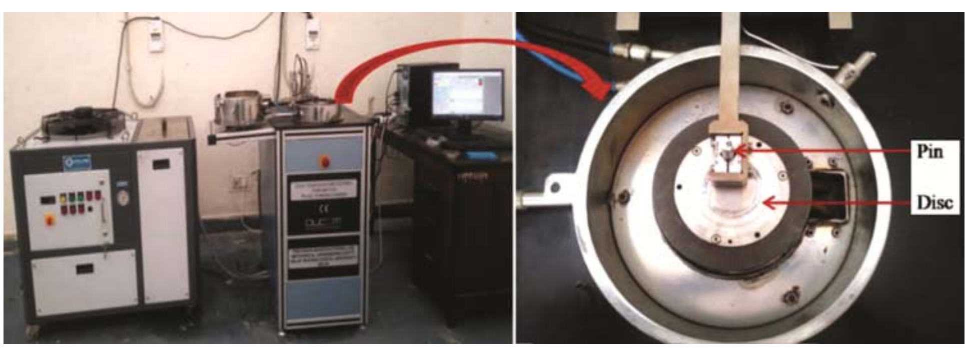

Fig. 3 — Pin- on-disk tribometer for tribological characterizations

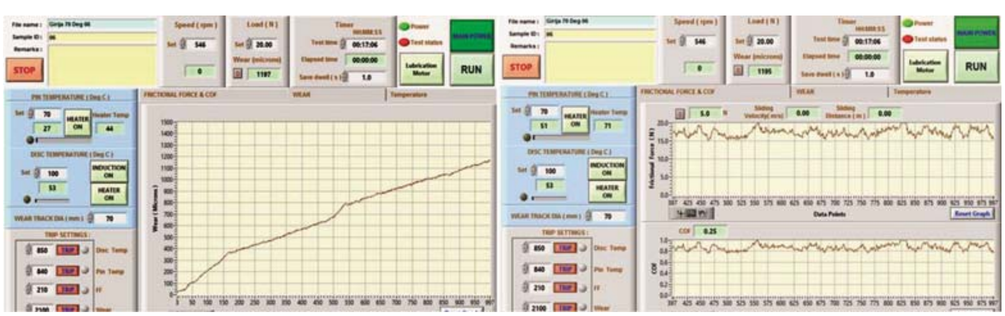

Fig. 4 — Wear parameters display on pin-on-disk rotary tribometer

loss in as-cast Al7075-T6 specimen and hybrid composite specimens under both the experimental conditions are shown in Fig. 5 and Fig. 6, coefficients of friction are shown in Fig. 7 and Fig. 8 and frictional forces are shown in Fig. 9 and Fig. 10. It was realized that, the wear loss of synthesized aluminium hybrid composites is significantly reduced as compared to the unreinforced base alloy. In dry wear condition, on running the wear test for 1000 seconds, as-cast Al 7075-T6 specimen S0 with coefficient of friction 0.83 and frictional force 17.4 N showed highest wear loss of 1295 microns whereas hybrid composite specimen S8 with coefficient of friction 0.5 and frictional force 10N displayed lowest wear loss of 515 microns only. Under the influence of lubricant, as-cast specimen S0 with coefficient of friction 0.13 and frictional force 2.67N demonstrated highest wear loss of 36 microns while the hybrid composite specimen S8 with coefficient of friction 0.04 and frictional force 0.82N was worn out only by 4 microns. At an elevated pin temperature of 70 °C, wear properties of all the specimens are shown in Fig. (11-16). At 70 °C, in dry wear test condition the as-cast Al7075-T6 specimen S0 with coefficient of friction 0.84 and frictional force 17.2 N showed highest wear loss of 1999 microns. The aluminium hybrid composite specimen S8 with coefficient of friction 0.25 and frictional force 4.9 N exhibited lowest wear loss of 354 microns only. Under lubricated wear condition, as-cast specimen S0 with coefficient of friction 0.2 and frictional force 3.92 N displayed highest wear loss of 44 microns while hybrid composite specimen S8 with coefficient of friction 0.03 and frictional force 0.48 N was worn out by only 8 microns.

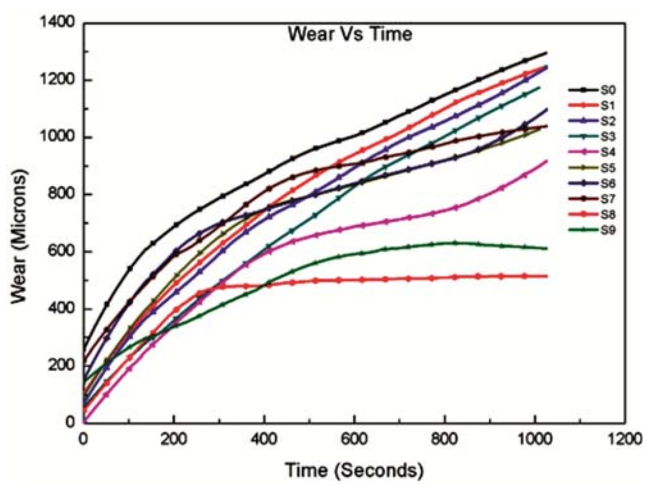

Fig. 5 — Wear of specimens at 30 °C pin temperature during dry wear condition

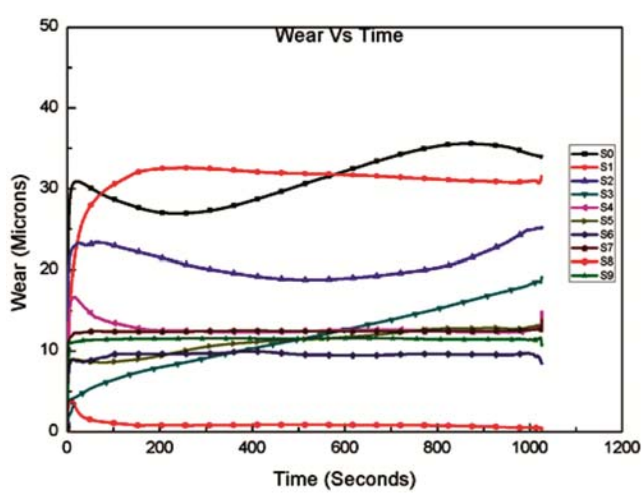

Fig. 6 — Wear of specimens at 30 °C pin temperature with lubrication

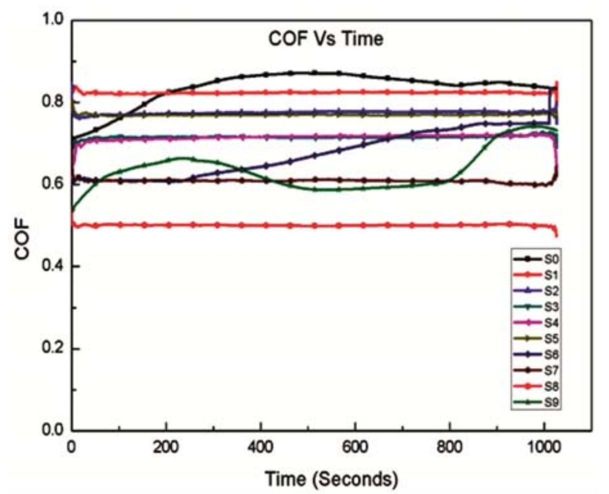

Fig. 7 — Coefficient of friction of specimens at 30 °C pin temperature during dry wear condition

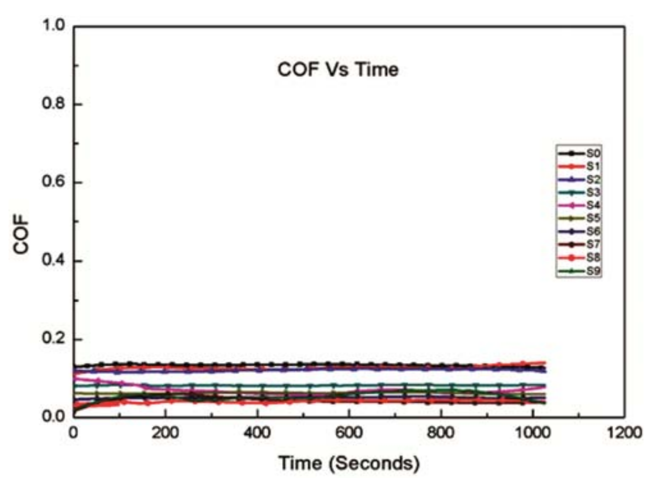

Fig. 8 — Coefficient of friction of specimens at 30 °C pin temperature with lubrication

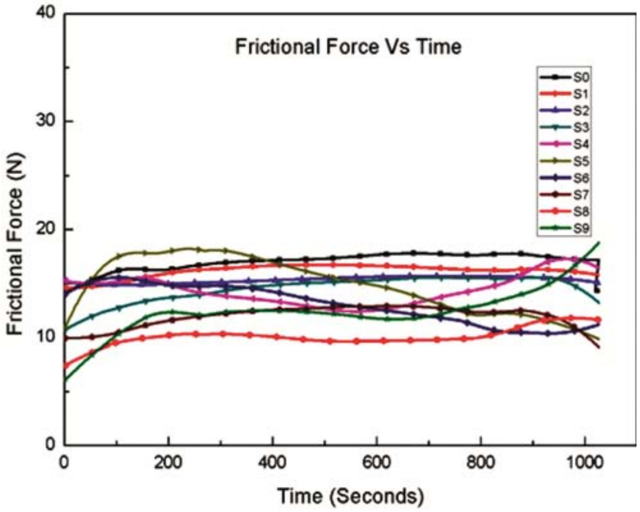

Fig. 9 — Frictional force of composite specimens at 30 °C pin temperature during dry wear condition

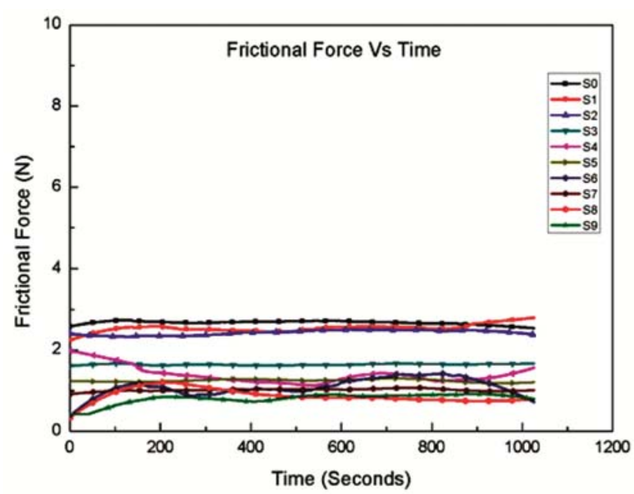

Fig. 10 — Frictional force of composite specimens at 30 °C pin temperature with lubrication

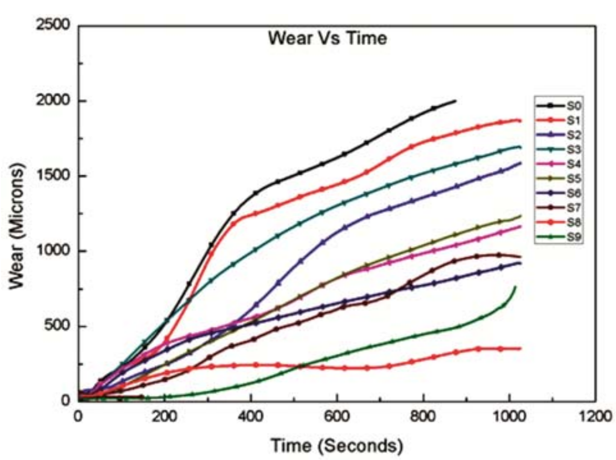

Fig. 11 — Wear of specimens at 70 °C pin temperature during dry wear condition

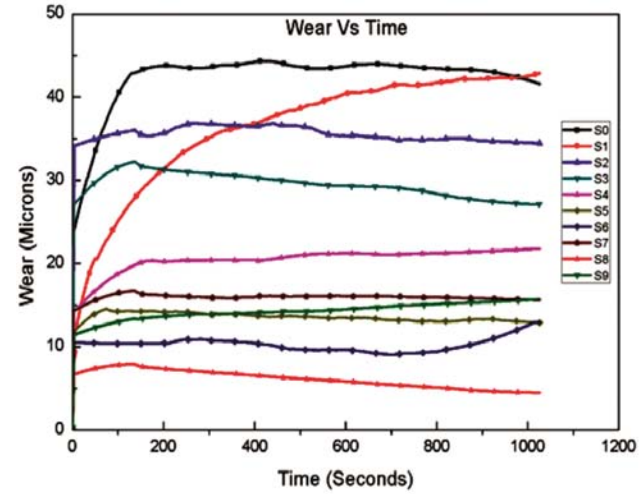

Fig. 12 — Wear of specimens at 70 °C pin temperature with lubrication

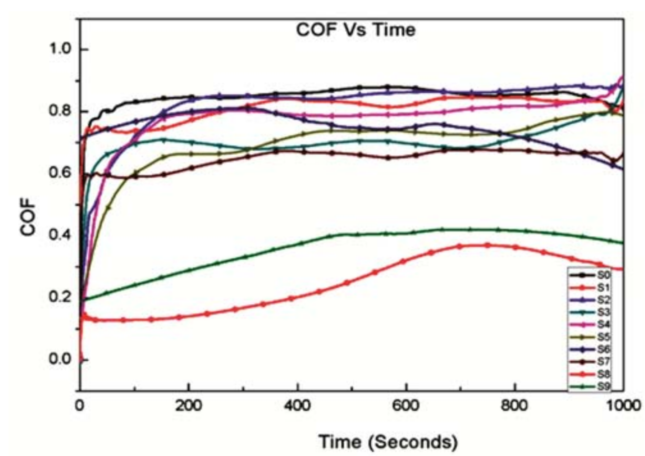

Fig. 13 — Coefficient of friction of specimens at 70 °C pin temperature during dry wear condition

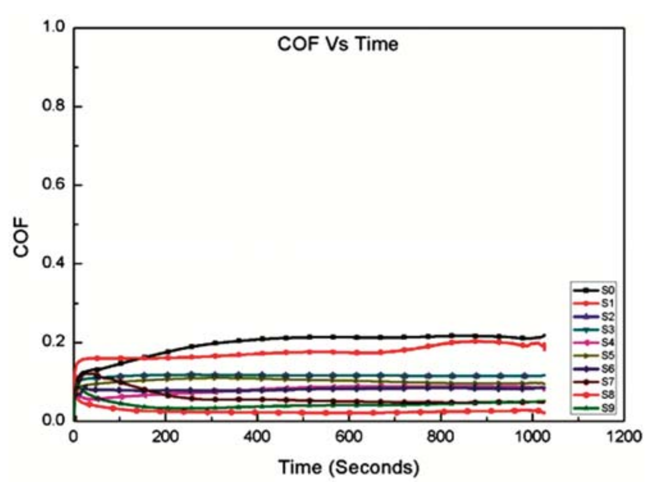

Fig. 14 — Coefficient of friction of specimens at 70 °C pin temperature with lubrication

As per Archard's law, the enhancement in tribological properties of synthesized aluminium hybrid composites as compared to their unreinforced counterpart may be attributed to the hardness of infused reinforcements providing secondary harder phases into metal matrix. At 30 °C specimen temperature, the strong interfacial bonding between hard filler and base metal played significant role in deporting applied load before the base material asperities got fractured, restricting surface delamination and plastic deformations. This maintains structural integrity of metal matrix composites leading towards improved wear properties, as observed by Prasad[15]. The microstructures of As-cast Al 7075-T6 specimen and nine hybrid composite specimens are shown in Fig. 17. Reduction in coefficient of friction of composites at 30 °C pin temperature as demonstrated in Fig. 7 was observed due to uniformly distributed filler particles (shown in microstructure of composites in Fig. 17), diminishing the contact between specimens and rotating disk. In presence of lubricant oil, the developed hybrid composite specimens at 30 °C exhibited superior wear characteristics because the thin lubricant film formed between specimen and disk reduced material loss due to relative movement. This film possibly accommodated clusters of reinforcement particles, which were ruptured into smaller particles and these particles realigned themselves along the sliding plane hence lowering the wear loss and coefficient of friction, as investigated by Moona *et al.*[16] (as shown in Fig. 6 and Fig. 8). On increasing the specimen pin

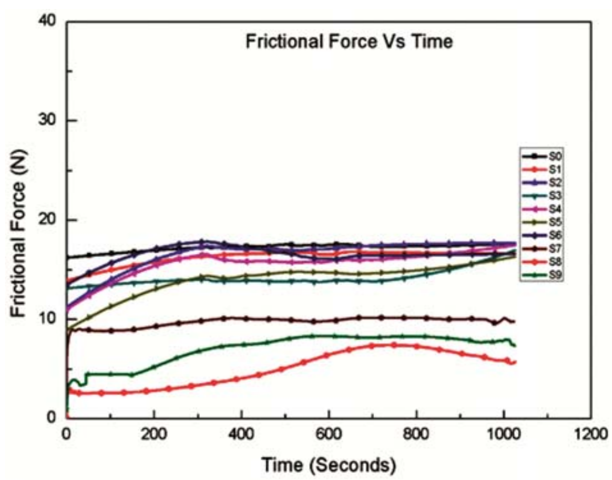

Fig. 15 — Frictional force of specimens at 70 °C pin temperature during dry wear condition

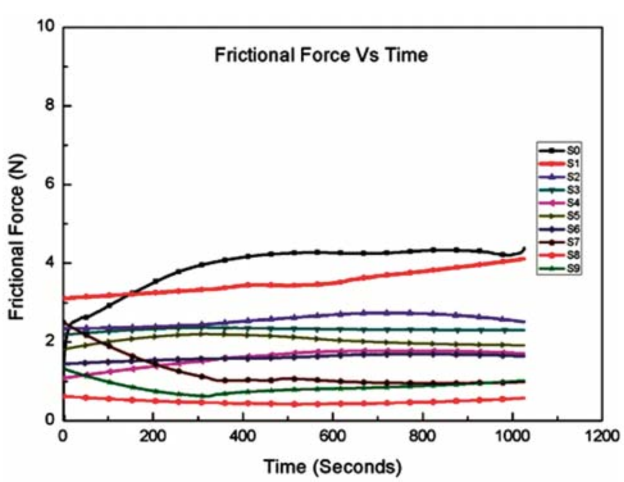

Fig. 16 — Frictional force of specimens at 70 °C pin temperature with lubrication

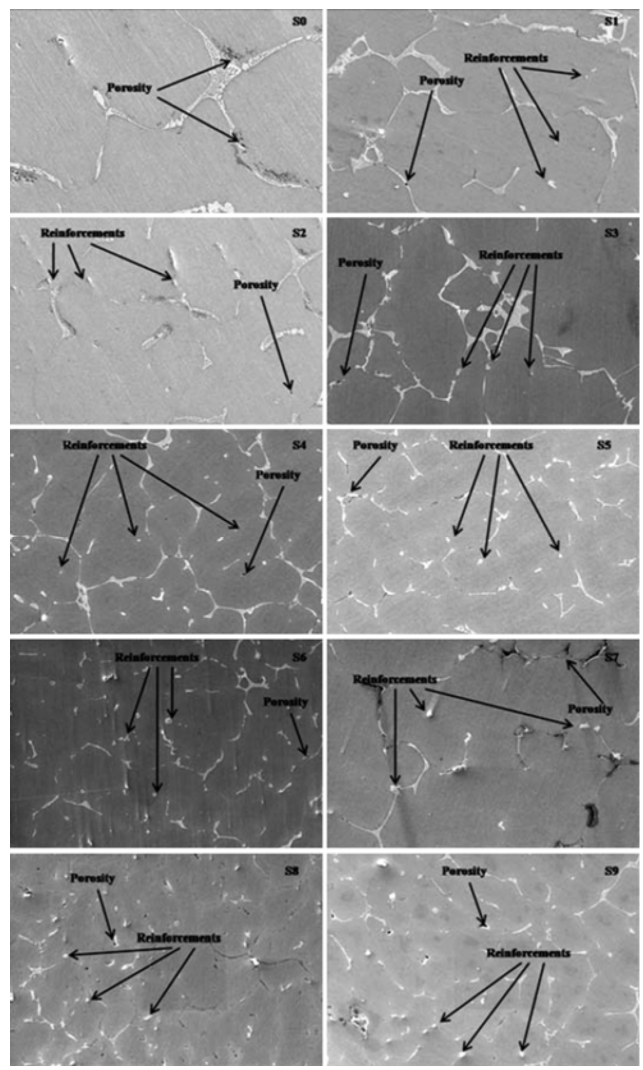

Fig. 17 — Microstructure of As-cast Al7075-T6 specimen S0 and hybrid composite specimens (S1-S9)

temperature, it was observed by Moona *et al.* [17] that the constituent material was transformed into softer one, leading towards increased material loss on rubbing against the rotating disk. At elevated pin temperatures, more frictional heating occurred between the contact surfaces due to less heat depletion and resulted into higher coefficients of friction and more wear, as observed by Sahin *et al.* [18] (Fig. 11 and Fig. 13). As-cast Al7075-T6 specimen S0 and composite specimen S8 (exhibiting most superior wear characteristics among all the developed hybrid composites) were further compared for tribological characteristics at higher pin temperatures of 150 °C and 250 °C under dry wear conditions as shown in Fig. (18-23). At 150 ℃ specimen temperature, the as-cast Al7075-T6 specimen S0 with coefficient of friction 0.72 and frictional force 14.4 N displayed maximum wear of 1693 microns whereas the composite specimen S8 with coefficient of friction 0.33 and frictional force 6.6 N showed maximum wear loss of 117 microns only. At 250 °C pin temperature, the as-cast Al7075-T6 specimen S0 with coefficient of friction 0.7 and frictional force 15.5 was worn out by 1760 microns and the composite specimen S8 with coefficient of friction 0.42 and frictional force 10.8 was worn out by mere 527 microns. It was ascertained from above tribological investigations, that the energy transformed due to frictional contact of specimen and rotating disk may be exhausted in terms of heat generation, vibrations and material deformation or may be stored in the wear system. This asymmetric segregation of energy between the specimen and disk material and within the specimen material may be attributed to the fact that specimen materials with same coefficients of friction could demonstrate

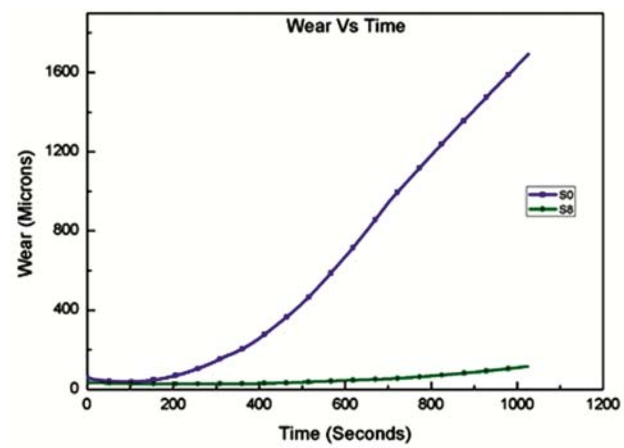

Fig. 18 — Wear of specimens at 150 ℃ pin temperature in dry wear condition

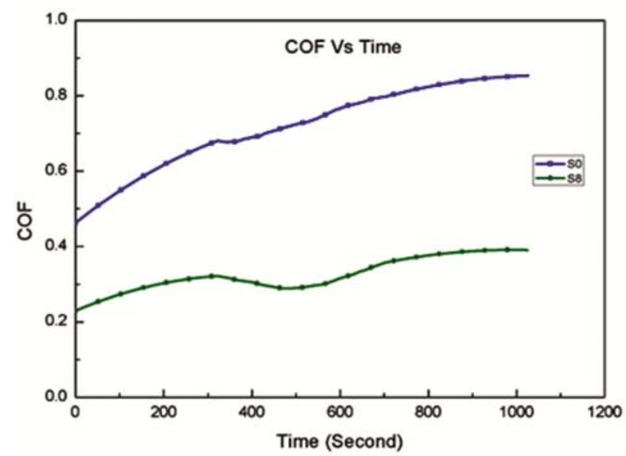

Fig. 20 — Coefficient of friction of specimens at 150 °C pin temperature in dry wear condition

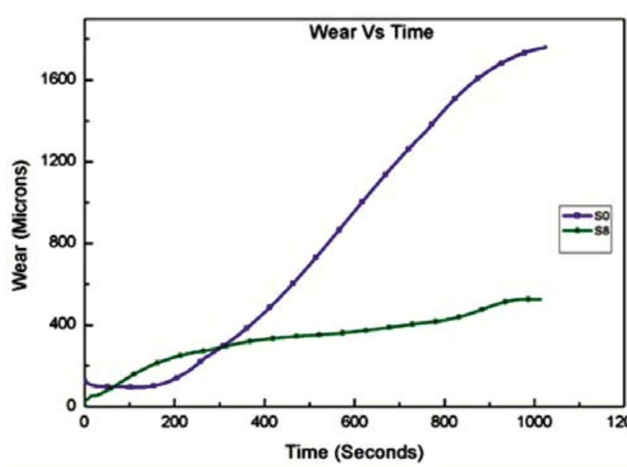

Fig. 19 — Wear of specimens at 250 ℃ pin temperature in dry wear condition

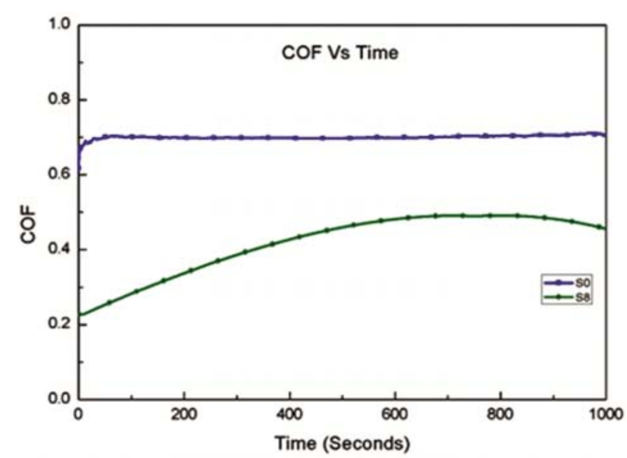

Fig. 21 — Coefficient of friction of specimens at 250 °C pin temperature in dry wear condition

different wear losses, as observed by Abeens *et al.*[19]. The specific wear energy (ratio of the friction work utilized at the materials interface and the mass loss due to the wear) can be expressed by equation given below:

$$E_W = \frac{E}{\Delta m} = \frac{\gamma w \int_{t_i}^{t_f} \mu(t)dt}{\Delta m} \quad \ldots (1)$$

where,

γ= mean relative sliding velocity
w= Normal load
μ= coefficient of friction
t_i = time at starting of test
t_f= time at the end of test
Δm=total mass loss during wear

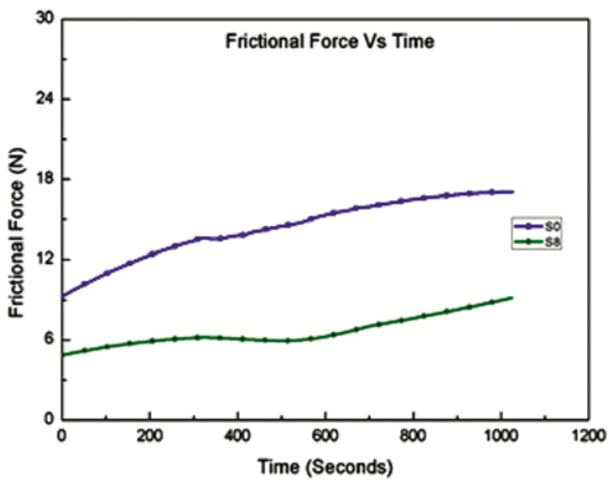

Fig. 22 — Frictional force of specimens at 150 °C pin temperature in dry wear condition

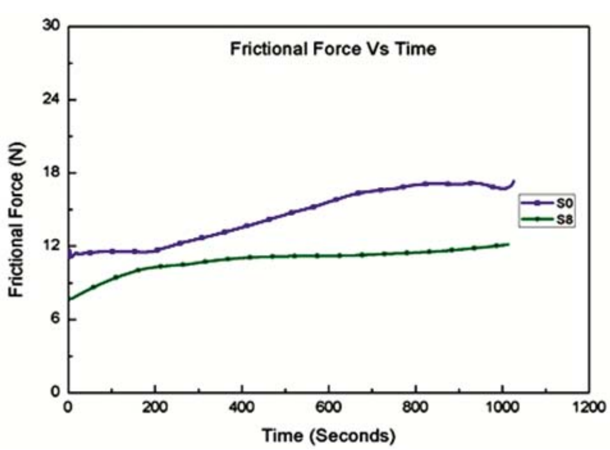

Fig. 23 — Frictional force of specimens at 250 °C pin temperature in dry wear condition

The optical micrographs of worn out surfaces using Field Emission Scanning Electron Microscope (Make: Zeiss; Model: Supra 40VP; Resolution: 1 nm; Magnification range: 12X - 900,000X; Acceleration voltage: Max. 30 kV with SmartSEM software) are shown in Fig. 24. FESEM images of worn surface of as-cast Al7075-T6 specimen S0 appeared to be rough and corrugated with deeper voids and adhesive grooves as compared to the aluminium hybrid composite worn surfaces. Hybrid composite specimens demonstrated improved wear resistance because uniformly distributed hard reinforcement particles in synthesized composites increased their strength, hardness, thermal stability, load bearing capacity and resisted penetration. In micrographs of worn out composite specimens, severe wear marks on friction surfaces substantiate higher hardness of

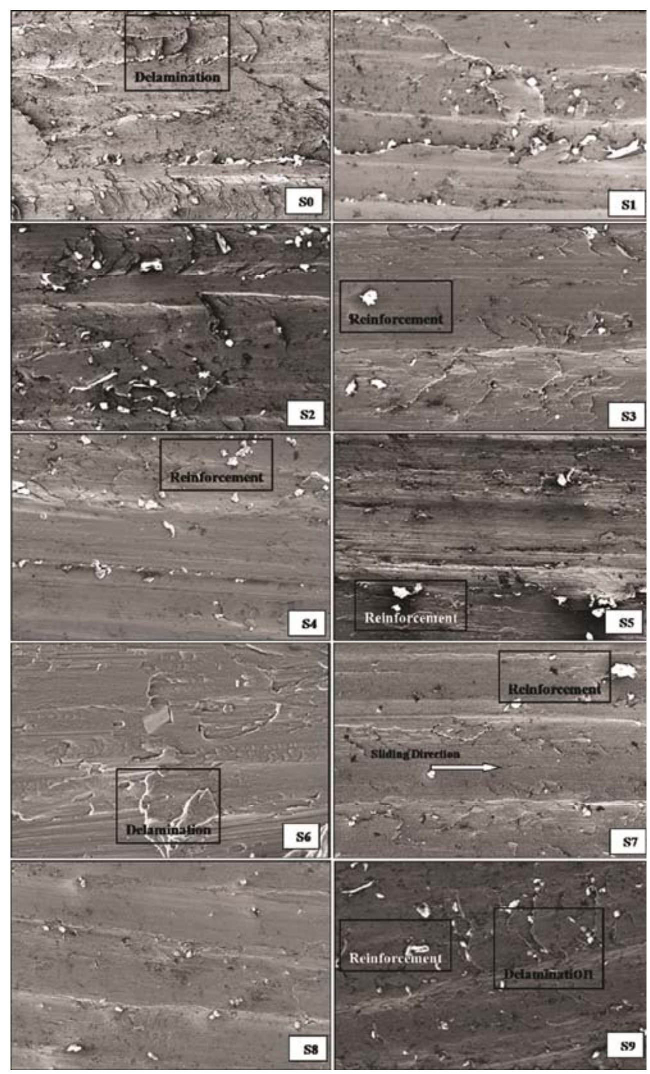

Fig. 24 — FESEM micrographs of worn out specimens

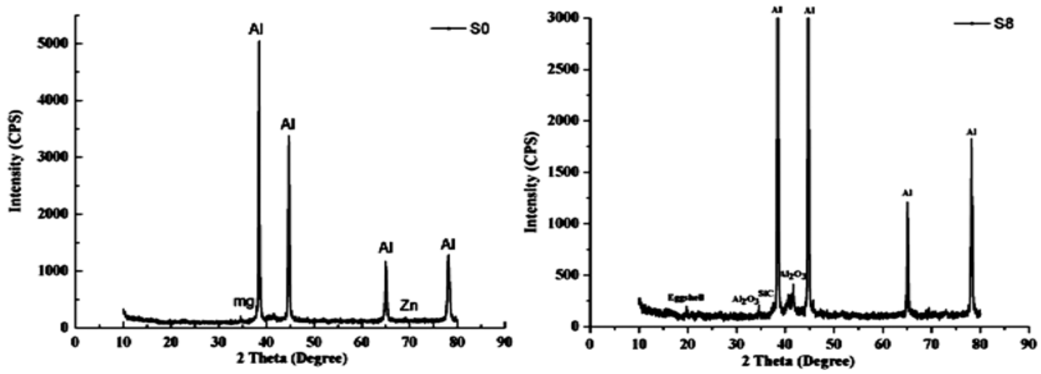

Fig. 25 — XRD Spectra of worn out As-cast Al 7075-T6 specimen S0 and Hybrid composite specimen S8

reinforcement particles as compared to the disk material EN31. Sometimes harder asperities penetrated the specimen surfaces and deep trenches occurred there, as in SEM images of specimen S2, S5 and S9. SEM micrographs of investigated specimens also displayed elongated craters laid parallel to sliding direction along with micro-ploughing marks, delamination and flaky wear sediments on wear surfaces indicating both adhesive and abrasive wear mechanisms. On further analysing the morphological images, worn surface of aluminium hybrid composite specimen S8 was realized to be homogeneous and covered with smaller wear debris in comparison of other specimens. Smoothest appearance of wear surface of hybrid composite specimen S8 can be attributed to the presence of oxide particles tribolayer formed between pin specimens and rotating disk, restricting metal-to-metal contact and chemical interactions with the counterface hence reducing coefficient of friction and wear loss. Traces of oxide particles in form of aluminium oxide in worn out composite specimen S8 are shown in XRD spectrogram displaying peculiar peaks at 35.41° and 44.25° in Fig. 25. On increasing specimen temperature, the occurrence of propagating cracks along weak regions of investigated wear surfaces may be attributed to thickening of the oxide layer and making it brittle. This fragile oxide layer exacerbated gluing of specimen material lumps on rotating disk causing vigorous pull-out of reinforcement particles in form of fragmented and agglomerated powder from metal matrix due to weak bonding strength at higher specimen temperatures. When pin temperature was increased, the softer base metal surrounding reinforcement particles started getting fractured and the particle reinforcements near the contact surface started surrendering their load bearing capacity causing increased wear loss. In synthesized hybrid composite at higher specimen temperatures, the reinforcement particles constrained the crack nucleation on reinforcement-metal interface. Also due to comparable thermal coefficients of expansion of all three reinforcements and base metal, the residual stresses in composites were reduced while exposing them to thermal fluctuations during wear investigations, hence posing them as thermally stable and high temperature deformation resistant materials.

4 Conclusions

In this experimental investigation, nine cost effective and environmental friendly Al 7075-T6/ Eggshell/SiC/Al_2O_3 hybrid composites with enhanced wear characteristics were synthesized through electromagnetic stir casting. Among all the hybrid composite specimens, specimen S8 represented outstanding tribological behaviour. Following conclusions were drawn from current experimental study:

(i) During wear tests conducted at 30 °C specimen temperature under dry wear conditions the hybrid composite specimen S8 displayed maximum decrease of 60% in wear loss, decrease of 40 % in coefficient of friction and decrease of 42% in frictional force as compared to unreinforced as-cast Al7075-T6 specimen S0.

(ii) On using synthetic oil (SEA10W30) as lubricant at 30 °C pin temperature, the hybrid composite specimen S8 demonstrated maximum decrease of 89% in wear loss, decrease of 69% in coefficient of friction and decrease of 69% in frictional force with respect to base metal as-cast specimen S0.

(iii) At higher specimen temperature of 70 °C under dry wear condition, for hybrid composite specimen S8 a maximum reduction of 82% in wear loss, reduction of 70% in coefficient of friction and reduction of 71%

in frictional force was observed in comparison of its unreinforced counterpart specimen S0.

(iv) With lubrication at specimen temperature 70 °C, synthesized hybrid composite specimen S8 exhibited a maximum abatement of 82% in wear loss, abatement of 85% in coefficient of friction and decrease of 85% in frictional force as compared to as-cast Al7075-T6 specimen S0.

(v) Further on elevating the specimen temperature upto 150 °C, hybrid composite specimen S8 represented 93% reduction in wear rate, 54% reduction in coefficient of friction and 54% reduction in frictional force relative to specimen S0.

(vi) On conducting wear tests at specimen temperature of 250 °C synthesized hybrid composite specimen S8 affirmed a reduction of 70% in wear, reduction of 40% in coefficient of friction and reduction of 42% in frictional force in comparison of specimen S8.

It was observed that by adding only a meagre reinforcement weight percentage of 4.5% (in specimen S8), the wear properties of synthesized hybrid composites were improved by many folds justifying them as reasonable alternatives for light weight and high temperature wear resistant applications.

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