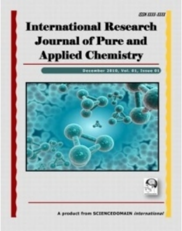

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Dry Sliding Wear Behavior of Aluminium Matrix Composite Using Red Mud an Industrial Waste

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Authors' contributions

This work was carried out in collaboration between the authors. Author NP carried out the experimental work supervised by author SKA. Author HS collected the data and did editing and write-up of manuscript. Authors SCM and SKS supported technically for completion of project successfully. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

The effect of fillers like red mud (RM) on dry sliding wear behavior of pure aluminium has been experimentally investigated. Pure aluminium of IE-07 grades from National Aluminium Company (NALCO), Angul of Odisha, India being collected with fillers in 10%, 15%, 20% and 30% based on weight were prepared using a stir casting technique. The dry sliding wear tests were conducted using pin-on-disc wear test machine. Tests were conducted for a sliding distance from 4.53×10^3m to 27.18×10^3m with wear track diameter 50mm-180mm. For each composition wear tests were conducted for different sliding speeds of 200 rpm (1.257m/s), 300 rpm (1.885m/s) and 400 rpm (3.141m/s) by applying normal loads of 10N, 20N and 30N. The wear rate and coefficient of friction were plotted against the normal load, sliding velocity and sliding distance for each filler composition. The results reveal that incorporation of red mud fillers leads to significant improvement in wear resistance of aluminium. The effect is the increase in interfacial area between aluminium matrix and red mud particles leading to the increase in strength appreciably.

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Keywords: Aluminum matrix; red mud fillers; wear characteristics.

1. INTRODUCTION

Composites consist of one or more discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger than the continuous phase and called the reinforcing material, where as the continuous phase is termed as the matrix. Its main function is to transfer and distribute the load to the reinforcement of the fibers. The matrix can be selected on the basis of oxidation and corrosion resistance. Metal matrix composites (MMCs) offer designers benefits, they are particularly suited for applications requiring good strength at high temperature, good structural rigidity, dimensional stability, and light weight [1–5]. The trend is towards safe usage of the MMC parts in the automobile engine, which work particularly at high temperature and pressure environments [6,7]. Particle reinforced MMCs have been the most popular over the last two decades. The modern trend for potential applications is to optimize the mechanical properties and heat treatment of MMCs. Now a day's researchers focusing mainly on aluminium, because of its unique combination of good corrosion resistance, low density and excellent mechanical properties.

Aluminium matrix composites have been emerged as advanced materials for several potential applications in aerospace, automobile, defence and other engineering sectors [8-15] because of their high specific strength and stiffness, superior wear and seizure resistance as compared to the alloy irrespective of applied load and sliding speed. Indeed, these promising new materials have found wide range of application in automobile industries, in the recent years in order to improve the fuel efficiency. Out of different automobile components, aluminium matrix composites (AMCs) have been found to be a more promising material, in brake drums, cylinder blocks, cylinder liners, connecting rods, pistons, gears, valves, drive shafts, suspension components, etc. Attempts have been made to examine the effect of sliding velocity on the wear behaviour of aluminium alloy and composites.Ranganath et al. [15] found that the wear rates of the composites were lower than that of the matrix alloy and further decreased with the increase in garnet content.

However, in both unreinforced alloy and reinforced composites, the wear rates increased with the increase in load and the sliding speed. Qin et al. [16] found that the rate of wear increases with increasing load, but it varies from linear to rapid increase for all the test materials, i.e., mild and severe wear regime. Similarly, with the increase of sliding velocity, the wear rate increases as well. With the increase of sliding velocity, the surface temperature of the materials increase, which leads to the rise of plastic flow of surface and subsurface, and therefore the wear rate increases. Uyyuru and Surappa [17] clearly demonstrated the strong interaction between load and sliding velocity to cause wear of a material, both wear rate and friction coefficient vary with both applied normal load and sliding speed. With increase in the applied normal load, the wear rate was observed to increase whereas the friction coefficient decreases. However, both the wear rate and friction coefficients were observed to vary proportionally with the sliding speed. Lim et al. [18] has reported that composites exhibit slightly superior wear resistance under the lower load, but the effects of the SiC particulate reinforcements on wear resistance are not as conclusive under the higher load. Ramesh et al. [19] observed Al6061–Ni–P–Si3N4 composite exhibited lower coefficient of friction and wear rate compared to matrix alloy. The coefficient of friction of both matrix alloy and developed composite decreased with increase in load up to 80 N. Beyond this, with further increase in the load, the coefficient of friction increased slightly.

However, with increase in sliding velocity coefficient of friction of both matrix alloy and developed composite increases continuously. Wear rates of both matrix alloy and developed composites increased with increase in both load and sliding velocity, similar observation was also made by Sharma [20]. Wear behaviour of aluminium matrix composite was studied by Rosenberger et al. [21] in which the matrix alloy AA6061, was reinforced with Al_2O_3, B4C, Ti_3Al, and B_2Ti in volume fractions ranging from 5% to 15%. The wear conditions generate in all cases a mechanically mixed layer (MML). The results were compared to those obtained with the non-reinforced alloy, which for the same conditions does not form the MML. Some observations are made by Tang et al. [22], the wear rate of the composite with 10 wt. % B4C was approximately 40% lower than that of the composite with 5 wt. % B4C under the same test condition. Sudarshan and Surappa [23] reported that the wear resistance of Al-fly ash composite is almost similar to that of Al_2O_3 and SiC reinforced Al-alloy. Composites exhibit better wear resistance compared to unreinforced alloy up to a load of 80 N. Fly ash particle size and its volume fraction significantly affect the wear and friction properties of composites. Venkataraman and Sundararajan [24] observed that the transition load as well as wear or seizure resistance of pure aluminium could be increased significantly with increase in SiC content. They reported that the transition load for Al, Al–10% SiC and Al–40% SiC are 45, 120 and 240 N respectively. They also tried to correlate transition load with hardness. It is observed by these investigators that even the hardness of other Al alloy is higher than that of composite; the transition load is noted to be less than that of composites. They explained on the basis of different nature of mechanically mixed layer (MML) in alloy and composites, subsurface cracking and micro structural change. It is reported that the transition load increases with increase in hardness of MML and with decrease in thickness of the MML. The thickness of MML is noted to be maximum at some intermediate load. The presence of oxygen in the environment in which a steel sliding system operates will promote a mild form of wear with wear debris consisting mainly of iron oxides. Of the oxidation dominated mechanisms, mild oxidational wear (the prefix describes the extent of oxidation and not the wear rate) has been most extensively investigated by Lim [25].Wilson and Alpas [26] constructed a wear mechanism map for temperature rise, wear rate and wear mechanism. The map clearly demonstrates that all these facts are the results of interaction of load and sliding velocity. With increase in sliding velocity, the transition load decreases and surface temperature increases. Zhang et al. [27] also made an attempt for predicting the effect of Al_2O_3 particle content on the steady state wear rate of 6061 alloy through the use of rule of mixture. After experimental verification, they suggested that if the reinforcement is strongly bonded with the matrix, wear resistance of composite would improve linearly with increase in reinforcement volume fraction. At the same time they concluded that the counterpart will be subjected to more and more wear with increase in the reinforcement content. Hence, one must consider a balance between these phenomena for developing wear resistant composite material. In view of the above, attempt has been made to evaluate the dry sliding wear behaviour of red mud reinforced Aluminium matrix over a range of loads and sliding speeds.

As red mud is cheap, abundance and it is a waste material from alumina production. The objective of the investigation is to examine the red mud, as to wear resistive or not.

2. EXPERIMENTAL ASPECTS

2.1 Pin-on-Disc Wear Testing Machine

Experiments have been conducted in the Pin-on-disc type Friction and Wear monitor (DUCOM; TL-20) with data acquisition system, (Fig. 1) which was used to evaluate the wear behaviour of the composite, against hardened ground steel disc (En-32) having hardness 65 HRC and surface roughness (Ra) 0.5 μm. It is versatile equipment designed to study wear under sliding condition only. Sliding generally occurs between a stationary Pin and a rotating disc. The disc rotates with the help of a D.C. motor; having speed range 0-2000 rpm with wear track diameter 50 mm-180 mm, which could yield sliding speed 0 to 10 m/sec. Load is to be applied on pin (specimen) by dead weight through pulley string arrangement. The system has a maximum loading capacity of 200N.

(A) Wear Tester (B) Pin on disc

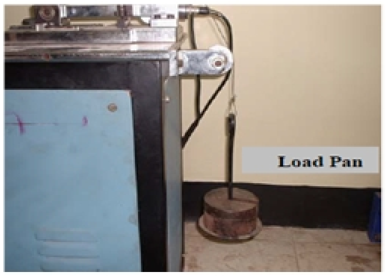


Fig. 1. Experimental set up

2.2 Materials Used

2.2.1 Aluminium

Commercially pure aluminium of IE–07 grades from National Aluminium Company (NALCO), Angul of Odisha, India was collected and used for experimental purpose. The composition analysis along with other test results such as hardness, density, and tensile strength are presented in Table [1-2].

Table 1. Compositional analysis of aluminium

Sl. No.	Si	Fe	Ti	V	Cu	Mn	Al
1	0.08	0.15	0.001	0.007	0.001	0.003	99.76

Table 2. Characteristics of aluminium

Density	2.7 gm/cc
Hardness	40.8 VHN
Tensile Strength	67 Mpa

2.2.2 Red mud

The red mud used for the present investigation was brought from the aluminum refinery of NALCO located at Damanjodi, Koraput, Odisha, India. Dust was prepared manually. The size of the dust was measured by using a sieve. As per this analysis the average size of the dust was 150 micron. Red mud dust was subjected to XRD, and chemical analysis. The presence of different elements as confirmed by chemical analysis is presented in Table 3.

Table 3. Chemical analysis of red mud

Constituents	Al_2O_3	TiO_2	Na_2O	P_2O_5	Ga_2O_3	Zn	C	Fe_2O_3	SiO_2	CaO	V_2O_5	Mn	Mg
Wt.%	15	3.7	4.8	0.67	0.096	0.018	0.88	54.8	8.44	2.5	0.38	1.1	0.056

2.3 Preparation of Test Specimens

2.3.1 Treatment of aluminium ingot

The cut pieces from ingot were pickled in 10% sodium hydroxide solution at 95-100ºC for 10 minutes. The sinuate formed was removed by immersion for one minute in a mixture of one part nitric acid and one part water followed by washing in methanol. Immediately after drying in air, the weighted quantity of pickled aluminium was melted in a crucible.

2.3.2 Preparation of red mud

The required quantities of red mud (10, 15, 20 and 30 percent by weight) were taken in powder containers. The red mud was preheated in a furnace up to 400ºC and maintained at that temperature before mixing with Aluminum melt.

2.3.3 Melting and casting of test specimen

The weighted quantity of pickled aluminium were melted to desired superheating temperature of 800ºC in graphite crucible 3-phase electrical resistance furnace with temperature controlling device was used for melting. After melting was over, the required quantity of red mud particulates, preheated to around 400ºC were then added to the molten metal and stirred continuously by using mechanical stirrer. The stirring time was maintained between 60-80 seconds at an impeller speed of 550 rpm. During stirring to enhance the wet ability small quantities of Magnesium was added to the melt. The melt with the reinforced particulates were then poured to a prepared cylindrical mould by bottom pouring method. After pouring is over the melt was allowed to cool and solidify in the mould. For the purpose of comparison, the matrix material was also cast under similar processing conditions. The schematic representation of the casting method used in the laboratory is shown in Fig. 2. After solidification the casting were taken out from the mould and were cut to required shape and sizes for wear testing. To ascertain the distribution of reinforcement particulates cut pieces of the samples were polished and were inspected under optical microscope. The distribution with different volume fraction of red mud particles in the matrix are shown in Fig. 3. It is clear from these figures that the reinforcing particles were distributed uniformly in the aluminium matrix.

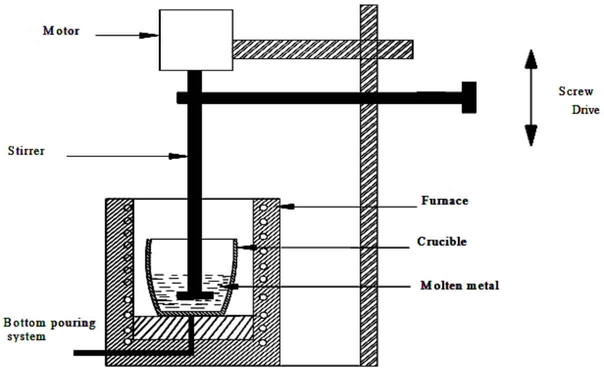


Fig. 2. AMC by stir casting method

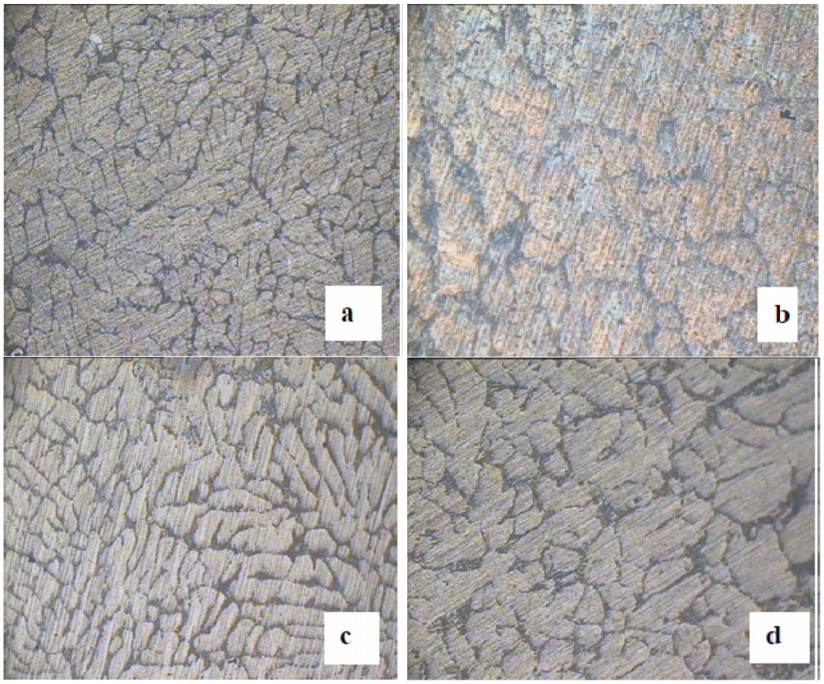


Fig. 3. Micrographs showing red mud distribution in the composites of different Volume fractions (a) 10% (b) 15% (c) 20% and (d) 30% at (200 X)

2.4 Determination of Amount of Wear

Before conducting the test, the pin and the disc surfaces were polished with emery papers, so that the contact will be a smooth one. All the wear tests were carried out as per ASTM G-99 standard under unlubricated condition in a normal laboratory atmosphere at 50-60% relative humidity and a temperature of 28-32ºC. Each test was carried out for 6 hours. The mass loss in the specimen after each test was estimated by measuring the weight of the specimen before and after each test using an electronic weighing machine having accuracy up to 0.01mg. Care has been taken so that the specimens under test are continuously cleaned with woollen cloth to avoid the entrapment of wear debris and to achieve uniformity in experimental procedure. The test pieces are cleaned with tetra-chloro-ethylene solution prior and after each test.

2.4.1 Calculation

Wear rate was estimated by measuring the mass loss in the specimen after each test and mass loss, Δm in the specimen was obtained. Cares have been taken after each test to avoid entrapment of wear debris in the specimen. Wear rate which relates to the mass loss to sliding distance (L) was calculated using the expression,

$$Wr = \Delta m/L$$

The volumetric wear rate W_v of the composite is relate to density (ρ) and the abrading time (t), was calculated using the expression,

$$W_v = \Delta m/\rho t$$

The friction force was measured for each pass and then averaged over the total number of passes for each wear test. The average value of co-efficient of friction, μ of composite was calculated from the expression,

$$\mu = F_f / F_n$$

Where F_f is the average friction force and F_n is the applied load.

Where F_f is the average friction force and F_n is the applied load. For characterization of the abrasive wear behaviour of the composite, the specific wear rate is employed. This is defined as the volume loss of the composite per unit sliding distance and per unit applied normal load. Often the inverse of specific wear rate expresses in terms of the volumetric wear rate as

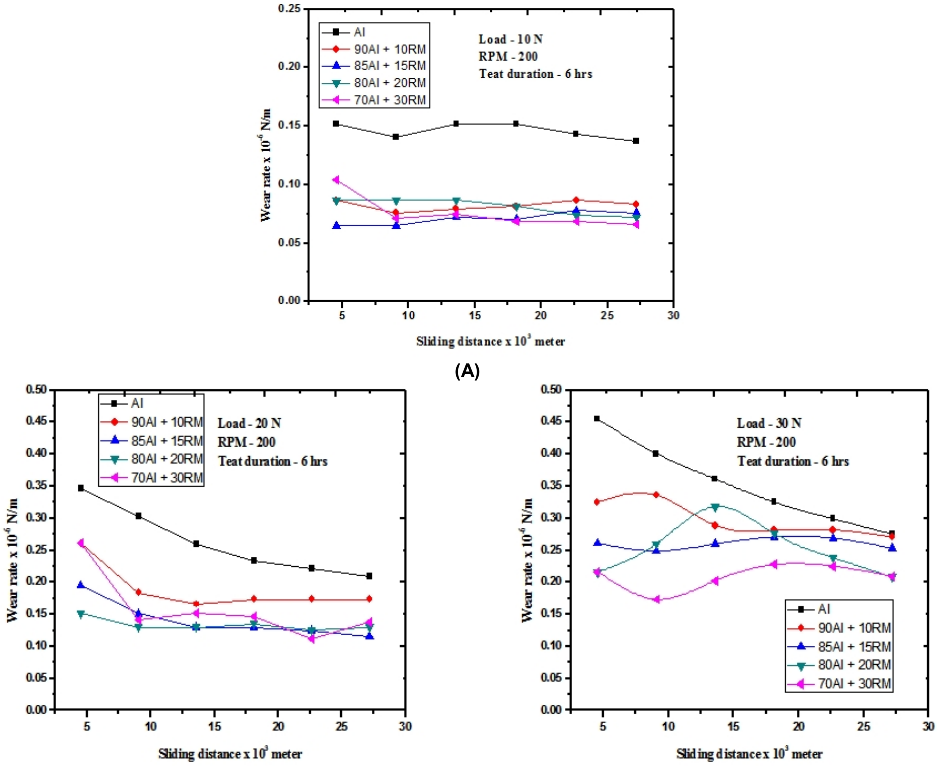
$$W_s = W_v/V_sF_n \text{ , Where } V_s \text{ is the sliding velocity.}$$

3. RESULTS AND DISCUSSION

Based on the results, various graphs are plotted and presented in Fig. [4-9] for different percentage of reinforcement under different test conditions. Fig. 4 shows the variation of wear rate with sliding distance for different loads (10N, 20N, 30N) at 200 rpm. It is seen from the plots that with addition of red mud particles the wear rate of the composite increases and decreases with increasing filler volume %. Also as the sliding distance increases the wear rate first decreases and then almost remains same for the entire test period. Fig. 5 shows the variation of specific wear rate with filler volume fraction i.e. red mud.

It is clear from the plot that the specific wear rate decreases with increase in filler volume fraction and after attaining a minimum value within 10-20% and then it passes through a maximum as shown in Fig. 5.

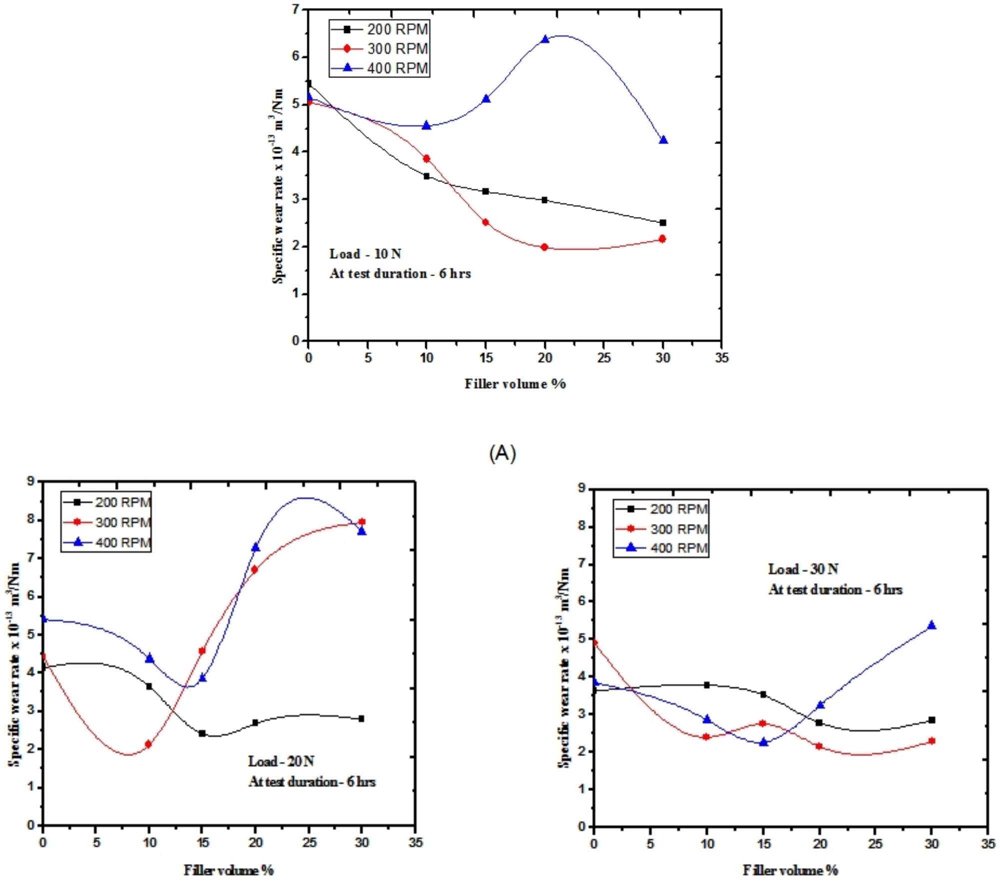
Thus there exists an optimum filler volume fraction, which gives maximum wear resistance to the composite. Fig. 6 shows variation of specific wear rate with sliding velocity. The plot shows that the specific wear rate of the composite increases with increase in sliding velocity. From the figure it is also clear that rate of increase of wear rate is initially high and decreases as the load increases. For 30% volume of red mud this is somewhat deviating in all cases i.e. the wear rate increases to a very high value in comparison to other. Fig. 7 shows the variation of volumetric wear rate with normal load. It can be observed from the plots that the volumetric wear rate increases with increase in normal load. This is because at higher load, the frictional thrust increases, which results in increased debonding and fracture. It is also evident from the plot that at higher speed and high volume fraction, the volumetric wear rate of the composite for a load of 20 N is higher than pure aluminium. This shows the dependence of load and the volume fraction of red mud on the volumetric wear behaviour of the composite over pure aluminium. At 400 rpm (i.e. velocity, V_s = 3.141 m/sec) the critical load (the load above which the composite shows higher volumetric wear rate than pure aluminium) was reduced to 20 N.



(A)

(B) (C)

Fig. 4. Varaiation of wear rate with sliding distance

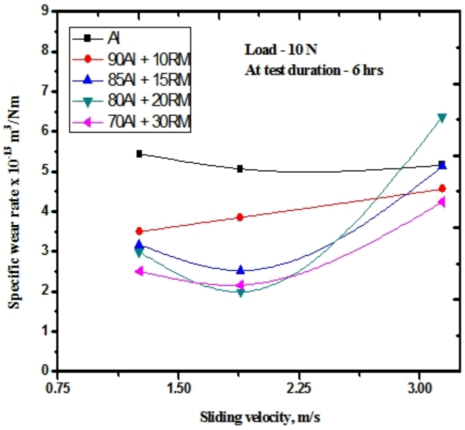


(A)

(B)

(C)

Fig. 5. Variation of specific wear rate with volume fraction



(A)

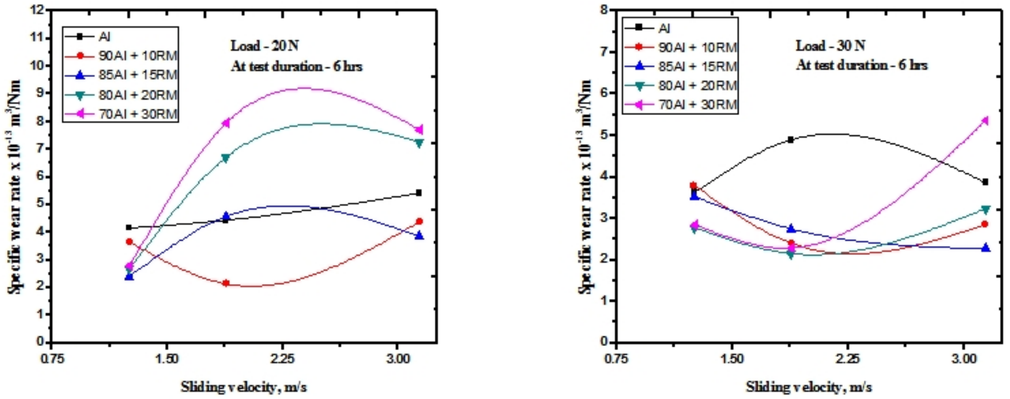
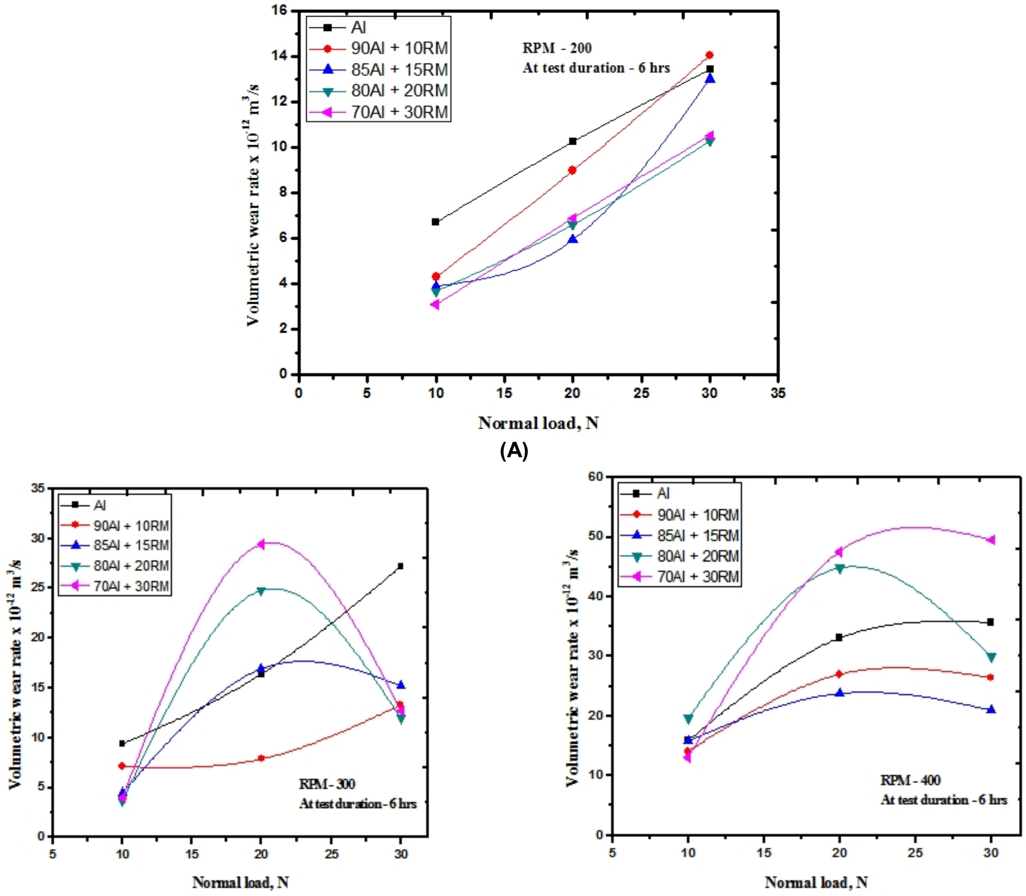


Fig. 6. Variation of specific wear rate with sliding velocity



(A)

(B)

(C)

Fig. 7. Variation of volumetric wear rate with normal load

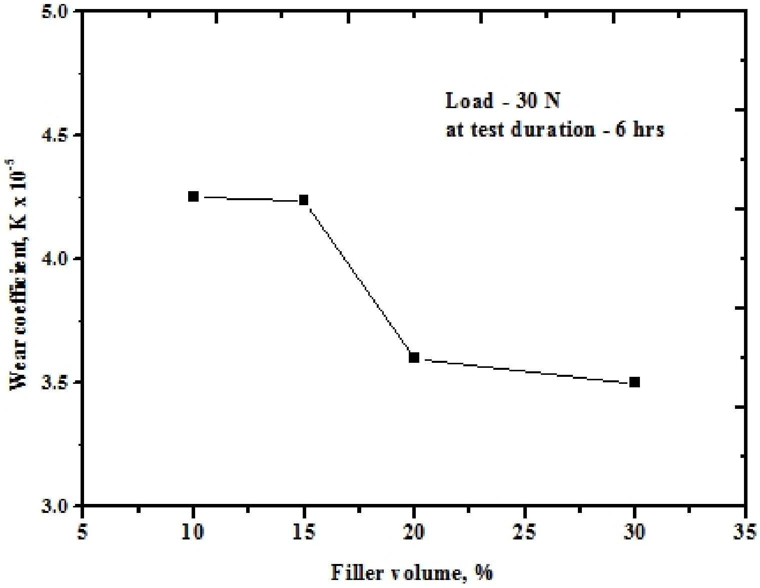
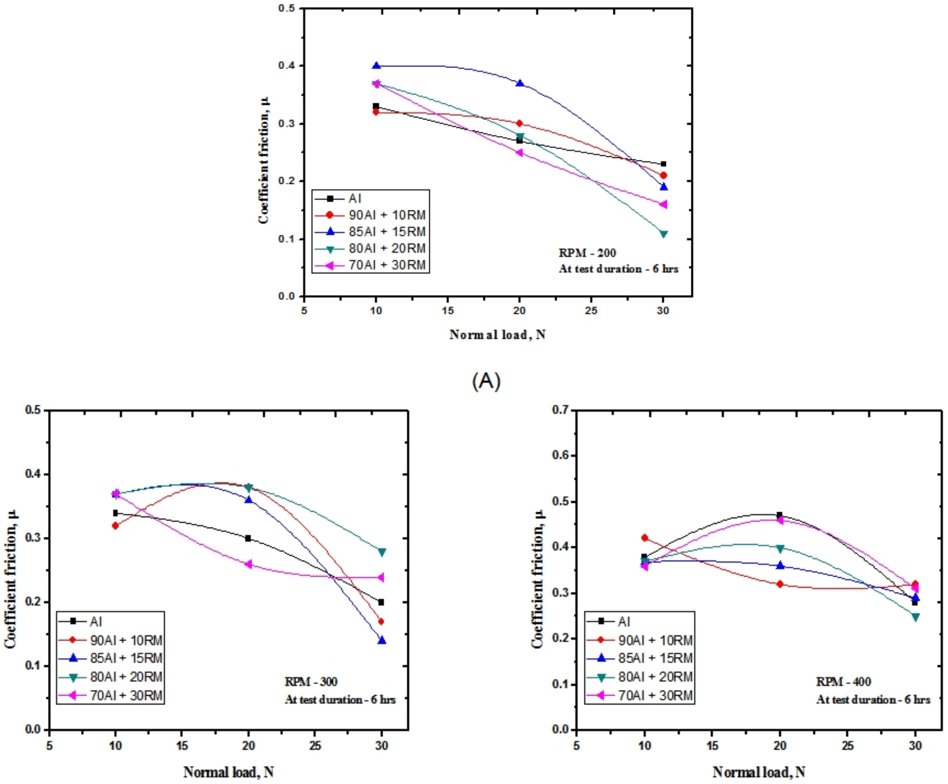


Fig. 8. Variation of wear coefficient with filler volume



(A)

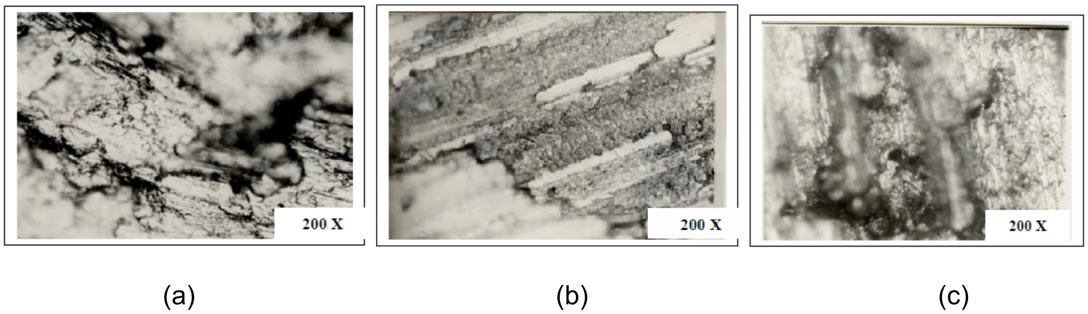
Fig. 9. Variation of coefficient of friction with normal load

As many parameters e.g. sliding velocity, sliding distance and load are responsible for wear and are expressed in the figures, it is more appropriate to express the sliding wear results in terms of the wear constant, K as extracted from Archard’s law. For known values of V (wear volume), H (Vickers hardness of the softer material), S (sliding distance) and L (normal load), the wear coefficient (K) can be determined from the following equations:

$$V = K\,L\,S / H$$

The wear constant K is a correlation factor between several variables of the sliding wear experimental results and is related to various microscopic mechanisms. Fig. 8 shows the variation of wear co-efficient with particle volume content. It is apparent in this figure that the wear co-efficient tends to decrease with increasing particle volume content. Thus red mud addition up to an optimum volume of (15-20) % is beneficial in reducing the wear of aluminium red mud composite. Fig. 9 shows the variation of coefficient of friction with normal load. This shows that the coefficient of friction in all cases decreases with the increase of normal load.

The worn out surface of some selected specimens after the wear test are observed under optical microscope Fig. [10(a-c)] shows the surface morphology of aluminium 10% red mud composite, tested under two different load and speed conditions . When the sample is tested at slow speeds i.e. at sliding velocity of 300 rpm, Fig. 10 (a), it appears that cavities are formed in the composite matrix and have aligned parallel to the direction of sliding. Some particles also have chopped off during sliding. With increase in sliding velocity i.e. at 400 rpm, Fig.10 (b), worn surface shows a different appearance. The amount of cavitations is less than that of the previous case.



(a) (b) (c)

Fig. 10. Micrographs showing wear surface of 10% red mud (a) load 20N and 300 rpm (b) load 20N and 400 rpm and (c) load 30N and 400 rpm

In some regions, the substructures are aligned parallel to the sliding direction. In some area smaller particulate have come out from the composite matrix. For the same composite, at same sliding speed of 400 rpm and with increasing applied load i.e. from 20 N to 30 N, cracks have appeared and are propagated in different direction. These might have help in chipping of hard particles i.e. red mud. In case of aluminium-15% red mud composite tested with sliding velocity of 300 and 400 rpm, are shown in Fig.[11(a-b)].

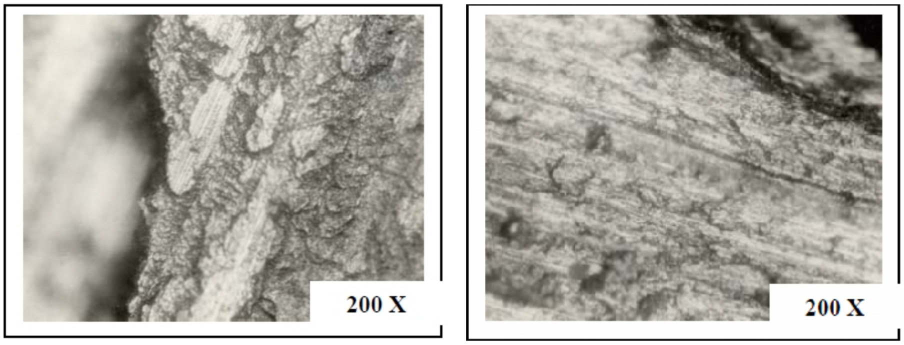


Fig. 11. Micrographs showing wear surface of 15% red mud (a) Load 20N and 300 rpm (b) load 20N and 400 rpm

From the figure it can be seen that with increasing the sliding velocity grooves have appeared [Fig. 11(b)] where as at lower speeds, wave types structures is observed [Fig. 11(a)]. The structures of the worn surfaces are greatly dependent on sliding speed and applied load conditions. The surface structures of the samples (Al+20% RM) are shown in Fig. [12(a-e)]. Comparing these figures it can be visualized that when the sample is rubbed, against steel wheel, at low sliding speed and low applied load hard particles might have chipped off and the aluminium grains are grown into bigger sizes with increase in applied load i.e. from 10 N to 30 N, Fig. [12 (b-c)], the aluminium matrix appears to be smeared along the direction of the sliding. Amount of cavitations also have increased. Some cavities appear to be formed around the hard particles, (i.e. red mud particulates). For the same composite the worn surfaces obtained at higher sliding velocity, (i.e.400 rpm), for two different applied load (i.e.10 N and 20 N) are shown in Fig. [12(d-e)]. The worn surfaces are relatively smoother than that at lower sliding speeds Fig. [12(a-b)]. It may be noted that cracks are formed parallel to the sliding direction. When the applied load is small, fragmentation of hard particles (i.e. red mud) occurs along the crack lines. With increase in applied load although the amount of cavitations appears to be low but deep cracks and grooves are clearly visible [Fig. 12 (e)].

Large plastics strains can arise in the composite matrix coming into direct contact with the steel counter face leads to subsurface crack propagation and subsurface delamination. From the micrograph Fig. [12(a-c)], it is seen that some cracks are formed at the grain boundaries of aluminium. This might be due to strain hardening of aluminium during sliding with a applied load and due to pulling up of hard phase particles i.e. red mud from the aluminium grain boundaries. With increasing the applied load this effect is more pronounced. This might have been caused due to embrittlement of hard particles during sliding.

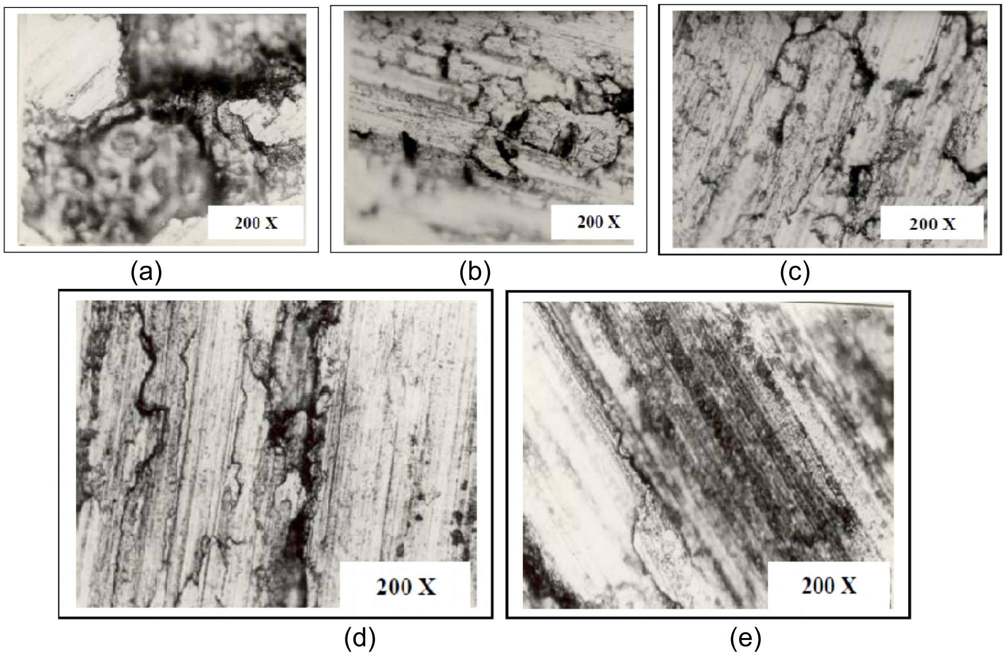


Fig. 12. Micrographs showing wear surface of 20% red mud (a) load 10N and 200 rpm (b) load 20N and 200 rpm (c) load 30N and 200 rpm (d) load 10N and 300 rpm & (e) load 20N and 400 rpm

4. CONCLUSIONS

Aluminium matrix composites have been successfully fabricated with fairly uniform distribution of red mud particles. Dispersion of red mud particles in aluminium matrix improves the hardness of the matrix material and also the wear behaviour of the composite. The effect is the increase in interfacial area between aluminium matrix and red mud particles leading to the increase in strength appreciably. Coefficient of friction decreases as the load increases. At higher load and higher speed specific wear rate decreases with increases in Red mud content. Wear coefficient tends to decrease with increasing particle volume content. It also indicates that red mud addition is beneficial in reducing wear of the aluminium red mud composite. Wear resistance of the composite increases due to addition of red mud particles. However there exists an optimum filler volume friction which gives maximum wear resistance to the composite.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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