Dry wear behavior of A356-SiCp functionally graded composite in unidirectional and reciprocating contacts

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Abstract

Purpose – The purpose of this study is to distinguish the difference in tribological behavior of functionally graded composites in two sliding modes, namely, unidirectional and reciprocating.

Design/methodology/approach – A356-(10 Wt.%)SiCp functionally graded composite material (FGM) was prepared by vertical centrifugal casting and then a comparison was made between the tribological characteristics using pin-on-disk and pin-on-reciprocating plate configurations under identical operating conditions (sliding distance (s): 350 m; load (W): 30 = W = 120 N, in steps of 30 N; and velocity (v): 0.2 = v = 1.2 m/s, in steps of 0.2 m/s). Two types of test pins were considered, namely, a test pin taken from the outer zone of the FGM with maximum particle concentration and a test pin taken from the inner zone of the FGM in a matrix-rich region.

Findings – The study revealed that, for the test pin taken from the outer zone of the FGM in the low-velocity range (0.2–0.4 m/s), the reciprocating wear of the friction pair was dominant, while unidirectional wear was dominant in the velocity range of 0.6–0.8 m/s for the entire load range investigated. However, when the velocity was increased from 1.0 to 1.2 m/s, conflicting nature of dominancy in the wear characteristics of the friction pair was observed, depending on the loading condition. In addition, the inner zone FGM pin underwent seizure in the reciprocating mode, whereas this phenomenon was not seen in the unidirectional mode.

Originality/value – Differences in wear and friction characteristics of FGM friction pairs in two different sliding modes were investigated over a wide range of operating parameters.

Keywords Hardness and microstructure, Wear and friction, Aluminium matrix composites, Continuous dry sliding, Reciprocating movement

Paper type Research paper

1. Introduction

Ceramic-particle-reinforced functionally graded aluminum alloy composites are advanced composite materials in which the composition and structure change gradually in the radial direction, resulting in modifications in the properties of the material. These materials exhibit properties such as elevated-temperature surface wear resistance, surface friction, thermal characteristics, crack retardation and improved fracture strength (Wang *et al.*, 2017; Rajan and Pai, 2009), making them ideal candidates for various engineering applications (Vieira *et al.*, 2009). The excellent surface wear characteristics at elevated temperatures facilitate the extensive use of these materials in various components of internal combustion engines. Therefore, it is of utmost importance to understand the wear behavior of such materials for the safe and efficient operation of internal combustion engines.

Most dry-sliding wear studies on functionally graded composite material (FGM) reported in the literature using a pin-on-disk tribometer wherein the relative motion is only in one direction (unidirectional). Unidirectional wear characteristics have been extensively investigated by researchers over the past few decades using block-on-ring and pin-on-disk configurations for various materials as a function of load, speed, sliding distance and temperature. Sarkar and Clarke (1980) studied the friction and wear characteristics of Al–Si alloys under unidirectional motion using a pin-on-disk machine and they reported that the eutectic alloy was the most wear-resistant alloy of the Al–Si alloy family. Kato (2002) reviewed the wear mechanisms in detail and categorized the various wear mechanisms under three types of wear, namely, mechanical, chemical and thermal. Experiments were conducted by Wilson and Alpas (1997) on an A356–SiC composite with the primary intention of constructing a wear transition map to demarcate the load and speed conditions under

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which the transition from mild to severe wear occurred. It was reported that the inclusion of SiC particles in the A356 matrix alloy allowed the transition from mild to severe wear to higher speeds and loads. Kwok and Lim (1999) studied the unidirectional friction and wear behavior of Al–SiC$_p$ composites under a wide range of speeds and loads. Their study identified three regimes of tribological behavior that were demarcated by the sliding speed, namely, regime I (speed = 0–3 m/s), where low rates of wear was observed; regime II (speed = 3–8 m/s), in which catastrophic failure occurred if the load exceeded a critical value; and regime III (speed = 8–29 m/s), in which extensive melting of the composite occurred and the size of the reinforcement particle appeared to have a significant influence on the wear rate of the composite.

The above literature survey on unidirectional wear indicates that substantial investigation has been conducted to analyze the influence of load and speed on the wear characteristics of Al–Si–SiC composites. However, in the case of automobile internal combustion engines, reciprocating motion between the cylinder liner and the piston ring results in bidirectional wear. This bidirectional wear depends on the conditions prevailing in the engine during operation, such as high speed, elevated operating temperature, combustive gas environment and lubricating conditions. In addition, in the reciprocating motion, the speed varies throughout a cycle from zero at the two ends to a maximum at the middle of the stroke, which is very different compared to unidirectional, continuous motion. Moreover, factors such as heat build-up, the effect of the change in stress direction on material soundness and entrapment of wear particles can significantly alter the wear characteristics of reciprocating motion in comparison to unidirectional sliding motion (Odabaş and Su, 1997). The reciprocating wear study on aluminum-alumina composite against steel by Nesarikar (1991) revealed that, as the load increased, the coefficient of friction (CoF) and wear initially increased and thereafter decreased. It was reported that the aforementioned behavior of the alumina-reinforced composite could be attributed to the increase in hardness resulting from re-embedding of the fractured alumina particles near the surface of the composite plate at high loads. Bai *et al.* (1995) reported that the Al–SiC whisker composite exhibited better wear characteristics and an increased CoF than 2024-Al alloy by the experimentation on the oscillating ball-on-plate wear test rig. They also concluded that delamination and adhesion are the two principal wear mechanisms at low loads, whereas plowing and oxidation are the principal wear mechanisms at higher loads. Reciprocating wear tests have been performed to study the effect of stroke length on the wear and friction characteristics of Al alloy–SiC composite by Gomes *et al.* (2005). They derived a relationship between the energy dissipated and wear volume with the intention of comparing the influence of stroke length on wear behavior and found that increase in stroke from 2 to 6 mm resulted with a higher wear/energy rate. Rajeev *et al.* (2010) conducted experiments to study the influence of load and speed on the mild to severe wear behavior of Al–Si–SiC$_p$ composites using a reciprocating tribometer with a longer stroke length of 100 mm. Their study revealed that, as the normal load increased, the wear rate increased. It was also reported that the change in wear behavior from mild oxidative to severe metallic wear was highly dependent on the reciprocating speed, load and the type of composite.

Apart from these separate investigations conducted on unidirectional and reciprocating wear, few studies pertaining to a comparison of the two modes can be identified in the literature (Marui and Endo, 2001; Cai *et al.*, 2019). Reddy *et al.* (1995) also investigated the dry wear behavior of Al–Si alloy pins sliding against steel, in both reciprocating and continuous sliding modes and reported that the wear and seizure resistance are highly dependent on the mode of sliding, as well as the reciprocating speed.

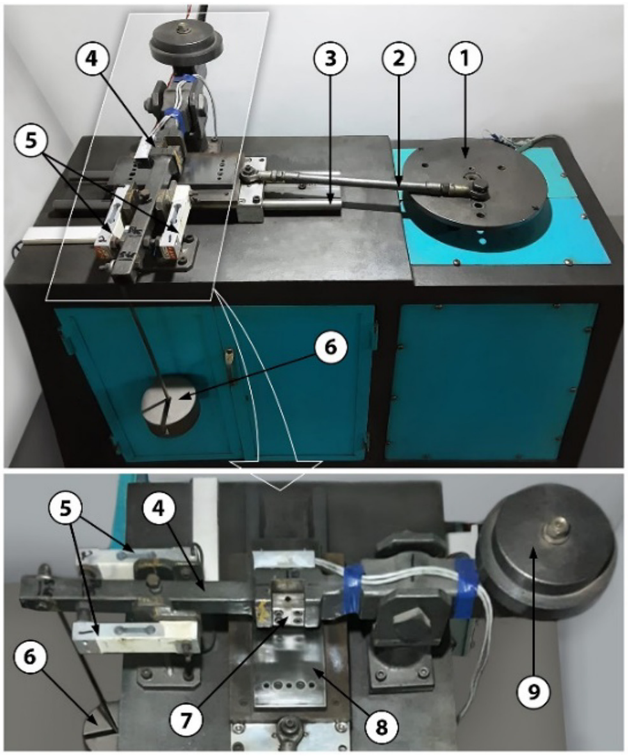
Although significant contributions have been made by many investigators on the wear characteristics of composite materials, most of these investigations were conducted for a stroke length of ≤ 80 mm. It is important to mention here that, in heavy-duty internal combustion engines such as caterpillar and marine engines, the stroke length encountered is >80 mm. In addition, owing to advances in materials technology, aluminum composites have been extensively used in high-speed reciprocating and rotating components such as pistons, cylinder liners and brake rotors because of their higher wear resistance, better strength-to-weight ratio and ease of formability (Miracle, 2005). Recently, FGMs have gained significant importance as candidate materials because of their excellent wear characteristics (Surappa, 2003). In centrifugally cast metal-ceramic FGMs, the graded distribution of the reinforced ceramic particles in the matrix is significantly influenced by the difference in density between reinforced particle and matrix metal, the applied G number, the particle size, the viscosity of the molten matrix, the volume fraction of particles, the cast ring thickness and the solidification time (Watenabe *et al.*, 1998). The computer simulation study by Ogawa *et al.* (2006) reported that the size and density of the reinforced particle in the molten matrix have a significant role in the formation of graded distribution. Al_2O_3 reinforced FGM is suitable for automotive application in view of its enhanced mechanical properties and wear resistance than its unreinforced aluminium matrix (Saleh and Ahemed, 2020). In view of the above, the aim of the present work is to study the influence of the load on the dry wear characteristics of A356–(10 Wt.%)SiC$_p$ functionally graded composite under identical sliding conditions in two different modes with a velocity in the range 0.2–1.2 m/s and an equal sliding distance of 200 mm for every sliding cycle.

2. Experimental methods

The base material used in this study was an A356 alloy for preparing a functionally graded composite with a 10 Wt.% SiC$_p$ dispersoid. This alloy was selected, as it is a hypoeutectic alloy with Si as the major alloying element and is extensively used in engine cylinder liners, pistons and brake rotors, etc. (Dwivedi *et al.*, 2014). In centrifugal casting, the addition of 10 Wt.% SiC to A356 alloy results in approximately 40–50 Wt.% SiC concentration in the outer periphery of the FGM casting, which could give sufficient engineering properties to automotive components (Rodriguez-Castro and Kelestemur, 2002). The average particle size of the SiC particles was 28 μm with a density of 3.2 g/cm^3. To produce the composite slurry, the A356 matrix material was first melted in a commercial bottom pouring electric stir casting furnace (SwamEquip Pvt., Ltd., India) by maintaining the temperature of the furnace at 750°C. Preheated SiC powder at 500°C was added at a controlled feed rate to the melt along with motorized stirring at 400–500 rpm for the preparation of the A356–SiC$_p$ composite. The port hole located at the bottom of the furnace was opened to pour the molten alloy composite through a funnel into the preheated rotating steel die of the vertical centrifugal casting machine (SwamEquip Pvt., Ltd., India). The preheating temperature and speed of rotation of the mold were maintained at 300°C and 1,300 rpm, respectively. The weight of the prepared A356–(10 Wt.%) SiC_p FGM composite ring was 3.36 kg with average radial and axial thicknesses of 90 and 28 mm, respectively. Samples were cut from the cast FGM ring to evaluate their microstructure and hardness. The microstructure of the as-cast FGM composite sample was characterized using an optical microscope (Leica DM2700M). A Brinell hardness tester was used to test the variability in hardness along the radial line from the external to internal edges of the cast FGM ring. The preparation and processing techniques of Al-FGM was detailed in the published work by Premkumar *et al.* (2021).

To study the wear characteristics of the cast FGM ring, wear test pins with a diameter of 6 mm and a length of 40 mm were cut radially inward to obtain a particle-rich zone (outer region) at one end and a matrix-rich zone (inner region) at the other end of the pin using a wire cut electric discharge machine. It was also evident from the microstructure-hardness correlation curve (Figure 3), that the hardness is higher toward the outer periphery indicating the significant presence of SiC particles in the outer periphery of the ring. Hence, the particle-rich sliding surface (i.e. one end) of the test pin was cut 5 mm away from the outer periphery. The matrix rich surface (i.e. other ends) of the pin was taken at 45 mm from the outer periphery of the as cast FGM ring. The pins were heat-treated under T6 conditions. The entire wear test was conducted using heat-treated pins with the contacting surface taken as a particle-rich zone. Comparative wear tests of FGM pin samples were conducted under similar sliding conditions (Table 1) using an in-house-developed pin-on-reciprocating plate tribometer (Figure 1), designed according to American Society for Testing and Materials G133–05 standards (Rajeev *et al.*, 2009) and pin-on-disk (Ducom TR20LE) tribometer. EN-31 steel was used as the counter surface for both the tribopairs; its average surface roughness (Ra) was 0.42 μm and its hardness was 60 Hardness Rockwell C. All the experiments were conducted in ambient air with a relative humidity of 78 ± 6% and a temperature of 30 ± 2°C. The weight loss was measured using an electronic weighing balance with an accuracy of 0.01 mg. Wear tests were conducted in two sliding modes with four different loads of 30, 60, 90 and 120 N and velocity in the range of 0.2–1.2 m/s.

Figure 1 Photographic view of an indigenously in house developed pin-on-reciprocating plate tribometer confirming to ASTM G-133-05 standard



Notes: 1. Crank disc; 2. Connecting rod; 3. Linear bearing; 4. Load arm; 5. Load cells; 6. Dead weights; 7. Test pin holder; 8. Reciprocating EN-31 steel counter surface; 9. Balancing weights

3. Results and discussion

3.1 Microstructure and hardness

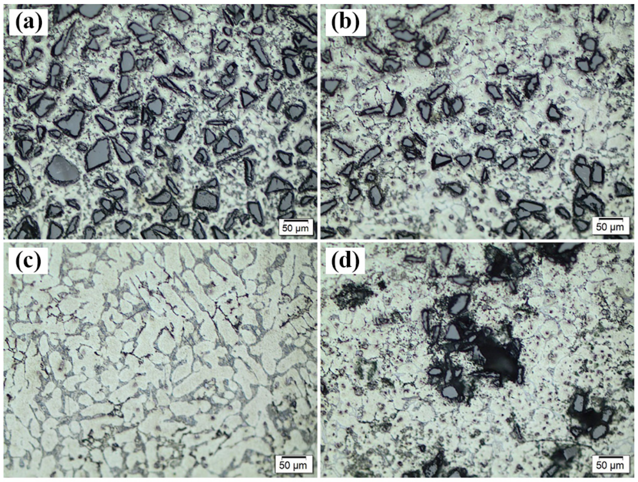
The variation in SiC particle concentration in the radial direction was observed in the microstructural images taken using an optical microscope (Leica DM2700M, Germany) of the sample cut from the centrifugally cast FGM disk. The assorted size and shape of SiC particles in the micrograph were measured using image analysis software and the average particle size was obtained as 28 μm. The microstructure images of the as-cast A356–SiC_p FGM depicted in Figures 2(a)–2(d) clearly show the presence of a particle-rich outer region (2–11 mm), a transition region (11–23 mm), a matrix-rich inner region (23–53 mm) and a region with porosities and particle agglomeration (53–90 mm). However, SiC particles were not observed in the matrix-rich region [Figure 2(c)]. The varying concentration of SiC particles in the FGM, as shown in Figures 2(a) and 2(b), can significantly alter the hardness of the ring in the radial direction. To obtain quantitative information about the hardness values of the as-cast sample, the Brinell hardness test was conducted at different locations on the sample at intervals of 2.5 mm. The variation in hardness value depicted in Figure 3 clearly indicates that the hardness decreases with distance from the

Table 1 Wear test conditions and range of operating parameters

Test type	Load	Sliding velocity	Sliding distance	Wear track (mm)	
	(*N*)	(m/s)	(m)	Radius	Stroke
Pin-on-disc	30–120	0.2–1.2	350	32	—
Pin-on-reciprocating plate	30–120	0.2–1.2	350	—	100

(Operating parameters spans Load through Wear track.)

Figure 2 Optical micrographs showing the microstructure of FGM



Notes: (a) – Outer particle rich region; (b) – transition region; (c) – matrix rich region; (d) particle agglomeration and porosities region

outer edge toward the inner edge in the radial direction, clearly demonstrating a reduction in SiC particles in the radial direction. As shown in Figure 3, a sharp drop in hardness was observed beyond 53 mm. The presence of particle agglomeration and gas porosity is clearly evident in the optical microscopic image depicted in Figure 2(d). The decrease in hardness is attributed to particle agglomeration and gas porosity (El-Galy *et al.*, 2017).

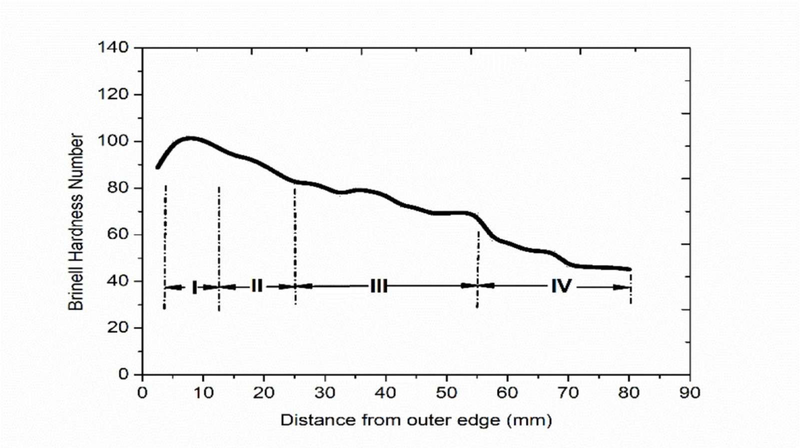
3.2 Wear characteristics

The dry wear behavior of A356–SiC$_p$ FGM sliding against an EN-31 steel plate–disk was studied in reciprocating and unidirectional sliding modes under similar operating parameters using a pin-on-reciprocating plate and pin-on-disk tribotesters. The wear test data presented here are an average of the three experiments. The scatter fall within 10% of the mean value.

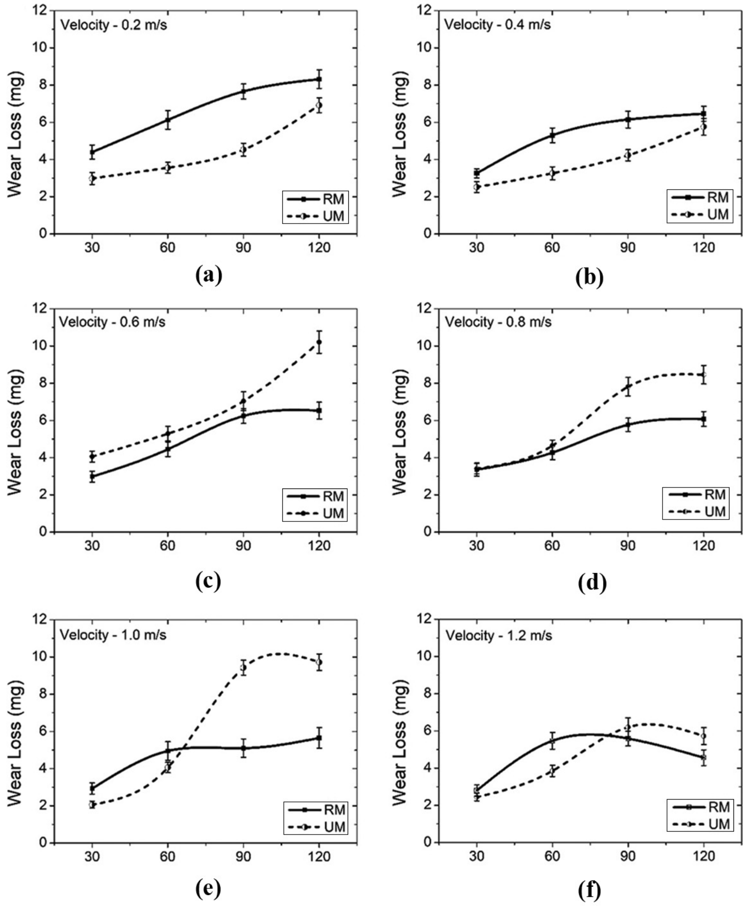
3.2.1 Influence of load on dry wear loss of the functionally graded composite material in two sliding modes

Figures 4(a)–4(f) show the wear characteristics of the FGM (outer cylindrical pin) versus the load with different sliding speeds (0.2–1.2 m/s) in tests in which a sliding distance of 350 m in both sliding modes was maintained. The total distance covered for each cycle was 200 mm for the two sliding modes. It can be inferred from Figures 4(a) and 4(b) in the speed range of 0.2–0.4 m/s that reciprocating wear dominates the unidirectional wear. This dominance of reciprocating wear was because of more chances of debris entrapment between the sliding interfaces during the wearing process in reciprocating mode (RM) compared to unidirectional mode (UM) at low sliding conditions, which, in turn, causes the trapped particle to roll and slide leading to three-body abrasion, as detailed by Ward (1970). However, in the speed range of 0.6–0.8 m/s, unidirectional wear dominated over reciprocating wear, as illustrated in Figures 4(c) and 4(d). The dominance of unidirectional wear over reciprocating wear is due to the displacement of wear debris from the surface in the RM, which, in turn, causes less three-body interaction compared to the UM. In addition, the particle size of the wear debris and less contact time contributes to reduced wear in the RM compared to the UM in the aforementioned speed range (Hwang *et al.*, 1999). Upon a further increase in speed from 1.0 to 1.2 m/s, conflicting behavior in wear was observed, as shown in Figures 4(e) and 4(f). At lower loads, the RM dominates the UM under this range of speed tested. This is attributed to the fact that, at higher speeds, the energy dissipation rate resulting from frictional heating is higher in the RM than in the UM, and hence, thermal softening is higher in the RM (Gomes *et al.*, 2005). At the same time, under higher loads and speeds of 1.0–1.2 m/s, unidirectional wear was dominant compared to reciprocating wear. The chances of debris entrapment between the sliding surfaces during the wearing process cause the trapped particle to roll and slide leading to three-body abrasion. From Figure 5(a), it was noticed that trapped wear particles in UM at higher sliding conditions joined to form larger ones with flat geometry having their size ranged approximately 200–430 μm, showing agglomeration dynamics because of

Figure 3 Variation of BHN radially inward direction; I-particle rich zone, II-transition zone, III-matrix rich zone, IV-particle agglomeration and porosities zone



Figures 4 Wear loss against load plots under RM and UM at velocities



Notes: (a) – 0.2 m/s; (b) – 0.4 m/s; (c) – 0.6 m/s; (d) – 0.8 m/s; (e) – 1.0 m/s; (f) – 1.2 m/s

three-body abrasion in UM (Hwang,1999). However, debris formed from RM [Figure 5(b)] was found to be flung from the sliding interface, which, in turn, reduced the chances of three-body wear.

3.2.2 Friction behavior of the functionally graded composite material in two different modes of sliding

The phenomenon of wear, which affects the quality of materials in contact with each other, occurs because of the frictional force existing between the contact surfaces. To study this, the CoF was plotted as a function of sliding speed for loads of 30 and 120 N for both sliding modes (Figure 6). It can be inferred from the figure that, for a load of 30 N, the CoF in the UM continuously decreases with an increase in speed. This behavior can be attributed to the tribochemical reaction occurring at the interface between the pin and the counter surface EN-31 steel, making the pin surface at the sliding interface red hot and soft. This causes the material to detach from the pin and subsequently cover the wear track surface as a layer. This layer because of its softness behaves like a solid lubricant under sliding conditions and reduces the CoF (Ravikiran and Surappa, 1997). However, for unidirectional sliding subjected

Figures 5 SEM images of wear debris under 120 N load and 1.2 m/s velocity

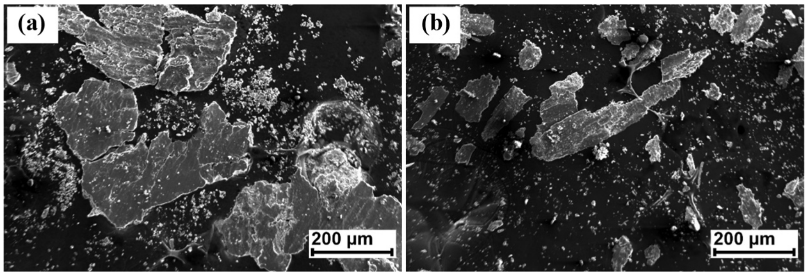
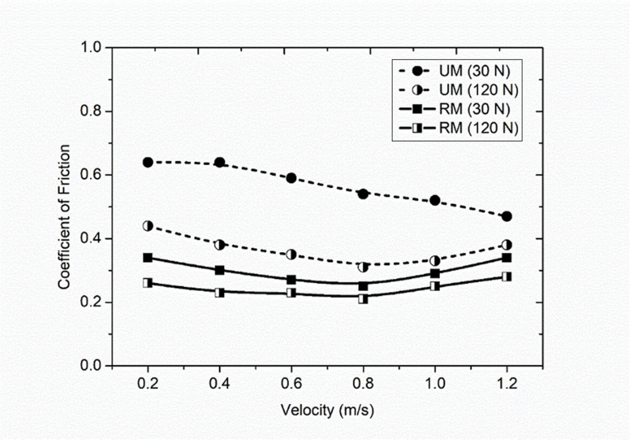


Figure 6 CoF – velocity plot at 30 N and 120 N loads in UM and RM

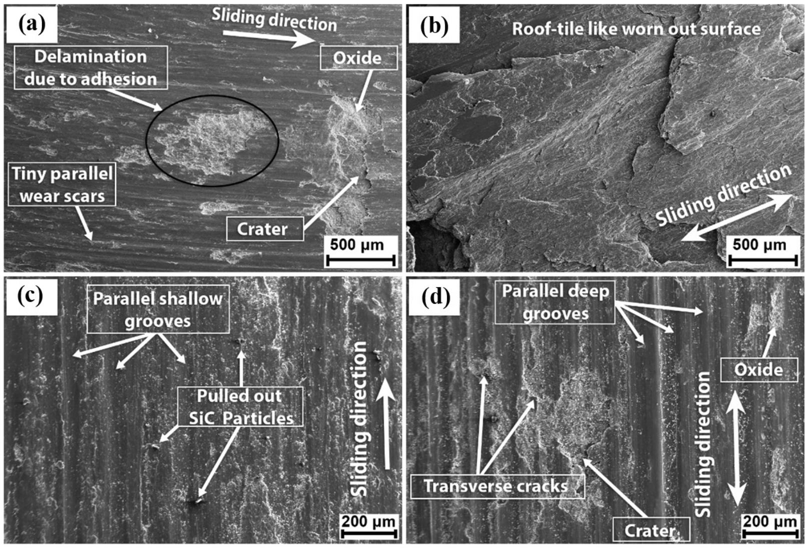


to a load of 120 N and reciprocating sliding subjected to loads of 30 and 120 N, the CoF decreased continuously up to a speed of 0.8 m/s and thereafter it increased. The increase in the CoF trend above 0.8 m/s in the two modes is attributed to thermal softening occurring on the sliding surfaces with increasing speed, which, in turn, causes SiC to protrude over the pin surface, leading to two-body abrasion. As the velocity increased above 0.8 m/s for load 120 N in UM and both loads 30 N and 120 N in RM, a slight increase in friction coefficient was noticed and was attributed to the frictional heating of the tribopair leading to the rise in temperature of the contacting surfaces resulting in the fast formation of tribolayer (Natarajan *et al.*, 2006). At a normal load of 120 N, the tribopair exhibited a lower CoF than at a 30 N load in both sliding modes. Increased surface roughening and a large quantity of wear debris are believed to be responsible for the decrease in friction with an increase in the normal load (Blau, 1986). It is also important to mention here that the CoF of the FGM in the UM was found to be higher than that in the RM at low and high loads for the entire speed range considered in this study. The higher CoF in unidirectional contact is because of the fact that deposits of plowed material ahead of the slider are likely to manifest over a longer period of time than those in reciprocating contact (Blau and Walukas, 2000).

3.2.3 Evaluation of wear behavior of test pins in two sliding modes

To study the influence of the concentration of SiC particles on the wear characteristics of A356–(10 Wt.%)SiC$_p$ FGM, two heat-treated test pins, one from the outer zone (SiC-particle-rich region) and the other from the inner zone (matrix-rich region) of the centrifugally cast FGM ring were taken. Experiments were conducted for a load of 120 N at a speed of 1.2 m/s. Qualitative insight into the wear characteristics of the test pins was obtained from the scanning electron microscope images of the worn-out pin surfaces and are depicted in Figures 7(a)–7(d). SEM micrograph [Figure 7(a)] of worn-out matrix rich inner pin surface revealed that in UM sliding condition wear scars, craters and oxidized surface characteristics were the main mechanisms responsible for material loss. The oxide debris generated during oxidative wear under dry sliding may have two contradictory roles. They may get locked between the sliding surfaces and promote three-body wear. Otherwise, these oxide particles in the debris between the sliding surfaces can also get compacted to form a protective transfer layer so as to reduce wear. However, at the same sliding condition in RM, revealed roof-tile such as surface, gross plastic deformation and damage [Figure 7(b)] characteristics of seizure phenomenon in severe wear condition. The severe wear manifested itself by massive surface damage and large scale aluminium transfer to the counter surface EN-31 steel accompanied by generation of coarse debris; typically in the shape of a plate with a shiny metallic appearance [Figure 5(b)] visible to the naked eye. The scale of surface deformation and

Figures 7 SEM images of worn out surfaces tested under 120 N load and 1.2 m/s velocity



Notes: (a) – Matrix rich inner pin in UM; (b) – matrix rich inner pin RM; (c) – particle rich outer pin in UM; (d) – particle rich outer pin in RM damage was considerably higher in RM compared with that in UM. However, in the case of the outer test pin, there was no clear evidence of metallic wear in the UM or the RM owing to the presence of load-bearing SiC particles. In the UM, narrow and parallel shallow grooves were observed [Figure 7(c)], while deeper grooves and wider plastic deformation ($\sim$40–150 μm) [Figure 6(d)] occurred in the reciprocating sliding mode of the FGM outer pin. In reciprocating sliding, rougher craters were observed in Figure 7(d) than in unidirectional sliding and closely spaced transverse cracks were also observed on the surface of wider grooves. Even though the dominant wear mechanism in both the modes was abrasive in nature, the scale of abrasive wear was more in RM than in UM.

4. Conclusion

In this work, the influence of sliding modes on the wear behavior of A356–SiC_p FGM was investigated using pin-on-disk and pin-on-reciprocating plate configurations. The salient conclusions of the study are as follows:

In the speed range of 0.2–0.4 m/s, reciprocating wear dominated over unidirectional wear and this behavior is attributed to more entrapment of wear debris in the RM than in the UM.

A further increase in speed (to 0.6–0.8 m/s) resulted in the dominance of unidirectional wear over reciprocating wear. This phenomenon is due to the displacement of wear debris from the sliding surface in the RM at a higher speed, causing less three-body interaction than in the UM.

In the speed range of 1.0–1.2 m/s, the wear characteristics in both modes were highly dependent on the load. At lower loads, RM dominates over UM whereas, at higher loads, UM dominates over RM. A higher energy dissipation rate resulting from frictional heating and thermal softening at lower loads in the RM results in higher wear. However, at higher loads, wear debris is found to be flung from the sliding interface, causing less three-body interaction, culminating in less wear in the RM.

The CoF in the UM is higher than that in the RM for the entire speed range and loads considered in this study. The higher CoF in unidirectional contact is because of more chances of there being deposits of plowed material ahead of the slider for a longer period of time.

The influence of SiC particles on the wear behavior of the centrifugally cast FGM inner and outer pin specimens was explained through scanning electron microscope images.

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