Fabrication and tribological study of AA6061 hybrid metal matrix composites reinforced with SiC/B_4C nanoparticles

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Abstract

Purpose – Composite materials are replacing the traditional materials because of their remarkable properties and the addition of nanoparticles making a new trend in material world. The nano addition effect on tribological properties is essential to be used in automotive and industrial applications. The current work investigates the sliding wear behavior of an aluminum alloy (AA) 6061-based hybrid metal matrix composites (HMMCs) reinforced with SiC and B_4C ceramic nanoparticles.

Design/methodology/approach – The hybrid composites are fabricated using stir casting process. Two different compositions were fabricated by varying the weight percentage of the ceramic reinforcements. An attempt has been made to study the wear and friction behavior of the composites using pin-on-disc tribometer to consider the effects of sliding speed, sliding distance and the normal load applied.

Findings – The tribological tests are carried out and the performances were compared. Increase in sliding speed to 500 rpm resulted in the rise of temperature of the contacting tribo-surface which intensified the wear rate at 30N load for the HMMC. The presence of the ceramic particles further reduced the contact region of the mating surface thus reducing the coefficient of friction at higher sliding speeds. Oxidation, adhesion, and abrasion were identified to be the main wear mechanisms which were further confirmed using energy dispersive spectroscopy and field emission scanning electron microscopy (FESEM) of the worn out samples.

Practical implications – The enhancement of wear properties is achieved because of the addition of the SiC and B_4C ceramic nanoparticles, in which these composites can be applied to automobile, aerospace and industrial products where the mating parts with less weight is required.

Originality/value – The influence of nanoparticles on the tribological performance is studied in detail comprising of two different ceramic particles which is almost new research. The sliding effect of hybrid composites with nano materials paves the way for using these materials in engineering and domestic applications.

Keywords Dry sliding wear, SEM/EDX analysis, Tribological behavior, Hybrid aluminium metal matrix composites

Paper type Research paper

1. Introduction

Aluminum-based hybrid metal matrix composites (AlHMMCs) have developed as a significant material for thermal, wear and structural applications over the past decade. These materials have found extensive application in the field of automobile and aerospace owing to superior properties like improved specific strength and modulus, exceptional low-temperature performance, low density, chemical inertness and good strength to weight ratio (Gava *et al.*, 2013). These materials are exposed to sliding movements in certain applications like cylinder liners, inlet and exhaust valve, piston, control rods, brake drums, transmission shafts resulting in wear which is the most prevailing problem in industries and thus reduces the lifespan of the components. Researchers have started investigating different grades of aluminum alloys (AA) such as 2,000, 5,000, 6,000 and 7,000 series reinforced with Al_2O_3, SiC, TiN, B_4C, MgO, ZrO_2, $MoSi_2$ (Dou *et al.*, 2014; Uzun *et al.*, 2017), etc. ceramic particles for

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better wear resistant applications. AA6061 have been used in various applications as the matrix material because of its good strength, workability and machinability (Dou *et al.*, 2014) reinforced with micro ceramic particles. But, very few have investigated on hybrid composites with reinforcements in nano form. Nano reinforcements improve interaction at the interface because of large surface to volume ratio and leads to enhancement in the material properties of these metal matrix nano composites. SiC has low density and is the most widely used ceramic reinforcements for aluminum based composites because of their greater hardness, thermal and chemical stabilities (Shivamurthy and Surappa, 2011). B_4C used as a ceramic reinforcement, had an improved interfacial bonding with aluminum than that of Al_2O_3 and SiC which leads to providing high-wear resistance (Lashgari *et al.*, 2010). Also, B_4C has an excellent neutron absorbing properties which assists the aluminum-based composites to be used as a more potential material for nuclear industry applications (Kalaiselvan *et al.*, 2011).

Rao and Das (2011) studied the result of SiC ceramic particle content and sliding speed on the wear rate (WR) of aluminum-based MMCs. They concluded that SiC content helped in decreasing the WR and temperature of these composites. Abdollahi *et al.* (2014) studied the tribological behavior under dry condition of AA2024-5 Wt.% B_4C nano composites produced by hot extrusion and mechanical milling. Research findings revealed that adding of B_4C increases the strength, micro hardness and WR of AA2024 and lowered its ductility. Uthayakumar *et al.* (2013) carried out wear investigation of AA1100-SiC (5 per cent)-B_4C (5 per cent) hybrid composites at dry sliding conditions. Experimental findings showed that the hybrid composites were able to resist wear up to 60 N load and sliding speed ranges of 1-4 m/s. Soy *et al.* (2011) compared the tribological properties of single reinforced Al/B_4C, Al/SiC with hybrid reinforced Al/SiC/B_4C micro composites. Results indicate that the hybrid composites exhibit enhanced WR than single reinforced composites. Also, the coefficient of friction (CoF) was approximately 25-30 per cent lower than the unreinforced aluminum.

The current work aims to examine the wear behavior of AA6061 HMMCs reinforced with SiC/B_4C nanoparticles fabricated using conventional stir casting technique. The effects of the tribological process parameters like sliding speed, sliding distance and normal load on the prepared nano composites were investigated. The different wear mechanisms were identified and studied in this research.

2. Materials and procedures

2.1 Fabrication of the hybrid nanocomposites

HMMC comprising AA6061 as matrix material and SiC and B_4C ceramic particles of average particle size of 50 nm as reinforcements was prepared using conventional stir casting technique. The major alloying constituents of AA6061 used as matrix material in weight percentage are Mg (0.953), Si (0.541), Fe (0.223), Cu (0.174), Mn (0.132), Cr (0.091), Zn (0.083), Ti (0.012) and balance aluminum. Wear performance of MMC materials varies depending on the material properties of matrix and reinforced elements. SiC reinforcement increases the tensile strength, hardness, density and wear resistance of aluminum and its alloys (Ramnath *et al.*, 2013). B_4C possess good mechanical, thermal and wear properties in terms of high melting point (2450°C), high modulus (445 GPa), good hardness, wear, impact resistance, high chemical resistance and low density (2.51 g/cm^3) (Cambronero, 2009). Besides, because of high capacity for neutron absorption in isotope B_{10}, Al–B_4C composites have special applications in nuclear industries (Chen *et al.*, 2015). Hence, SiC and B_4C are considered as the reinforcing material for producing AA-based composites for possible structural applications in nuclear industries.

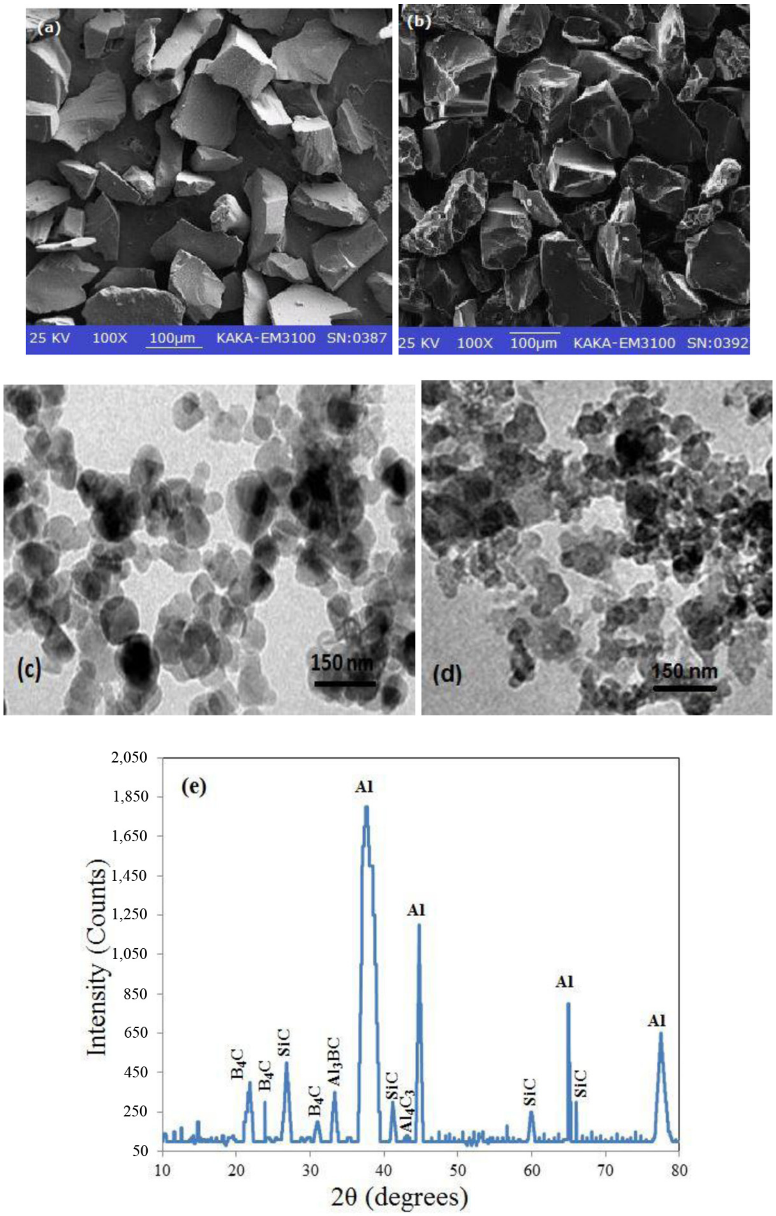
Researchers have studied the mechanical and tribological properties of AA based MMC and found that increasing the weight percentage of reinforcements leads to clustering, agglomeration and hinders uniform particle dispersion on the matrix (Padmavathi and Ramakrishnan, 2014). (Ge and Gu, 2010). It is reported that the weight percentage of nano reinforcements should be within 4 Wt.%. Thus, the composition of hybrid A was 0.5 Wt.% SiC + 1.5 Wt.% B_4C and for hybrid B was 1.5 Wt.% SiC + 1.5 Wt.% B_4C. Also, increase in the weight percentage of the ceramic particles leads to transition from ductile to brittle fracture. (Alizadeh *et al.*, 2011) compared the mechanical properties of AA-based composites reinforced with B_4C nanoparticles and found that increasing weight percentage of B_4C nanoparticles increases yield and tensile strength but elongation to fracture decreased. Hence, weight percentage of B_4C was not increased when SiC ratio in hybrid B was increased.

The SiC and B_4C ceramic reinforcements were fractured from large micron size particles using cost effective ball milling process. The field emission scanning electron microscopy (FESEM) of the ceramic particles used and XRD pattern of hybrid B before wear are shown in Figure 1. Two compositions of the composites viz. Hybrid A: AA6061 + 0.5 Wt.% SiC + 1.5 Wt.% B_4C and hybrid B: AA6061 + 1.5 Wt.% SiC + 1.5 Wt.% B_4C was prepared. The weighted pieces of AA6061 was placed in a crucible made of silicon carbide inside the electric furnace at a fixed temperature of 800°C to confirm full melting of the ingot. The measured quantity of reinforcements enveloped by aluminum foils was pre-heated to 250°C for 3 h to eliminate moisture, thermal mismatch and to enhance the distribution of the particles within the melt. The reinforcements was then added (at a constant rate) to the molten material in steps. A mild steel impeller was used for stirring the metal in the molten state for 5-10 min at a stirring speed of 700 rpm so as to ensure uniform distribution of the ceramic particles. A zirconium-based coating was applied to the impeller to minimize blade dissolution. The immersed impeller was set at a depth of around 2/3 of the height of the crucible containing the mixture from the bottom. A pre-heated mild steel metallic mold was used to pour the molten material and get the desired shape.

2.2 Sliding wear test under dry condition

The dry sliding wear tests was performed on a pin on disc friction and wear monitor (Model: TR20LE, DUCOM). The tribology test was based on ASTM G99-05 (2010) standards. Three important tribological parameters, namely, sliding distance (1,000, 1,500 and 2,000 m), sliding speed (100, 300 and 500 rpm) and normal load (10, 20 and 30 N) was considered during experimentation. Taguchi's L_{27} orthogonal array was used for experimentation. A

Figure 1 FESEM morphology before ball milling process



Notes: (a) SiC; (b) B_4C particles; FESEM morphology after 30h of ball milling process; (c) SiC; (d) B_4C particles; (e) XRD analysis of hybrid B

cantilever mechanism was used for applying the normal load on samples during sliding and the samples were brought in contact at a track radius of 120 mm. The samples were prepared and weighted (using a precision balance, accuracy up to 0.001 mg) before and after each test. WR and CoF was measured as the output responses. The WR and CoF of the test specimens was calculated as per equation (1) and (2) respectively:

$$WR\left(mm^3/m\right) = \frac{\Delta m}{\rho L} \tag{1}$$

$$COF = \frac{f}{F_n} \tag{2}$$

where Δm = mass initial − mass final (g), ρ = experimental density (g/mm^3), L= total distance travelled/sliding distance (m), F_n is the normal load applied (N) and f is the frictional force. The time taken by the sliding pins to cover the entire sliding distance is calculated using equation (3).

$$T(\min) = \frac{1000 \times d}{\pi \times D \times N} \tag{3}$$

where d is the sliding distance (m), D is the track diameter (m) and N is the sliding speed (m/min) of the specimens on the steel discs. The total time required to cover the entire sliding distance was calculated initially and was given as an input while performing the experiments.

3. Results and discussion

3.1 Taguchi modeling of wear rate and coefficient of friction

The experimental data are analyzed using Taguchi method. The most essential criterion is signal-to noise (S/N) ratio. S/N

Figure 2 Mean effect plot of S/N ratio for hybrid A and B (a) WR; (b) CoF

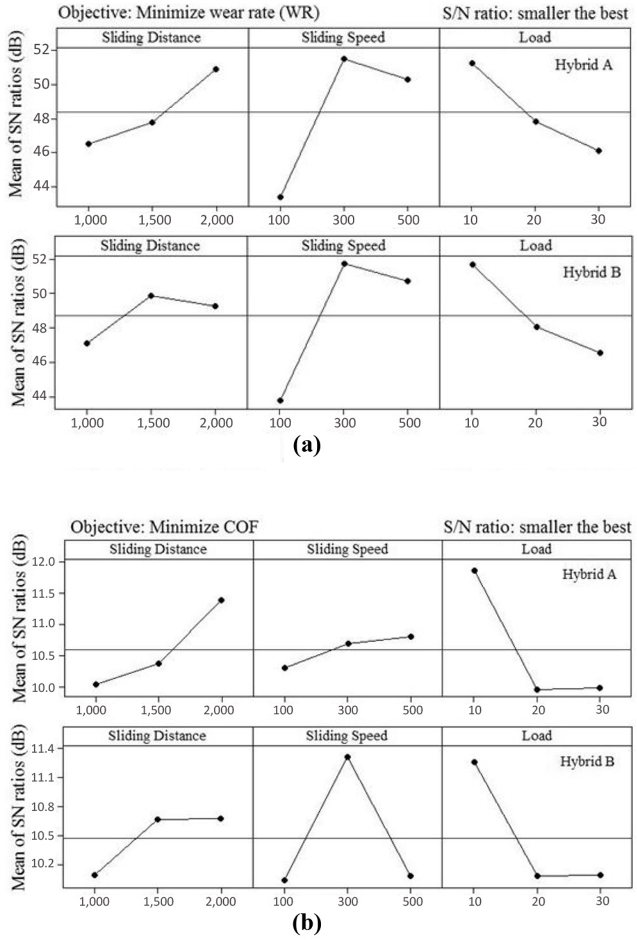


Table I Rank table for WR and CoF of hybrid A and hybrid B

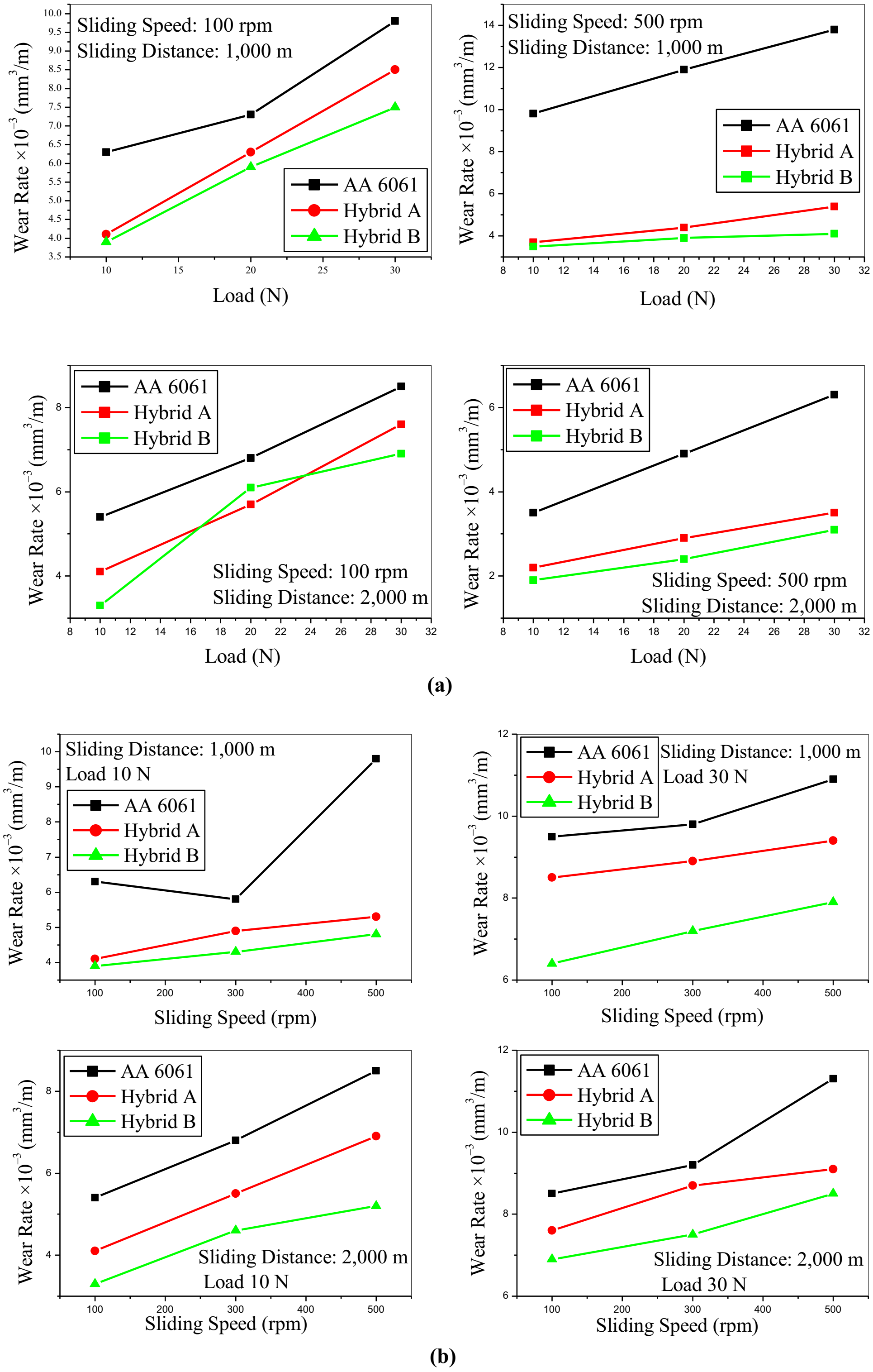
	Rank table for WR			Rank table for CoF		
	Hybrid A			Hybrid A		
Level	**Sliding distance**	**Sliding speed**	**Load**	**Sliding distance**	**Sliding speed**	**Load**
1	46.49	43.35	51.24	10.040	10.303	11.854
2	47.77	51.52	47.81	10.364	10.687	9.954
3	50.87	50.26	46.08	11.388	10.803	9.984
Delta	4.38	8.17	5.16	1.348	0.500	1.901
Rank	3	1	2	2	3	1
	Hybrid B			Hybrid B		
1	47.06	43.77	51.64	10.09	10.03	11.26
2	49.84	51.70	48.01	10.66	11.31	10.08
3	49.26	50.69	46.52	10.67	10.08	10.08
Delta	2.79	7.93	5.13	0.59	1.28	1.18
Rank	3	1	2	3	1	2

ratio is used instead of mean value to interpret the experimental results into a value for the evaluation characteristic in the optimum setting analysis (Phadke, 1989). In this study, smaller-the better S/N ratio is used and is defined by equation (4).

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} R_i^2\right) \tag{4}$$

where η is the S/N ratio, n is the number of data sets and R_i is the center line average of the responses.

Figure 3 (a) Plot of WR vs applied load; (b) plot of WR vs sliding speed



(a)

(b)

Analysis of interaction effects of parameters on performance characteristics (*i.e.*, WR and CoF) is performed to study the various effects on the performance characteristic with change of parameters. The interaction plots on S/N ratio on output characteristics are generated using MINITAB17® statistical software. Figure 2(a) shows the mean effect plots for WR of hybrid A and B composites. The study shows sliding speed (SS) is the most influencing parameter followed by load (L) and sliding distance (SD) for both the composites. The higher value of sliding distance, medium value of sliding speed and lower value of load provide better S/N ratio and it provides minimum WR. Figure 2(b) shows the mean effect plots for CoF of hybrid A and B composites. The study shows load is the most influencing parameter followed by sliding distance and sliding speed for hybrid A while for hybrid B sliding speed is the most influencing parameter. The higher value of sliding distance and lower value of load provide better S/N ratio and it provides minimum CoF. The response table (rank table) for the output responses are shown in Table I for hybrid A and B respectively.

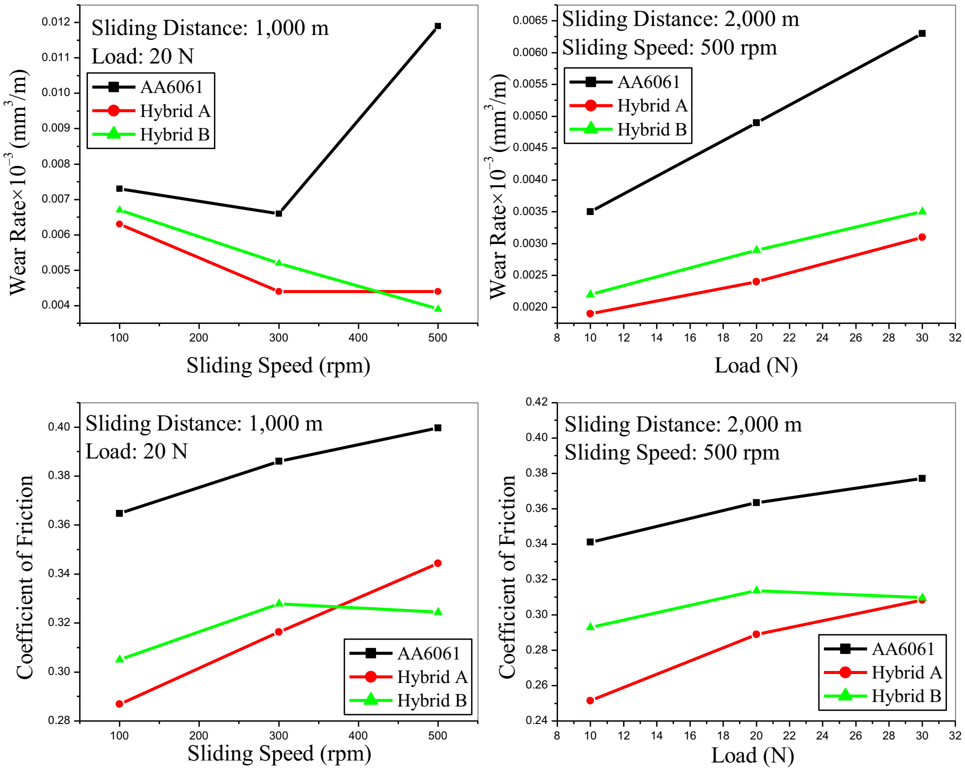
From Table I, it can be concluded that increasing the sliding speed will increase the WR and CoF for hybrid A. While for hybrid B, increasing the load and sliding speed will increase the WR and CoF, respectively. S/N ratio of the output responses is used to determine the optimum parameter settings of the input variables. The optimum parameter setting for WR of hybrid A and B are A3-B2-C1 (SD: 2000 m; SS: 300 rpm; L: 10 N) and A3-B3-C1 (SD: 2000 m; SS: 500 rpm; L: 10 N) respectively while the optimum setting for CoF of hybrid A and B are A2-B2-C1 (SD: 1,500 m; SS: 300 rpm; L: 10 N) and A3-B2-C1 (SD: 2,000 m; SS: 300 rpm; L: 10 N), respectively. The value of WR at the above combination of inputs for hybrid A and B are 0.0015 mm^3/m and 0.0012 mm^3/m respectively, while for CoF of hybrid A and B, the values are 0.2515 and 0.2381 respectively.

3.1.1 Influence of normal load and sliding speed on wear rate

The WR of AA6061 and the hybrid nanocomposites AA6061 reinforced with SiC and B_4C with respect to normal load and sliding speed are shown in Figure 3(a, b). The intensity of wear was extreme at 30 N load. Hybrid B was seen to have the least WR compared to hybrid A at most of the working conditions, because of higher SiC content. Increase in SiC content reduces the amount of actual contact surface in between the asperities of the composite surface and the sliding surface, thus assisting in decreasing WR. Presence of these SiC particles also helps in enhancing the elastic modulus, hardness and high temperature strength of the composites (Mondal *et al.*, 2005). The rise in temperature aids in softening the matrix and hence leads to higher WR for the AA. Lowering of the WR at higher sliding distance can be attributed to the existence of SiC and B_4C ceramic particlces which leads to the development of a mechanically diversified layer at the tribosurface. The mechanically mixed layer at the tribosurface aids in minimization of the shear stress being shifted to the composite pins beneath the sliding area in contact. This results in drop of the plastic distortion and thus decreases the WR of the prepared HMMC when compared to the alloy matrix in the sub surface region.

Figure 4 shows the effect of WR with respect to sliding speed and load at 20 N load. The WR seems to decrease for the hybrid composites with increase in sliding speed at 20 N load.

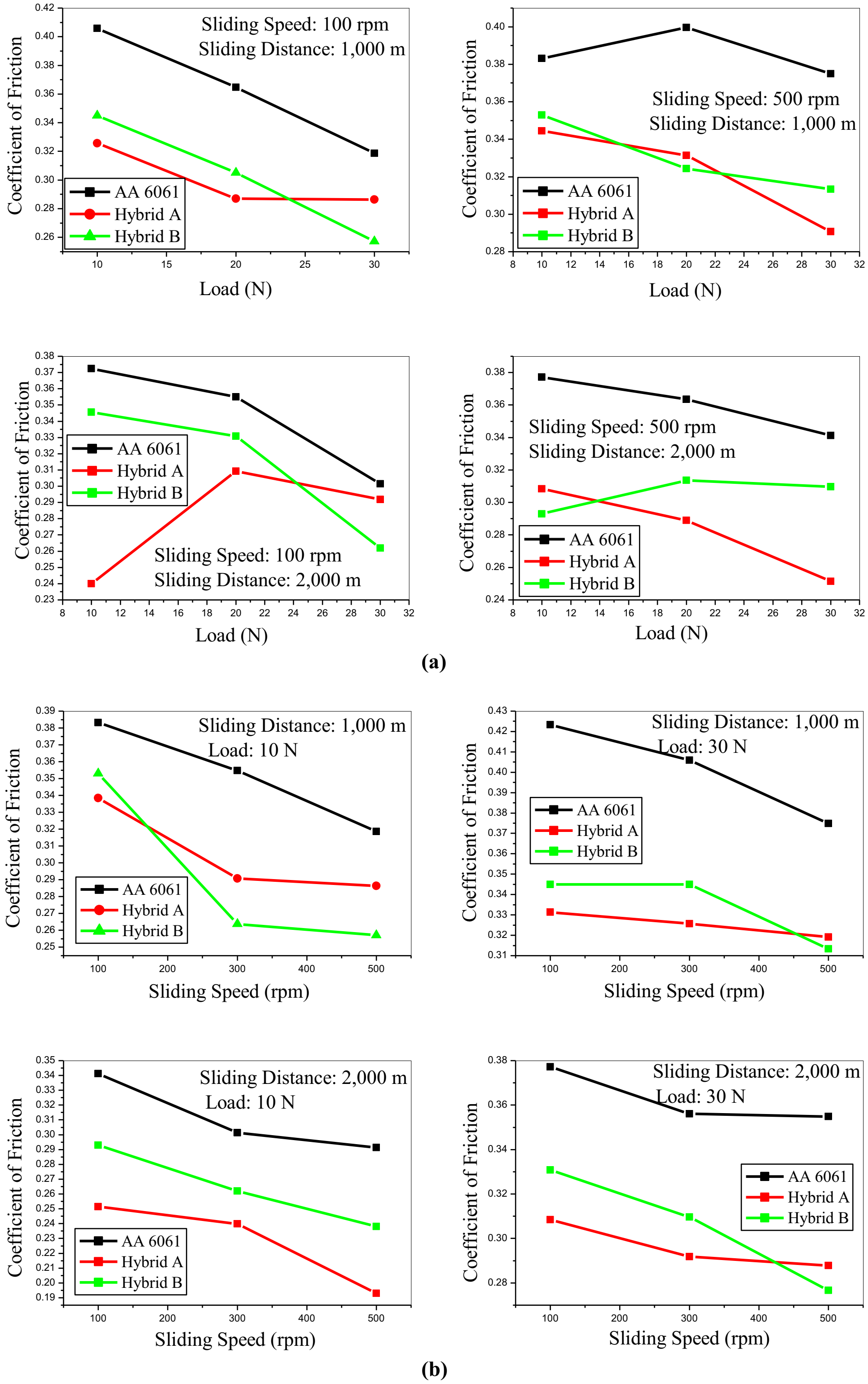
Figure 4 Plot of WR and CoF with respect to sliding speed and load



3.1.2 Influence of load and sliding speed on coefficient of friction

Variation of CoF with respect to normal load (in minimum and maximum loading conditons) and sliding speed are shown in Figure 5 (a) and (b). The variation in CoF might be because of inadequate interaction among the tribosurface of the test pins and the disc material. Increase in SiC content resulted in decreasing the effective contact area of the tribosurface causing in fall of temperature rise in hybrid B. Consequently, the frictional

Figure 5 (a) Plot of CoF vs load; (b) plot of CoF vs sliding speed



force required for the hybrid composites to slide over the mating surface is much higher. The ceramic particles decrease the relative contact area of the tribosurface with the mating surfaces and aids in the formation of a more resistant tribolayer. Because of the development of an oxide layer, at higher sliding speed and loading conditions, the variation in CoF for hybrid A and B is not that significant. However, the CoF at 20 N load increased with increase in sliding speed and sliding distance as seen in Figure 4.

3.2 Surface morphology

FESEM was performed of the worn out samples and are shown in Figure 6 (a) and (c). The AA6061 worn samples shows wear debries along the sliding distance. Plowing and oxidative wear was noticable on the wear surface for the AA6061. Minor transfer of elements initiates the formation of the wear debris in the form of loose particles on the sliding surface.

Numerous parallel groves was also observed along the sliding track because of the sliding action of the pins. The adhesive wear resulted because of the sticking of these loose debris during unidirectional relative motion between the sliding disc and the sample pins. Hybrid B shows the formation of moderate plowing along the sliding direction. The sliding of the SiC and B_4C ceramic particles over the mating surface damage the pin layer by plastic deformation or fracture leading to abrasive wear. These ceramic particles also result in plastic flow of the matrix material even at low load conditions. Abundant scratches are observed along the sliding direction resulting in plowing. This was because of the flow of the soft matrix material plastically. Plowing also results in wedges along the sides of the ridges.

Cracks and adhesive were more prominent on the surface of hybrid B. With increase in the load, there is a tendency of the brittle ceramic particles to fracture and dislodge from the matrix material forming loose debries. Because of continuous unidirectional relative motion of the sliding surface, these debries adhere to the sample surface. Also the increase in the interface temperature leads to work hardening of these loose debries which at times leads to the development of micro cracks on the sliding surface. Figure 7 shows the worn out samples at maximum loading conditions of 30N. Abrasive wear in the cutting form was seen in the hybrid A. This resulted in the formation of ribbon-shaped discontinuous debries. The alterations in the governing wear mechanisms differs with variation in normal load and sliding speed. Plastic deformation was the main cause for severe wear in all the three samples at high normal loads, sliding speed and distance. Figure 8 shows the energy dispersive spectroscopy (EDS) spectrum of the hybrid composites both before and after wear. The presence of oxygen peak in the EDS confirms the formation of the oxidative wear on the sample specimens. EDS also confirms the transfer of disc material to the tribology specimens on the basis of high carbon (C) and silicon (Si) content.

Figure 6 SEM images of worn out samples of (a) AA 6061; (b) hybrid A; (c) hybrid B

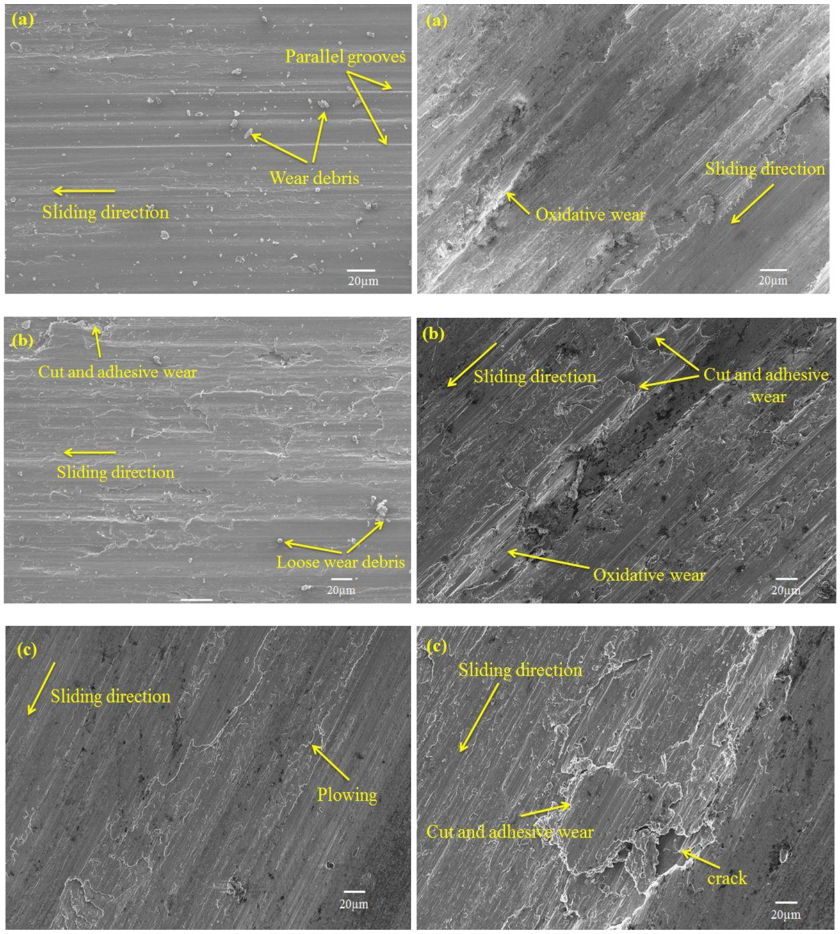


Figure 7 FESEM images at 30 N load, sliding speed of 500 rpm and sliding distance of 2,000 m (a) AA6061; (b) hybrid A; (c) hybrid B

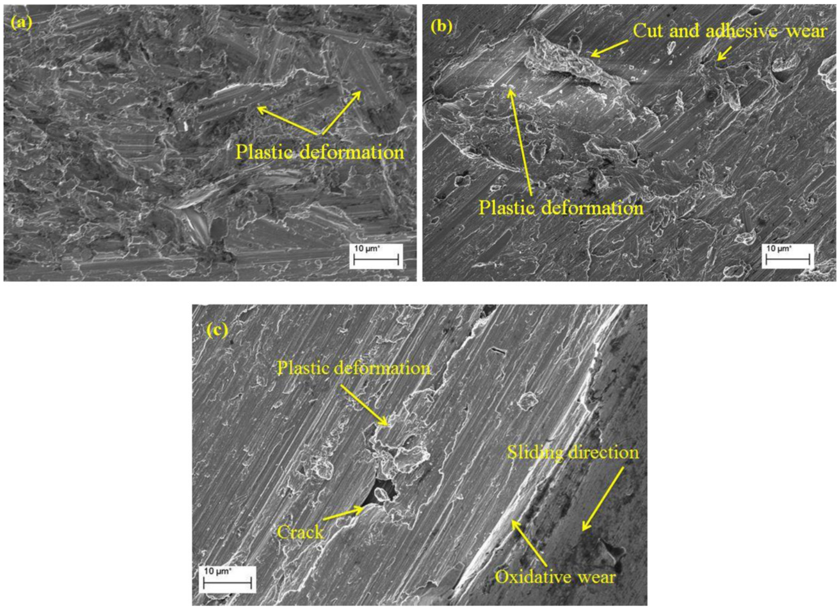
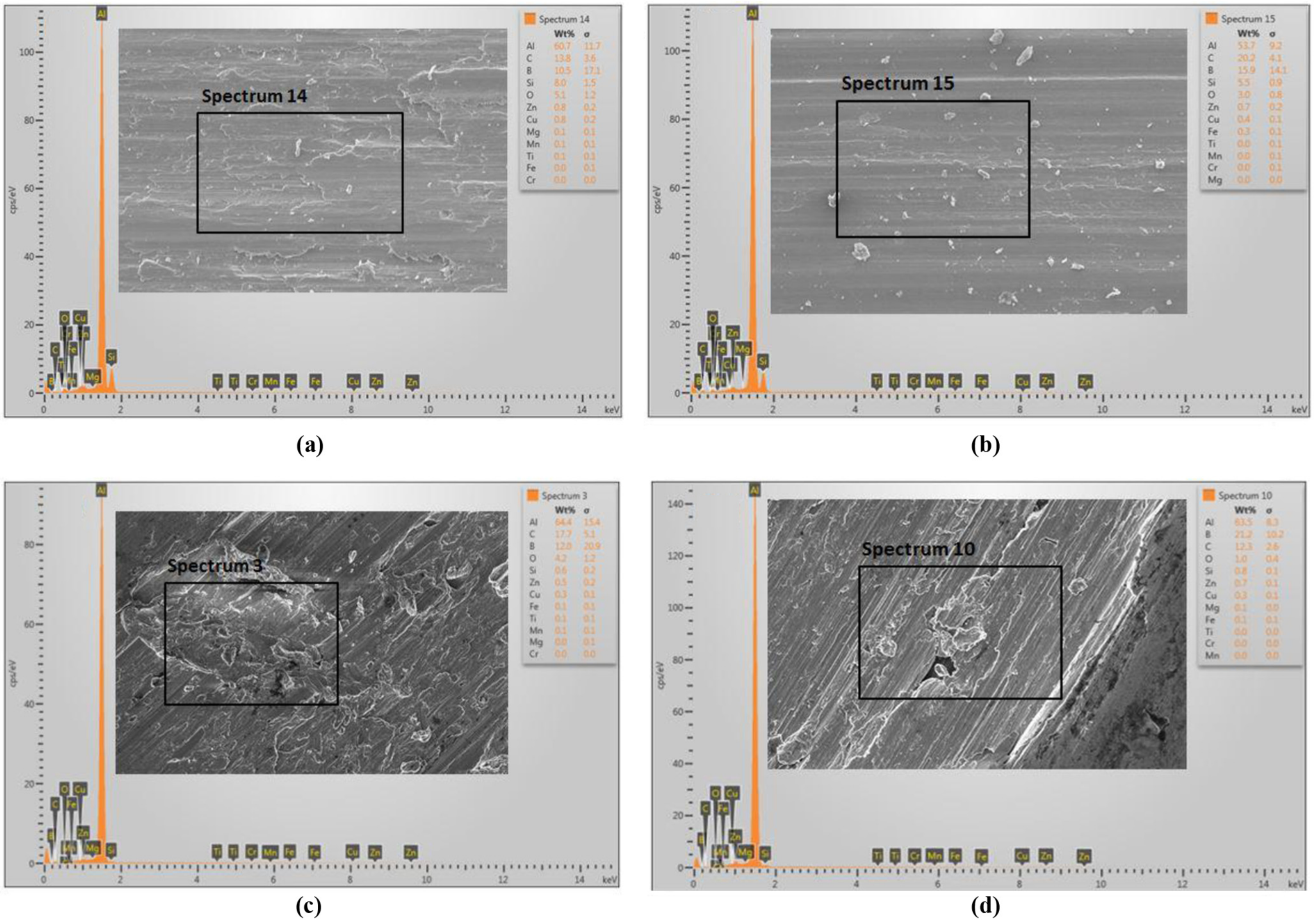


Figure 8 EDS spectrum of before wear (a) hybrid A; (b) hybrid B; after wear; (c) hybrid A; (d) hybrid B



(a)
(b)
(c)
(d)

4. Conclusions

In the present work, two compositions of Al-HMMCs (Hybrid A: AA6061 + 0.5 Wt.% SiC + 1.5 Wt.% B_4C and Hybrid B: AA6061 + 1.5 Wt.% SiC + 1.5 Wt.% B_4C) have been fabricated using conventional stir casting method and tribological characteristics i.e. WR and CoF has been studied. Based on the experimental results and Taguchi analysis, the following conclusions are arrived:

- The WR of the prepared composites incresed with increase in the applied load and it is maximum at load 30N at sliding speed of 500 rpm. It is found that the rise in temperature with sliding speed softens the matrix material which initiates the wear.
- The CoF decreases with rise in the normal load and sliding speed for both the nanocomposites (Hybrid A and Hybrid B). This was because of decrease in the relative contact area of the sliding surface because of the presence of the ceramic nanoparticles.
- FESEM and EDS of the worn out surface revealed that adhesion, abrasion and oxidation were the main dominating wear mechanisms for the hybrid nanocomposites.
- The ability of the composite to preserve the stable oxide film considerably affects the wear of the pins and enhances the load bearing capacity of the composites.
- Taguchi's analysis reveals that sliding speed and load were the significant factors in affecting WR and CoF for hybrid A, while sliding speed was the most significant factor affecting WR and CoF for hybrid B.
- The optimum parameter setting for WR of hybrid A and B are A3-B2-C1 (SD: 2,000 m; SS: 300 rpm; L: 10 N) and A3-B3-C1 (SD: 2,000 m; SS: 500 rpm; L: 10 N) respectively while the optimum setting for CoF of hybrid A and B are A2-B2-C1 (SD: 1,500 m; SS: 300 rpm; L: 10 N) and A3-B2-C1 (SD: 2,000 m; SS: 300 rpm; L: 10 N) respectively.

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