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Mechanical and dry sliding wear properties of silicon carbide particulate reinforced aluminium–copper alloy matrix composites produced by direct squeeze casting method

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ABSTRACT

In this study, the microstructural features, mechanical properties and dry sliding wear characteristics of Al–4.5Cu–3Mg/15 vol.% SiCp matrix composites, manufactured by squeeze casting technique, were investigated. Wear tests were carried out at 0.5, 1 and 2.0 m/s sliding speeds under the loads of 5, 10, and 15 N for a 1000 m sliding distance versus AISI D2 steel disc. The results showed that, the composites have homogeneously distributed porosity free SiC particles. The failure in composites occurs in both matrix and particles simultaneously implying good bonding between matrix and particles. Friction coefficient of the composites decreased with an increase in the applied load and the sliding speed. In addition, the higher the applied load and the faster the sliding speed are, the higher the wear rate is. SEM analysis indicated that worn surfaces consisted of plastically deformed and oxidized particles removed by the micro-machining effects of the reinforcement phase.

1. Introduction

Aluminium-based alloys are widely used in the automotive and aerospace industries because of their low densities and good mechanical and tribological properties. However, the relatively poor seizure resistance of aluminium alloys has restricted their uses in such engineering applications [1]. The wear resistance of these alloys can be improved considerably by adding ceramic reinforcements into aluminium, leading to the formation of the metal-matrix composites (MMCs). Incorporation of ceramic reinforcements can result in a favourable combination of the high ductility and the high strength [2,3]. The ceramic reinforcements generally can be in the form of particles, whiskers and fibres. Particulate reinforced MMCs appear to be the most popular choice because they can offer relative ease in processing, lower fabrication cost, and nearly isotropic properties in comparison to fibre-reinforced materials [4–6].

Al-matrix composites are preferred in many applications such as, bearings, gears, seals, guides, piston rings, pistons, cylinder heads, brakes and clutches [4,7]. It has been observed that abrasive characteristics are of importance in such applications [8]. Materials possessing high wear resistance (under dry sliding conditions) are associated with a stable tribolayer on the wearing surface and the formation of fine equiaxed wear debris. For adhesive wear, the influence of applied load, sliding speed, wearing surface hardness, reinforcement fracture toughness and morphology are critical parameters in relation to the wear regime encountered by the material [9].

Wear is one of the most commonly encountered industrial problems, leading to frequent replacement of components [7]. During the last two decades, superior wear performance of MMCs reinforced with ceramic particles has been reported [2,3].

Extensive review papers on the dry sliding wear characteristics of composites based on aluminium alloys have been presented by Sannino and Rack [10], and abrasive wear behaviour by Deuis et al. [4]. In their studies and discussions, the effect of reinforcement volume fraction, reinforcement size, sliding distance, applied load, sliding speed, hardness of the counter face and properties of the reinforcement phase which influence the dry sliding wear behaviour of this group of composites are discussed in greater detail. Sliding wear rate and wear behaviour were reported to be influenced by various wear parameters [11–14]. Lim et al. [15] studied the tribological properties of Al–Cu/SiC metal-matrix composites prepared using different processing routes. They reported that the wear resistance of these composites were influenced significantly by the process techniques used to make this composites [5].

In this study, improving the dry sliding wear behaviour of Al–4.5Cu–3Mg matrix composites reinforced with SiC particles

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Table 1
The chemical composition of the matrix alloy (wt.%).

Cu	Mg	Zn	Fe	Si	Mn	Sn	Pb	Cr	Ni	Ti
4.45	3.14	0.50	0.20	0.08	0.01	0.009	0.006	0.002	0.001	0.001

(SiCp) at different loads and speeds has been investigated. Results have been discussed and relevant tribological applications are identified.

2. Experimental details

In this study, direct squeeze casting technique was used to production of Al–Cu/SiCp metal-matrix composite. The details of experimental setup and production route were given in the previous publication [16]. The mean value of spectrographic analysis of matrix alloy is given in Table 1.

The matrix alloy was dispersed with 15 wt.% SiC particles to synthesize the composite. The SiC particles, which were used to fabricate the composite, had an average particle size of 36 μm and average density of 3.2 g/cm^3.

The squeeze cast composites were machined by using diamond blades in CNC machine to obtain tensile and wear specimens. Tensile test samples, have 6.4 mm diameter with a gauge length of 26 mm, were prepared for testing in Hounsfield Tensometer. Standard microscopic methods were used to study the composite structure, particle distribution and porosity. Microstructure and fracture surfaces (obtained by tensile test) were studied by SEM. Hardness has some influence on the wear behaviour on any material. Hardness measurement was carried out using a Brinell hardness tester. Before testing, specimen surfaces were polished using emery papers down to 1000 mesh. At least 10 measurements were taken for each sample and the average was taken as the hardness value.

Wear tests were carried out under dry sliding condition on a pin-on-disc apparatus. A steel disc (AISI D2) was used as counter surface and composites were made into pins having 6 mm diameter and 30 mm in height. The steel disc was heat treated to achieve 61 HRC, then polished with 600-grid emery paper. Average roughness (Ra %) of the disc was 1.2 μm. The pins were made to slide on the steel disc at 0.5, 1.0 and 2.0 m/s sliding speeds under the loads of 5, 10, and 15 N for a 1000 m sliding distance. The wear was measured in terms of weight loss of the materials measured to 0.0001 g resolution. The wear damage on the specimens was evaluated via wear rate (mm^3/m) calculated by using ASTM formulas.

Steady state friction coefficient values were also measured by a load cell-equipped with the pin-on disc apparatus. A complete wear microstructural characterization was carried out via scanning electron microscopy (JEOL JSM 5410 and JEOL JSM 5600). The wear tracks on the disc were also investigated with optical microscopy.

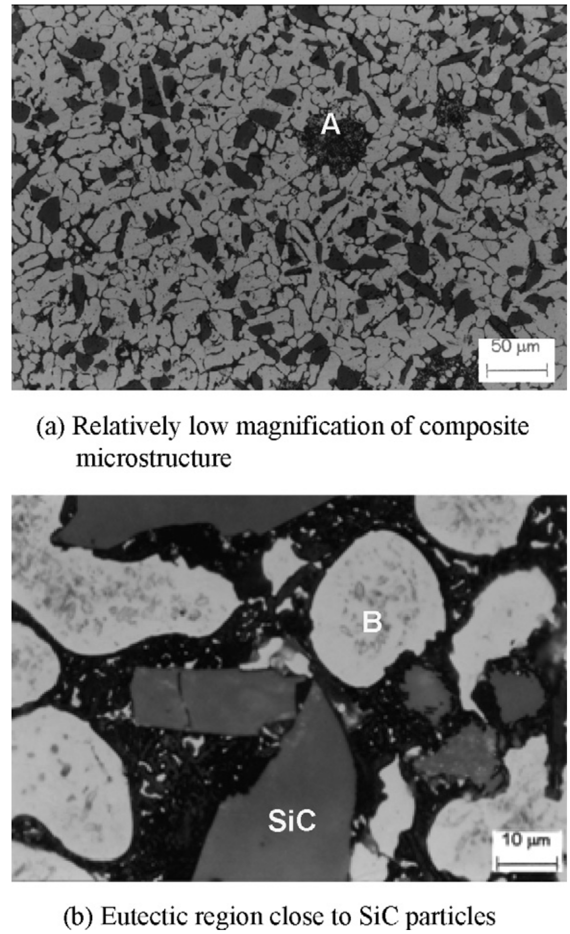


Fig. 1. Optical micrographs of specimen: (a) relatively low magnification of composite microstructure; (b) eutectic region close to SiC particles.

3. Results and discussion

3.1. Microstructure

Microstructure of composite consists of primary phase and eutectic regions. SiC particles were surrounded by eutectic region. SiC particles are behaving as a nucleation agent for Al and eutectic phase during solidification. In general, eutectic phase was formed on the SiC particles and/or SiC particles were segregated into last frozen eutectic regions (Fig. 1).

Fig. 1a represents relatively low magnified typical microstructure of composite specimens. This micrograph indicates that distribution of SiC particles in the matrix was uniform with no agglomeration. SiC particles in the matrix are observed to be angular in shape and apart from the large SiC particles; fine SiC particles are also present.

It can be clearly seen that eutectic is accumulated into two regions (eutectic close to SiC and eutectic away from SiC). Additionally, there were relatively large islands that consisted solely of eutectic (marked A in Fig. 1a). The eutectic region close to SiC (marked A in Fig. 1b) and away from the particles (marked B in Fig. 1b) had somewhat different composition (Table 2). From the local chemical analysis, it can be concluded that SiC particles are behaving as a nucleation agent for Al and eutectic phase during solidification.

As can be seen from the micrographs, the solidification started at in the interparticle channels, and growing dendrites rejected solute-rich liquid to the particle surfaces, which were the last locations to solidify. Mg also segregated towards the particles that are generally believed to promote good bond strength through limited chemical reaction. Mg is expected to improve composite properties by both providing in limited chemical interaction at the particle surface, and by increasing matrix strength, while Cu has the opposite effect [17].

Interdentritic segregation of particles during casting of discontinuously reinforced Al-matrix composites is a serious problem. In some situations, this segregation causes severe agglomeration and interparticle contact. The factors believed to influence dendrite segregation is the dendrite arm spacing (DAS) of matrix that is proportional to the dendrite growth rate, the size of the particles, the relative thermal conductivities, and the difference in contact angles between a particle/solid interface [16]. In this study, since solidification rate was very high in squeeze cast composites, so serious agglomerations have not been observed.

3.2. Fracture

Fig. 2 represents the fracture surface of the composite. It can be seen that fracture started and initiated along the grain boundaries,

Table 2
The qualitative element identification of composite microstructures (wt.%).

Element	Eutectic region	Island region
Al	87.11	34.49
Mg	3.50	11.47
Cu	9.40	54.04

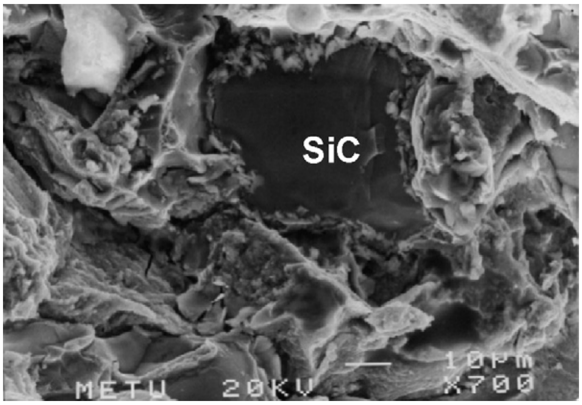


Fig. 2. SEM micrograph of fracture surface.

relatively brittle fracture and a limited amount of ductile fracture of the surrounding matrix.

The extremely limited amount of damage below the fracture path noted on sectioned fractured specimens confirms that the nucleation of defects is the stage governing the fracture process in composites. Apparently, the growth and coalescence of fracture do not require significant remains of strain energy. Consequently, factors influencing the fracture of the MMCs must be sought among the aspects of nucleation. In the present investigation, initiation of voids was assumed to depend mainly on a particle cracking, particle/matrix debonding and grain boundary fracture. Both of these are complex phenomena influenced by a number of factors such as the local stress field, the presence of the interface inhomogeneities, structural alterations in the matrix close to the interface, or notch effects around and inside the brittle ceramic particles. From the tensile fractographic results, it may be inferred that completely ductile behaviour was not totally achieved. The hardness results, also, supply this brittle fracture state (Table 3). Mechanical properties of matrix alloy and composite produced by direct squeeze casting method is tabulated in Table 3.

As can be seen in Table 3, particle reinforcement increases hardness but affects toughness properties inversely.

3.3. *Friction and wear behaviour*

Fig. 3 presents the variation of friction coefficients of Al–Cu/SiC MMCs with applied loads at 0.5, 1 and 2 m/s sliding speeds.

It can be seen that the friction coefficient of the composites decrease with increasing applied load. This is an agreement with the results obtained by Zhang [18] and Yalcin [19]. There is an average 16.9%, 29.7% and 11.9% decrease in friction coefficient value at 200% increase in applied load with sliding speeds, respectively. The variations of friction coefficient with increasing normal applied load is more distinctly at sliding speed 1 m/s than other conditions. Moreover, there is an average 31.6% decrease with the 300% increase in sliding speed.

Fig. 4 represents the variation of wear rates of composites with applied load at 0.5, 1, and 2 m/s sliding speeds.

An increase in the normal applied load will lead to an increase in the wear rate. This is an agreement with studies of some researchers

Table 3
The hardness and mechanical properties of composite specimens.

	Hardness (BHN)	UTS (MPa)	Elongation (%)	Reduction in area (%)
Matrix alloy	100 ± 1.94	247	3.30	2.51
Composite	139 ± 2.41	239	0.45	0.44

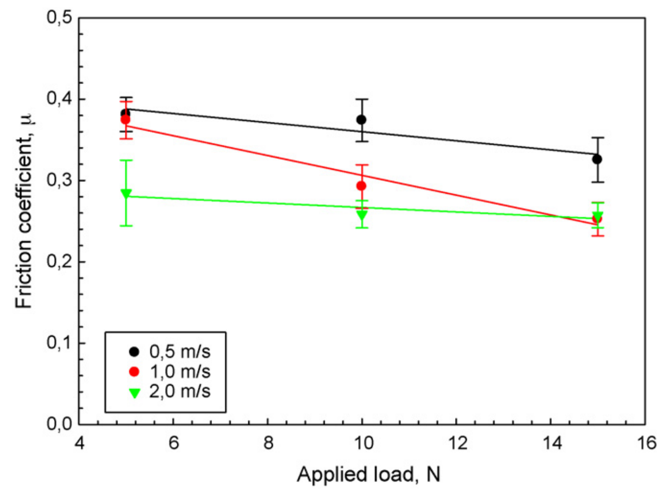


Fig. 3. Steady state friction coefficient variations with applied load and sliding speed.

[1,4,5,7,8]. Increasing sliding velocity also increases wear rate [4,5]. Mild wear was observed for a small-applied load, but as the load was further increased up to 15 N, the wear rate of composite increased. There is an average 167%, 350% and 227% increase in wear rate for a 200% increase in applied load with sliding speeds, respectively. Moreover, there is an average 30% increase in wear rate for 300% increase in sliding speeds. Heavy noise and vibration were observed during the process and transfer of the pin material to the disc was observed.

Specific wear rate of the MMC materials calculated from Fig. 4 increases with the increase in sliding speed shown in Fig. 5.

The worn surfaces were examined with scanning electron microscopy (SEM). As can be seen in Fig. 6, the presence of grooves of varying sizes was observed frequently on the worn surfaces. The formation of such grooves during the sliding of composites had been, on numerous occasions, linked to the process of delamination [20–23] which according to Suh [24], is the preferential propagation of sub-surface cracks along the sliding direction, giving rise to the detachment of wear particles in the form of sheets or flakes. These grooves are also the evidence of abrasive actions during sliding as a result of SiC particles standing proud of worn surface of composite sample as well as dislodged SiC particles trapped at the sliding interface. It is therefore proposed that the dominant wear mechanism operating during sliding over this range of loads at 1 m/s is a combination of abrasion and delamination [9].

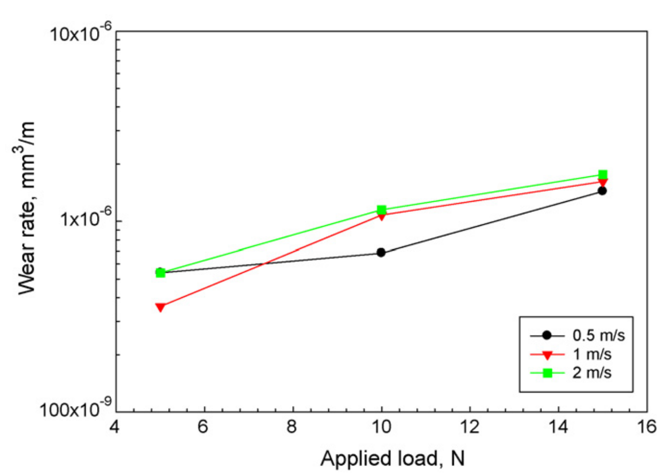


Fig. 4. Variations in wear rates a function of applied load and sliding speed.

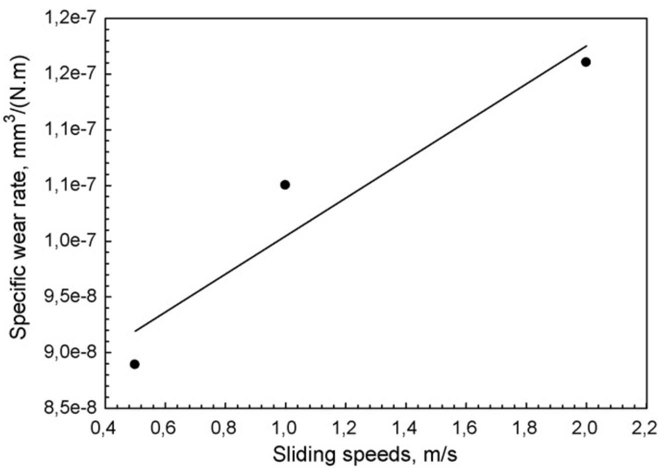


Fig. 5. Variations in specific wear rate as a function of sliding speed.

At lower loads, the projected SiC particles in the composites will be in contact with the counterface during the course of wear. The asperities of the sliding composite material surface come into contact with the steel disc surface, and are work hardened under the applied load and speed due to cold working on the surface of the composite material [5].

As the load increases, the morphology of the worn surfaces gradually changes from fine scratches to distinct grooves, and damaged spots in the form of craters can be seen. The asperities of both the composite material and counterface are in contact with each other and are subject to relative motion under the influence of applied load. Initially, both the surfaces are associated with a large number of sharp asperities, and contact between the two surfaces takes place primarily at these points. Under the influence of applied load and speed, when the asperities on each surface come in contact, they are either plastically deformed or remain in elastic contact.

At higher applied loads, higher wear rates are observed. The wearing surface is characterised by a significant transfer of material between the sliding surfaces. A delamination wear mechanism has been inferred for this wear regime, where the tribolayer is removed by sub-surface plastic deformation and fragmentation of the SiC particles [25].

Similar changes in wear behaviour with increase in applied load were reported by Lim et al. [15] for an A356 alloy reinforced with SiCp. At a slow sliding velocity (0.5 m/s), the wearing surface was covered with a transferred material layer. At higher speeds, an oxide-like transferred layer formed at the sliding interface and reduced direct metallic contacts. At very high speeds, thermal softening of the matrix was reported. The oxide layer was observed to break down and allow greater direct metallic contact during sliding and SiC particles became dislodged and three-body abrasive wear was predominant.

The worn surface produced by adhesive wear, is defined as the transfer of material from one surface to another during relative motion by a process of solid-phase welding or because of localised bonding between contacting surfaces. Particles, which are removed from one surface, are either permanently or temporarily attached to the other surface resulting in a tribolayer (Fig. 7).

This layer generally consists of plastically deformed and oxidised particles that reduce the wear rate of the material [25,26]. The formation of wear debris was directly related to delamination wear active within this region. Studies of the tribolayer reveal that it is composed of a mechanical mixture derived from the wearing alloy and the counterface (Table 4).

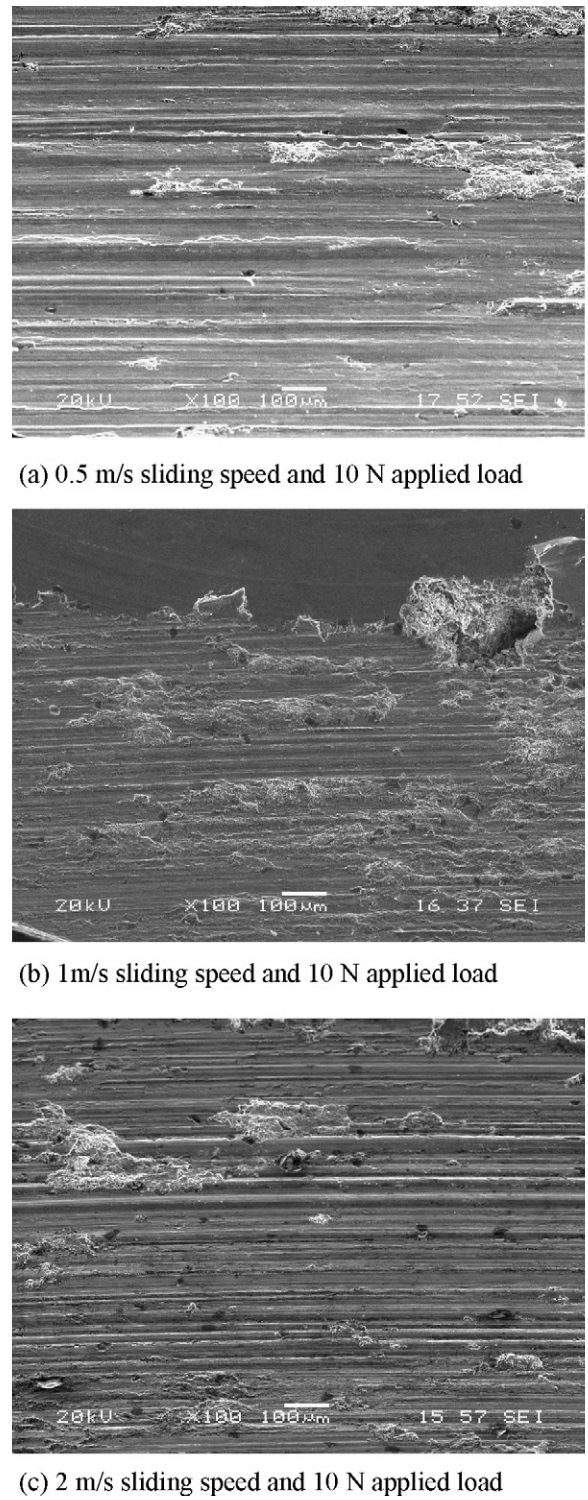
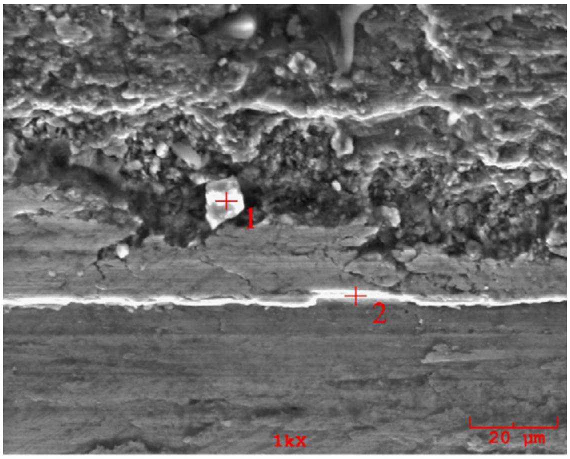


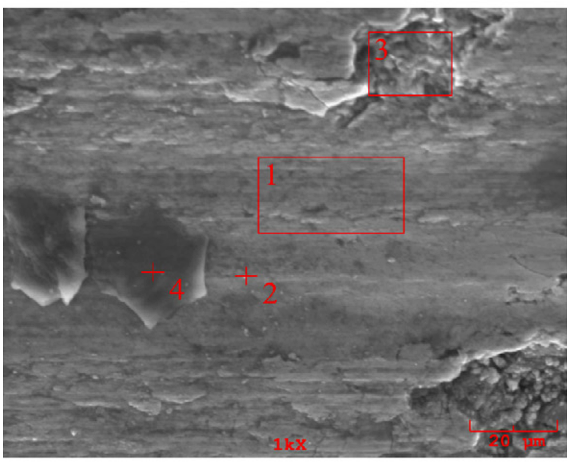
Fig. 6. Micrographs of worn surface of composite materials: (a) 0.5 m/s sliding speed and 10 N applied load; (b) 1 m/s sliding speed and 10 N applied load; (c) 2 m/s sliding speed and 10 N applied load.

Table 4
EDS analysis of tribolayer as a function of applied normal load and sliding speed (wt.%).

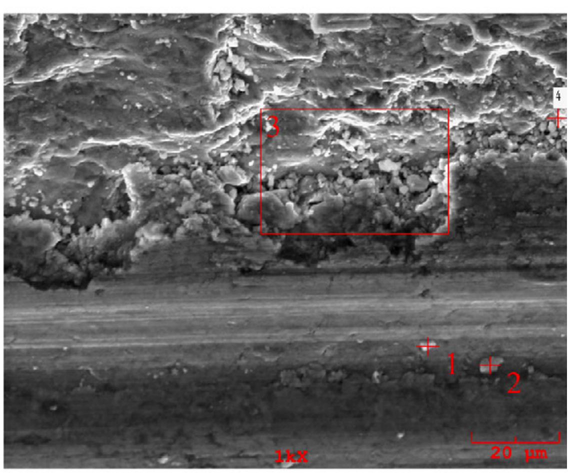
	0.5 m/s			1.0 m/s			2.0 m/s		
	Fe	Cr	O	Fe	Cr	O	Fe	Cr	O
5 N	30.44	2.77	43.89	48.67	3.66	11.66	91.63	7.88	12.88
10 N	18.46	1.86	25.00	29.56	2.13	22.59	84.75	5.60	20.98
15 N	56.53	3.41	15.00	26.17	2.49	24.66	83.48	5.57	22.76



(a) 0.5 m/s sliding speed and 15 N applied load



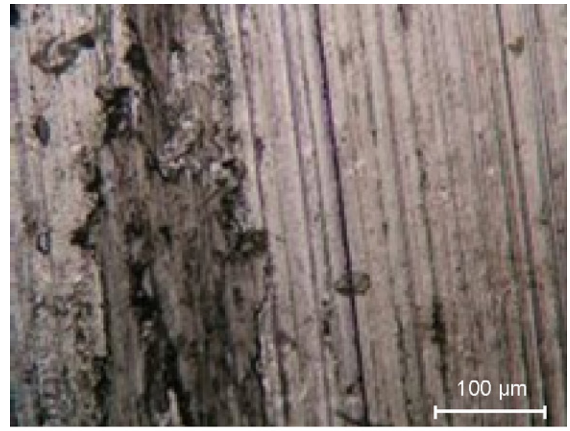
(b) 1m/s sliding speed and 15 N applied load



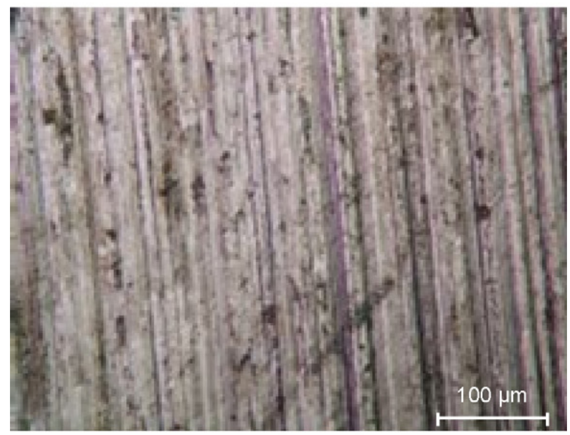
(c) 2 m/s sliding speed and 15 N applied load

Fig. 7. EDS analysis of worn surface of composite materials. (a) 0.5 m/s sliding speed and 15 N applied load; (b) 1 m/s sliding speed and 15 N applied load; (c) 2 m/s sliding speed and 15 N applied load.

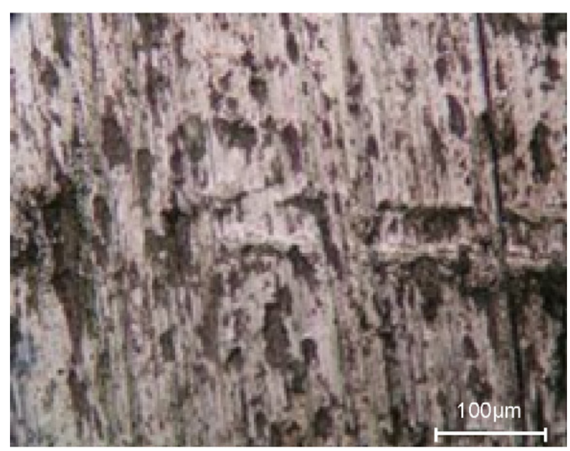
The transition from one wear mechanism to another as a function of applied pressure and sliding speed has also been documented in literature [27–31]. Moreover, some researches developed wear mechanism maps for Al alloys and composites wear encountered in dry sliding of steel [32–36]. At low loads, where a mild wear regime was reported, the wearing surfaces was



(a) 0.5 m/s sliding speed and 10 N applied load



(b) 1m/s sliding speed and 10 N applied load



(c) 2 m/s sliding speed and 10 N applied load

Fig. 8. Micrographs of worn surface of counterface (AISI D2 steel has 61 HRC): (a) 0.5 m/s sliding speed and 10 N applied load; (b) 1 m/s sliding speed and 10 N applied load; (c) 2 m/s sliding speed and 10 N applied load.

described as relatively smooth and wear debris as small and brittle. Oxidation of aluminium was considered an important part of this wear mechanism even though no quantitative data regarding oxidation was given. With increased load and sliding velocity, the delamination wear mechanism was the dominant wear process. Formation of wear debris and associated transfer of material onto the steel counterface was related to the poor whisker/matrix interfacial bond strength. The wearing surface at low speeds exhibits a low wear rate and a stable tribolayer. In a defined sliding speed range, the extent of the tribolayer formation becomes significant and a reduction in direct sliding surface contact results in a lower wear rate. At higher speeds, thermal softening of the matrix indicates a breakdown in the tribolayer, corresponding to a high wear rate and oxidation (see Table 4).

Worn surfaces of the counterface are given in Fig. 8. Findings indicate that a proportion of the counterface material removed by the micro-machining effects of the reinforcement phase is subject to oxidation. This oxidised material is present as Fe, O, in the tribolayer of both wearing surfaces. Furthermore, this oxidised phase helps stabilise the tribolayer on the MMC surfaces.

4. Conclusions

The findings in this investigation can be summarized as follows:

1. The microstructure of the SiCp-reinforced composite showed a reasonably uniform distribution of particles and good interfacial bonding of dispersed particles with the matrix alloy. Failures in composites, produced by squeeze casting, occur simultaneously both matrix and SiC particles implying that here is a good bonding between the matrix and the particles.
2. Composite material that possesses superior adhesive wear resistance is associated with a stable tribolayer. The creation of this layer depends on the magnitude of the applied load and sliding speed.
3. The amount of wear generally increases with increasing sliding speed and the extent of wear generally becomes greater with an increase in applied load. The specific wear rate also increased from 8.9×10^{-8} to 1.2×10^{-8} mm^3/Nm with increasing sliding speed.
4. The friction coefficient decreased with increasing applied load and sliding velocity. Variations of friction coefficient with increasing normal applied load are more distinctly at sliding speed 1 m/s than other conditions.
5. SEM analyses indicate that a proportion of the counterface material removed by the micro-machining effects of the reinforcement phase is subject to oxidation. This oxidised material is present as Fe, O, in the tribolayer of both wearing surfaces in EDS analysis. Furthermore, this oxidised phase helps stabilise the tribolayer on the MMC surface by pinning dislocations.

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