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Dry sliding wear behavior of stir cast aluminium base short steel fiber reinforced composites

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Abstract Dry sliding wears behavior of die cast aluminium alloy composites reinforced with copper-coated short steel fibers were investigated using a pin-on-disk wear-testing machine. The composites were prepared by liquid metal route using vortex method. The weight percentage of copper-coated steel fibers was varied from 2.5 to 10. The density and hardness of the composite increased linearly with increasing wt% of steel fibers. The wear rate decreased by 40% with addition of 10% weight percentage of fibers. A linear dependence of wear rate on fiber content and hardness of MMC is observed. The unreinforced aluminium and composites containing upto 5-wt% of fibers exhibited a sliding distance dependent transition from severe to mild wear. However, composites containing 10-wt% fiber showed only mild wear for all sliding distance. It was also observed that with increase in the fiber content to 10-wt% the coefficient of friction decreased by 22%. The duration of occurrence of the severe wear regime and the wear rate decreased with increasing fiber content. For the composite the wear rate in the mild wear regime decreased with increase in fiber content reaching a minimum. From the analysis of wear data and detail examination of (a) wear surface and (b) wear debris two modes of wear have been identified to be operative, in these materials. These are (i) adhesive wear in the case of unreinforced matrix and in MMC with low wt% (upto 5-wt%) fibers (ii) abrasive wear in case of MMC with high wt% of fibers.

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Introduction

The demand for inexpensive lightweight stiff and strong materials has lead to the development of Al alloy matrix composites containing hard ceramic dispersoids. SiC-whisker, particles and short fiber reinforced aluminium composite possesses good mechanical properties and hence considered as potential engineering materials for various tribological applications [1, 2].

Several previous studies on the wear behavior of composites reported that the composites exhibited superior wear resistance over unreinforced alloys [3, 4]. Wang and Rack [5–7] studied the effect of the volume fraction and orientation of reinforcement on the wear behavior of SiC–Al composites under various conditions. The results indicated that the predominant wear mechanism was a function of sliding distance and type of reinforcement; below 10 vol% of reinforcement, abrasive wear predominated throughout the test period, while above 10 vol%, a transition from abrasion to adhesion dominated wear occured with increasing sliding distance. From a study on wear mechanism of composites under dry sliding condition it was concluded that the mild wear mechanisms of aluminium alloy/composites was oxidational wear [8].

On the wear of ceramic particulate reinforced aluminium alloy composites a reasonable amount of data has been obtained [9–11]. Therefore, the effects of the structure and the working condition on the wear are also known to some extent. Saka et al. [12] showed that the friction and wear behavior of MMCs depends on the orientation of the reinforcement. Randomly orientated MMCs showed better friction and wear property.

An intimate contact between the reinforcement and the matrix needs to be established through satisfactory wetting [13, 14] of the reinforcement by the matrix to ensure adequate adhesion and the rate of chemical reaction at the interface should be very low. On the way of achieving such a desired interface of the composites it is often advised to apply a thin coating on the reinforcement [15, 16], which is chemically compatible with both the reinforcement and the matrix.

Although the mechanical properties of MMCs have been investigated extensively, the potentially good wear properties have had less attention. The friction and wear behavior of MMCs containing graphite [17] and carbon fibers have been studied fairly extensively, and limited researches on other reinforcement including SiC_p [3] and Al_2O_3 have also been reported. However, the wear properties of composites reinforced with short steel fiber have not been studied, despite an increase interest in such composites as high specific strength materials.

The present investigation it is attempted to develop wear resistance of aluminium alloy base copper-coated short steel fiber reinforced composites. The composites were prepared by liquid process vortex method with varying wt% of fibers. The composites were then die cast into plate shapes and their microstructure, friction, wear behavior and wear mechanism were studied.

Experimental procedure

Materials

The short steel fiber reinforced aluminium composites used in this study were prepared by the stir casting or vortex method. The steel fibers were coated with copper by electroless process to obtain fibers of around 120 μm diameter and 450–550 μm length. The matrix alloy used for this work was the widely used commercially pure aluminium. Composition of commercially pure aluminium and steel fibers are shown in Tables 1 and 2. Composites were prepared with varying wt% of Cu coated steel fibers from 2.5 wt% to 10 wt%.

Wear test

Alloy and composites were subjected to wear test under dry sliding condition. The tests were conducted on 6 mm diameter, 35 mm long cylindrical specimens against a rotating EN-32 steel disc (count face) having hardness 63Rc. A Ducom Bangalore make, pin-on-disc wear test machine (Model—TR-20LE) was used for carrying out these tests, where tangential friction force and wear were monitored with the help of electronic sensors. These parameters were measured as a function of load and sliding distance. For each type of material tests were conducted at four different nominal loads (10 N, 20 N, 30 N and 40 N) keeping the sliding speed fixed to 1.85 m/s, for a test run of 2,000 m. During the test the end of the pin was pressed against the upper surface of the steel disc. Wear test were carried out at room temperature without lubrication for 20 min. After each test, worn out surface was preserved and debris were collected for micro structural studies, to get an insight to the wear mechanism. For this purpose, a SEM (Model JEOL 840A and JSM-5800 Jeol make, Japan) with EDX facilities (Camscan series 2 with Link AN10000 10/25S energy dispersive X-ray microanalyser) was employed. Wear rate was calculated from measured cumulative volume loss and sliding distance.

The bulk hardness measurement test was carried out using a standard Brinel hardness tester with 500 kg load and 10 mm steel ball indenter. An average of five reading was taken for each sample for hardness measurements.

Table 1 Composition of commercial pure aluminium

Sample	Si	Fe	Cu	Mn	Ti	Al
Al	0.09	0.168	0.04	0.03	0.01	Bal

Results and discussion

The optical microphotographs of composites with varying wt% of fibers are shown in Fig. 1a–c. Fiber distributions in composites were fairly homogeneous with randomly orientation. Copper-coated steel fiber reinforcement changed the microstructure that effects the wear behavior of materials. The volume fraction of the reinforcement can be obtained from quantitative metallography. However, the exact determination from quantitative metallography was difficult. From the density data an approximate relation between the

Table 2 Composition of steel fibers

Sample	C	Si	Mn	Cu	S	P	Cr	Fe
Fe	0.2	0.24	0.38		0.045	0.05	0.12	Bal
Fe_{Cu}				25.38				

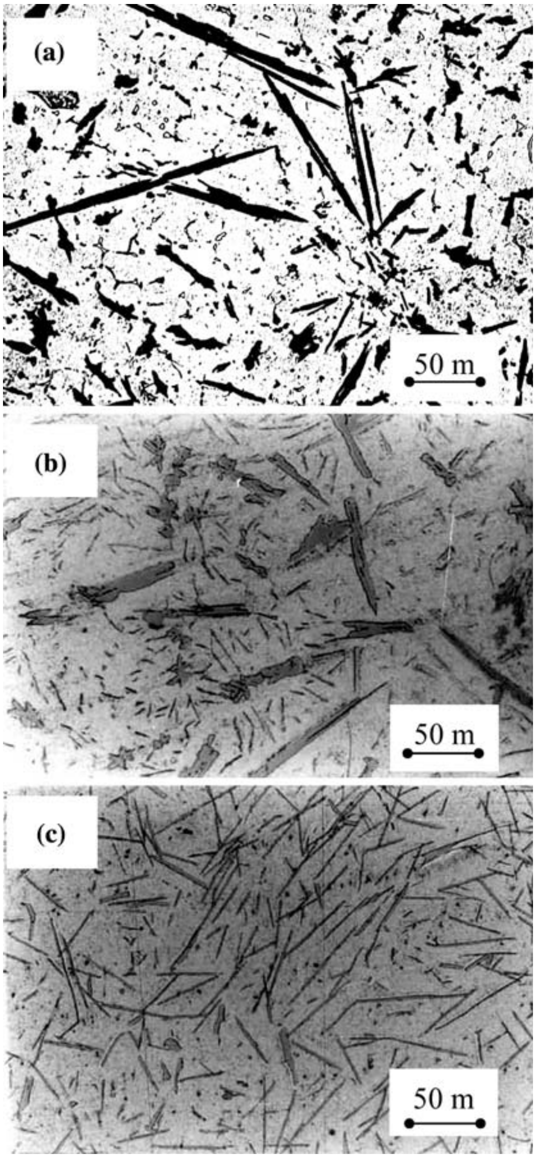

Fig. 1 Optical microstructure of aluminium base short steel fiber reinforced composites, varying wt% of fibers **(a)** Al–2.5FeCu, **(b)** Al–5FeCu and **(c)** Al–10FeCu

weight percentage and volume fraction is as follows, 2.5 wt% is equivalent to 1% by volume percentage.

It may be noted that the copper-coated fibers, copper present on the fiber surface diffused into the molten aluminium (shown in Fig. 1) leading to better wetting, as a result better fiber distribution and good interface bonding is obtained. The diffusivity and solubility of copper in aluminium being high there is little possibility of formation of new secondary phase such as $CuAl_2$. Dissolution of copper coating on the fibers has been observed and reflected in a previous study [18]. In case of Al–10FeCu composite a longer stirring time was used as the addition was high. This leads to higher dissolution of the coating giving rise an apparent decrease in the fiber diameter.

In MMCs steel fibers are distributed randomly throughout the matrix. The mechanical properties of aluminium and composites are listed at Table 3. In case of 5 wt% fiber composites shows maximum improvement in UTS. The yield strength of composites was increased with increasing wt% of steel fibers that influenced wear properties. 10-wt% fiber reinforced composites showed increase in yield strength but decreased in UTS.

The variation of density, hardness and porosity of the composites with wt% fibers are shown graphically in Figs. 2, 3 and 4. Density and hardness of the composites increased with increasing wt% of fibers. The porosity as calculated from the observed density value and theoretical density value increased with increasing wt% of fibers is shown in Fig. 4. Previous study has also reported an increase in porosity with increase in wt% of particle addition [19]. During preparation of composites, incorporation of higher wt% of fiber required longer stirring time, which also results in increased entrapment of gas.

Wear behavior

Cumulative volume loss against sliding distance for a number of composites determined under different wt% of fibers is shown in Fig. 5. The volume loss was higher at initial stage substantially reduced with increasing sliding distance. Cumulative volume loss was higher in case of matrix compared to composites. The volume loss continuously decreased with increasing wt% fibers.

The dry wear rate against sliding distance results are plotted in Fig. 6 for the matrix alloy and the composites. This graphs show that the incorporation of steel fiber substantially reduced volume loss and wear rates in comparison with the matrix alloy. For instance the averages wear rate of 10-wt% fiber composite was reduced by 40% in comparison with the matrix alloy. In general the data in Figs. 5 and 6 show that for any given specimen the volume loss continuously increases

Table 3 Mechanical properties of cast aluminium base composites

Sample	Hardness (BHN)	Y.S (MPa)	U.T.S (MPa)	%El
Al	19	24	39	18
Al–2.5FeCu	28	48	97.75	12
Al–5FeCu	38	77.42	123.79	10
Al–10FeCu	44	83	99.10	1.65

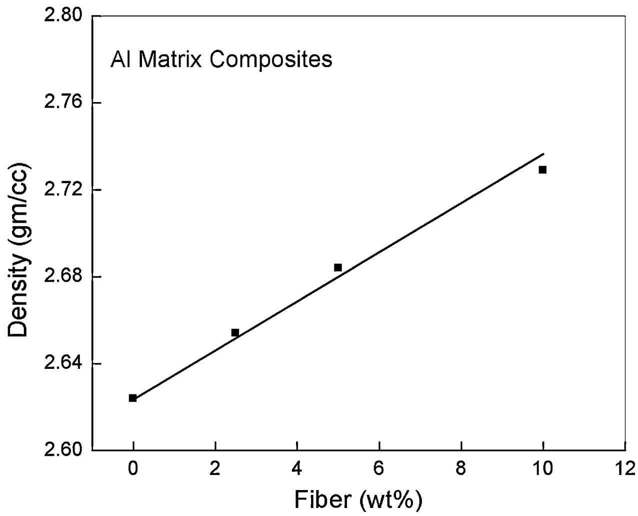

Fig. 2 Variation of density with wt% of copper-coated fiber reinforced Al composites

with increasing sliding distance but wear rate decreases with increasing sliding distance.

The coefficient of friction was also derived from the measured normal and friction forces. In all cases the test indicated an initial period, in which the coefficient of friction decreased considerably followed by a steady state and nearly constant friction. Figure 7 shows the coefficient of friction against sliding distance curves for Al alloy and different % fiber reinforced composites at a load of 10 N. At each load the coefficient of friction gradually decreases with sliding distance and increasing fiber content. Taking the average coefficient of friction for each material at all loads, the minimum average coefficient of friction of about 0.51–0.55 was

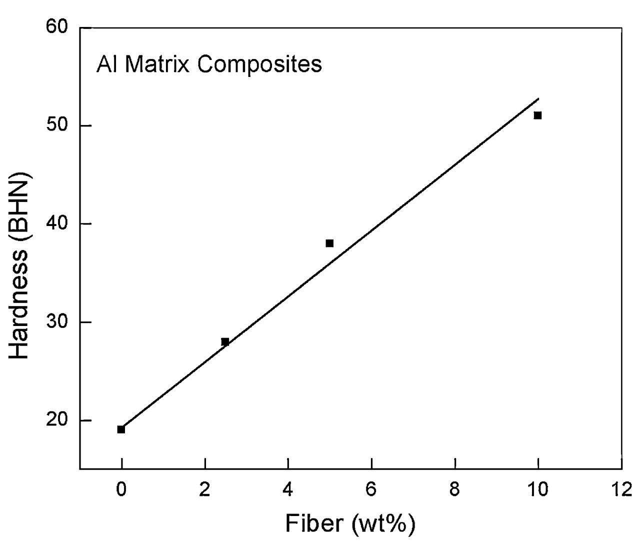

Fig. 3 Variation of Brinell hardness with wt% of copper-coated fiber reinforced Al composites

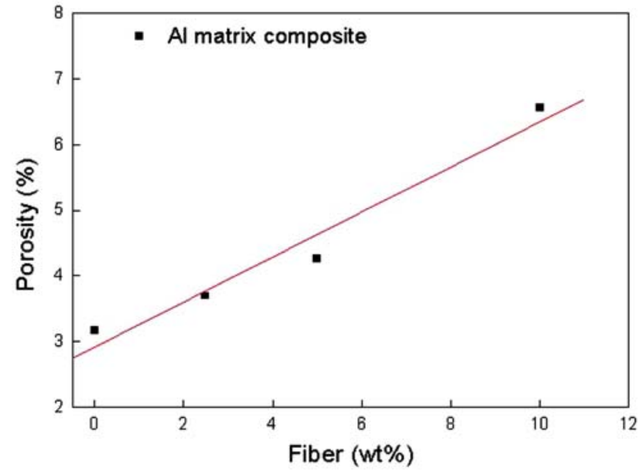

Fig. 4 Porosity variations with wt% of copper-coated fiber reinforced Al composite

observed with the matrix alloy, while the average coefficient of friction of composites was 0.41–0.43.

Figure 8 shows cumulative volume loses against applied load conditions for composites. The load is varying from 10 N to 40 N. Increase in the amount of steel fiber additions resulted in reduced wear loss when all other variables were kept constant. At 40 N load rate of volume loss reduced with increasing wt% of fibers (vide Fig. 8, slope of the curve).

Wear surface analysis

The SEM micrograph of Fig. 9a–d shows a typical worn out surface of alloy and composite materials under 10 N load. This micrograph shows extensive long continuous grooves on the surface parallel to the sliding direction. The composites were tested under

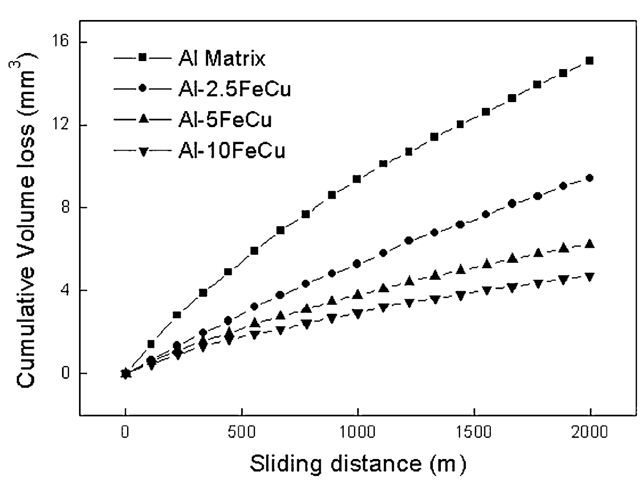

Fig. 5 Cumulative volume loss against sliding distance of composites with varying wt% of copper-coated fibers at 10 N load

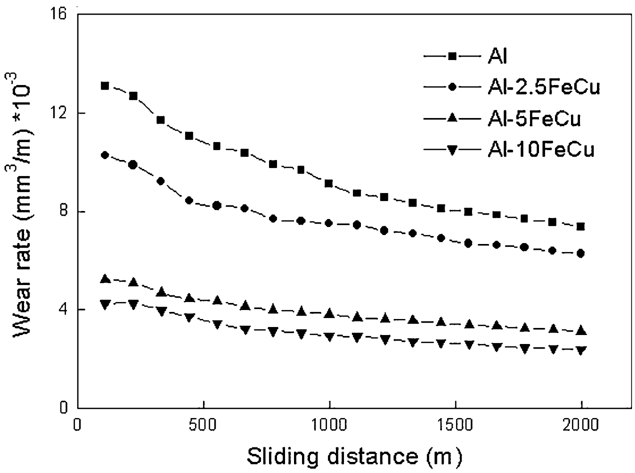

Fig. 6 Wear rate against sliding distance of aluminium base composites with varying wt% of copper-coated steel fibers at 10 N load

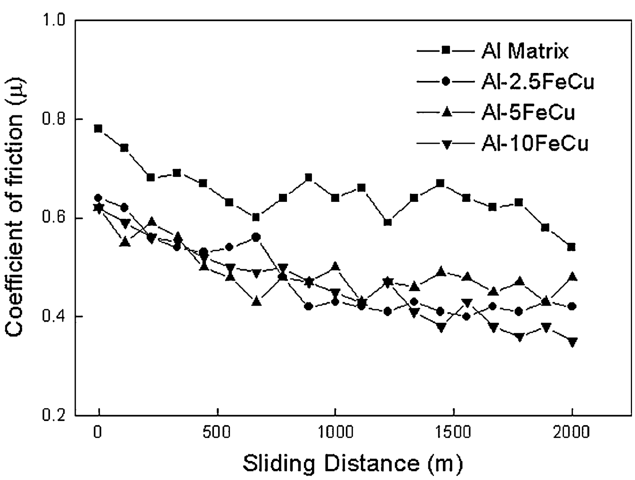

Fig. 7 Coefficient of friction against sliding distance of aluminium base composites with varying wt% of fibers at 10 N load

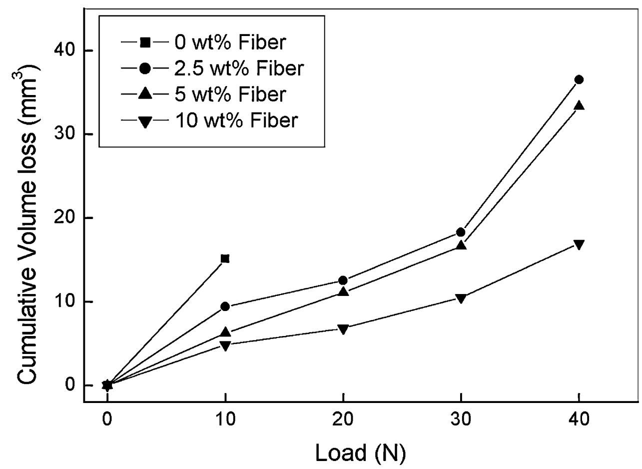

Fig. 8 Cumulative volume loss of aluminium base composites with varying wt% of fibers against varying load

similar conditions, a quite different form of wear surface was observed. Figure 9b depicts a micrograph of the worn surface of composites containing 2.5-wt% fiber tested at a load of 10 N. In sharp contrast to the matrix alloy micrograph shows a relatively extensive long continuous grooves on the surface but increasing wt% of fibers smooth surface appears with no evidence of deep ploughing grooves. There was a little evidence of plastic deformation, but some of the matrix alloy was smeared over the ends of the projecting fibers.

The SEM micrograph of Fig. 10a–d shows a typical worn out surface of 5 wt% fiber reinforced composite materials under 10–40 N load. At higher load extensive surface ploughing was evident. Local delamination was observed and the damage region was more extensive. It is noted that surface ploughing increased with increasing load. Figure 10b shows the surface of the 5-wt% fiber reinforced composites tested at 20 N load. Chipping of the fibers and smearing of the matrix over the protruding fiber ends is evident along with slight surface grooving. The size of the chips varied from place to place on the surface but in general they increased with increasing test load, for example at 40 N load the ploughing was higher as compared to that with 10 N load.

Micrograph examination shows that fibers reduced the depth of subsurface plastic deformation and prevented the development of long subsurface cracks, which led to surface spalling in the un-reinforced alloy.

Wear debris analysis

Wear debris generated during the wear test was collected after the end of the test and examined under SEM. Figure 11 showed the wear debris of different composites at 10 N load. It is observed that there is no large variation of debris size with increase in wt% of fibers. Figure 12a–d shows the wear debris of 5 wt% copper-coated fiber composite for 10–40 N load, respectively. Wear debris appeared dark in color and was mainly in the form of fine particles or plates for both 10 N and 40 N applied load. Size of plates is larger and irregular for 40 N applied load as compared to those at 10 N load. Further the size of the wear debris increase with increasing loads resulting in greater wear loss at higher loads. Small cracks can be seen on the wear debris at 10 N and 20 N load. These cracks are disappeared at 30 N and 40 N load shown in Fig. 12c, d. At low load oxides are formed on the surface of pin, which control the debris formation. At higher loads the mechanism of debris formation was delamination on the pin surface. The X-ray diffraction

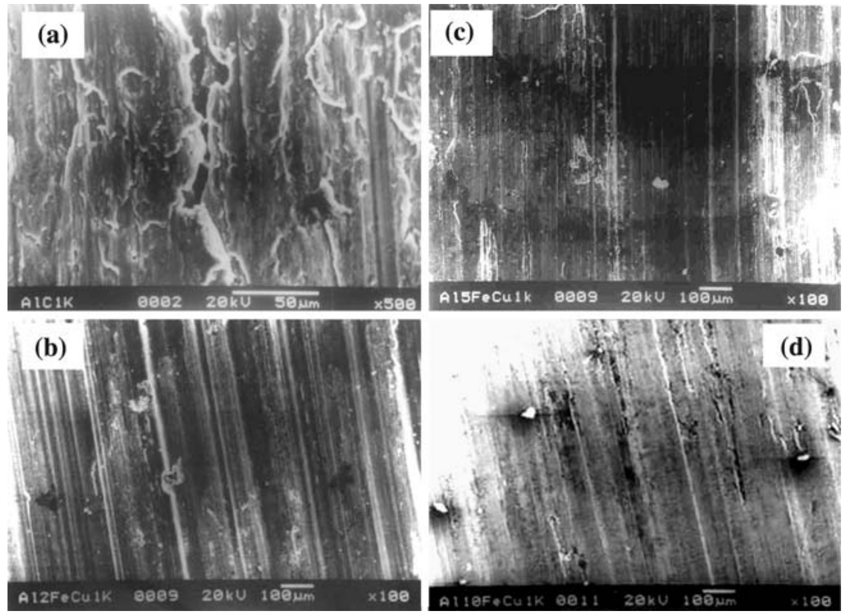

Fig. 9 (**a**–**d**) SEM photographs of wear surface of aluminium matrix and composites varying wt% of copper-coated steel fibers at 10 N load (**a**) Al matrix (**b**) Al–2.5FeCu (**c**) Al–5FeCu and (**d**) Al–10FeCu

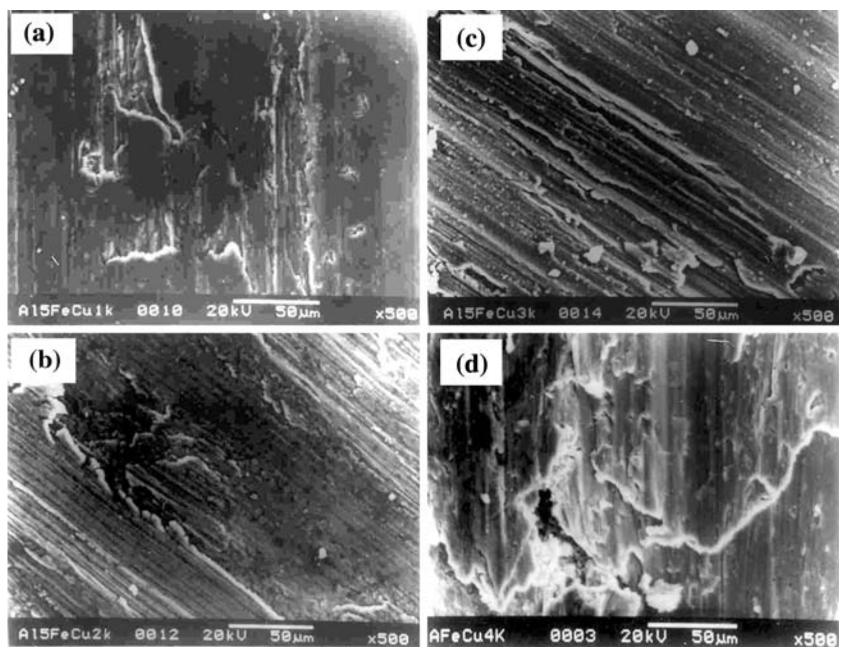

Fig. 10 (**a**–**d**) SEM photographs of wear out surfaces of aluminium matrix and composites after 2,000 m sliding distance at varying loads (**a**) 10 N, (**b**) 20 N, (**c**) 30 N and (**d**) 40 N

could not detect the oxide layer on the wear debris as the element was very low. However, such changes have been reported in a previous study where the mild wear is termed as oxidative wear as oxide layers are formed on the surface of the debris [3]. Crack formation on the wear debris was observed in case of lower load. These were absent at higher loads. The crack formation is attributed to the oxide formation as reported earlier [3]. So there is an indirect evidence of oxidation wear at lower loads in the present study.

Increase in wt% fiber and decrease in load appear to reduce both plastic flow in the matrix and the metal transfer from the pin. This is evident from the dot mapping of the wear surface, which shows negligible Fe pick up from the disc. Table 4 shows the results of EDX quantitative analysis of the main element in the debris generated at different loads. The composition of debris generated at the load of 40 N was consistent with the bulk materials of the pin. Higher level of Fe was found in the debris obtained at the loads of 10 N and 20 N. Relatively small amount of Fe and O_2 existed in the debris at 30 N and 40 N. Based on the above EDX analysis it is indicated that the wear debris generated at lower load consists of mainly Al, Al_2O_3, Fe and Fe_2O_3,

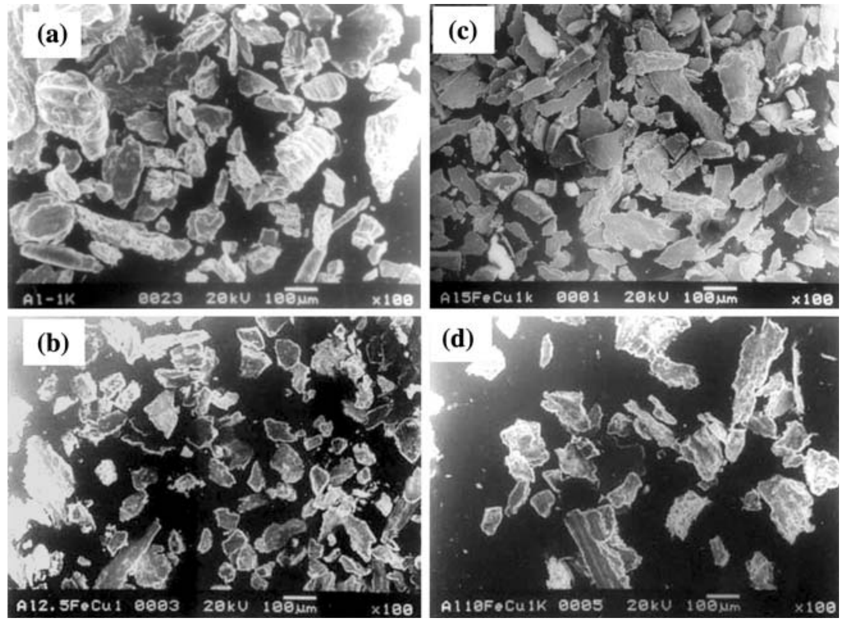

Fig. 11 (**a**–**c**) SEM photographs of wear debris of aluminium matrix composites with varying wt% of copper-coated fibers after 2,000 m sliding distance at 10 N load (**a**) Al matrix, (**b**) Al–2.5FeCu (**c**) Al–5FeCu and (**d**) Al–10FeCu

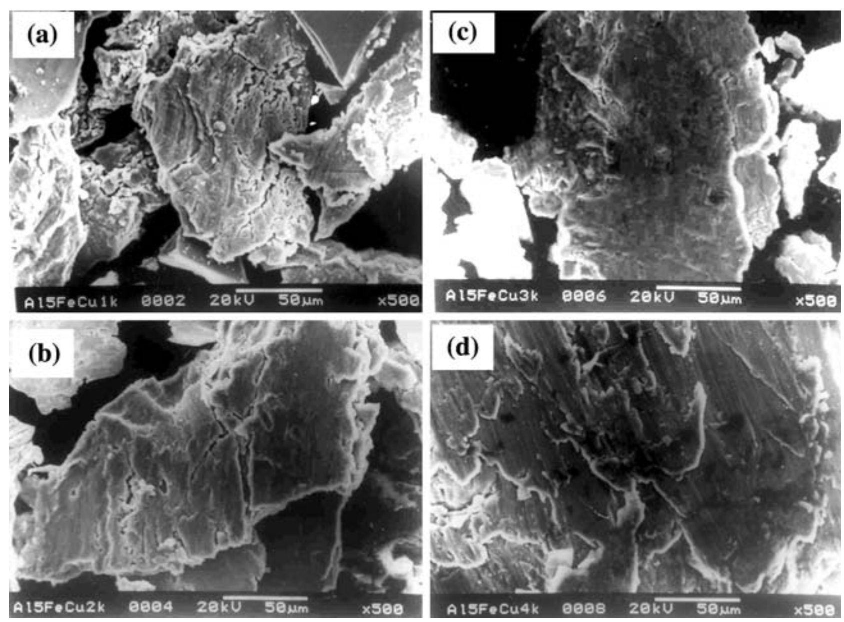

Fig. 12 (**a**–**d**) SEM photographs of wear debris of copper-coated fiber Al base composites after 2,000 m sliding distance at different loads (**a**) 10 N load (**b**) 20 N load (**c**) 30 N load and (**d**) 40 N load

while wear debris generated at higher load has the same constituent as the bulk materials of the pin. In case of composites, size of debris was reduced with increasing wt% of fibers (vide Fig. 11).

Statistical analysis

The adhesive wear theory stated by Archard [20] defined wear volume as a function of the sliding speed, normal load and the materials hardness. However, this theory ignored the effect of the materials microstructure on wear and was limited to idealized sliding conditions. Archard developed the following expression for wear rate,

$$W = \frac{k * L * P}{3H} \tag{1}$$

where the W is volume of material worn, k = wear coefficient, L = sliding distance, P = applied normal load and H = bulk hardness.

In the present study the experimental wear data obtained is used to develop a generalized equation (A simplest version of Archard equation) to estimate specific wear loss of composite materials. The modified equation is proposed by the authors to take

$$W = b_0 * L^{b1} * P^{b2} * H^{b3} \tag{2}$$

Table 4 Levels of different elements on wear debris of Al–5FeCu composites at different load

Element	10 N	20 N	30 N	40 N
Al	92.87	93.29	94.58	95.93
Fe	5.73	5.33	4.90	3.44
Cu	1.40	1.37	0.71	0.63

where W = Wear loss (volume loss) (mm^3), L = Sliding distance (m), P = Applied loads (N) H = Hardness (BHN).

Statistical analyses of the wear data for aluminium base composites with varying wt% of copper-coated steel fibers are done and an exponential Eq. 2 was fitted. The coefficients of regression obtained are given in Table 5.

Correlation between experimental and observed values is shown in Fig. 13. This shows a good correlation between observed and predicted values of specific wear loss of aluminium matrix composites with varying wt% of copper-coated fibers Table 6.

The density and hardness of the MMCs increased linearly with increasing wt% of steel fibers in the Al matrix, but the wear rate decreased. It is clear from the Fig. 6 that the wear rate decreases with increased fiber contains. The results show that wear rate has a linear dependence on fiber content and thus simply vary with the hardness of the materials.

The coefficient of friction of the MMCs is much lower than that of the matrix alloy, and it is also seen that with increase in fiber content the coefficient of friction decreases and wear resistance increases. Copper coating on the fibers improves the wettability, giving a better distribution of fibers in the aluminium matrix, resulting in higher hardness and yield strength finally lowers coefficient of friction and improve wear resistance. The addition of 10 wt% steel fibers appears to reduce both the plastic flow in the matrix and the metal transfer to the pin.

In general, it can be concluded that with increasing the addition of steel fibers to aluminium matrix, the wear mechanism changes from a purely adhesive to oxidative wear. The addition of copper-coated steel fibers reduces both the plastic flow in the matrix and the metal transfer from the pin. This reduction increases with increase in fiber content. The mean size of the debris decreases with increasing wt% of fibers. The sliding distance corresponding to the transition from severe wear to mild wear is observed to increase with increasing wt% of fibers.

Table 5 Results of multiple regressions of volume loss for aluminium base composite with varying wt% of copper-coated fibers

Composites	Variable	Coefficients				R^2	Final loss (Obs-Pre)^2
		b_0	b_1	b_2	b_3		
Al base wt% variation	L, P, H	0.000905	0.6941	1.5667	–0.4530	0.95	1279.048

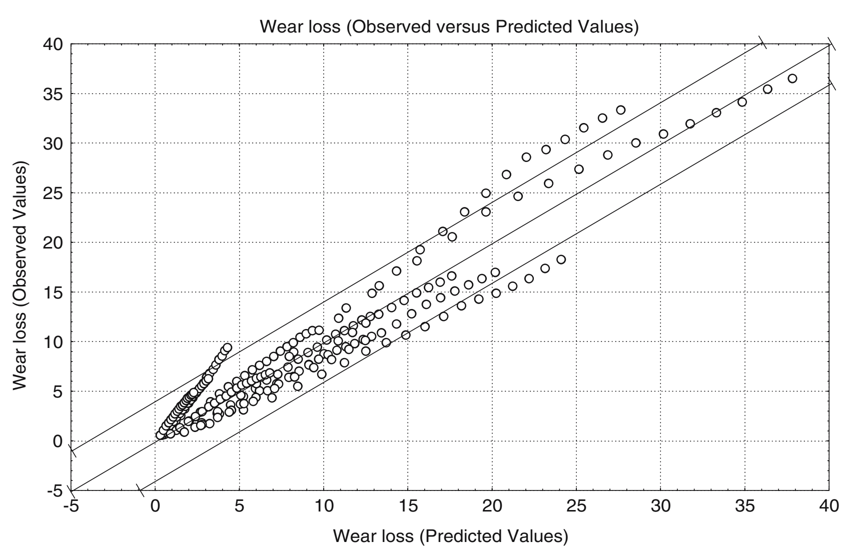

Fig. 13 Correlation between observed and predicted values of specific wear loss of aluminium matrix composites with varying wt% of copper-coated fibers

Table 6 Results of multiple regressions of volume loss for each aluminium base composites with varying wt% of copper-coated fibers

Composites	Variable	Coefficients			R^2	Final loss (Obs-pre)^2
		b_0	b_1	b_2		
Al–2.5FeCu	L, P	0.00059	0.6322	1.679	0.96	537.753
Al–5FeCu	L, P	0.00021	0.7589	1.681	0.97	229.044
Al–10FeCu	L, P	0.0009	0.7745	1.0526	0.98	38.293

Conclusions

(1) Density and calculated porosity of composites increased with increasing wt% of copper-coated steel fiber. There is a significant improvement in hardness with addition of fibers. For example the hardness value doubled with addition of 5% copper-coated fiber to the aluminium matrix.

(2) Cumulative volume loss decreased with increasing wt% of fibers in aluminium base composites. Wear properties of composites improved as compared to base metal. Volume loss decreases and wear resistance increases with increasing wt% of copper-coated steel fibers. For example on incorporation of 10% copper-coated fibers to aluminium matrix the cumulative volume loss decreased from 15 mm^3 to 6 mm^3.

(3) The wear data obtained can be fitted to an exponential equation ($W = b_0\ L^{b1}\ P^{b2}\ H^{b3}$) with good correlation and high coefficient of determination. Correlation between observed and predicted values of specific wear loss of composites lie well within ±10% range.

(4) There is a change in wear mode of the composites from mild to severe when the applied load is increased. The transition load is dependent on fiber content with the load, increasing with increase in fiber content. For 10% fiber content this is beyond 40 N whereas in case of base alloy severe wear is noted even at 10 N.

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