JuniKhyat (UGC Care Group I Listed Journal)
ISSN: 2278-4632 Vol-8 Issue-02 Nov 2018

Dry sliding wear characteristics of Silicon metal matrix composites: a brief overview

Dr. Saumya Darsan Mohanty
College of Engineering Bhubaneswar, BPUT, Odisha, India

Abstract

Si MMCs, or Silicon metal matrix composites, are silicon composites reinforced with continuous/discontinuous fibers, whiskers, or particulates.When compared to traditional engineering materials, these types of composites can be effectively engineered to provide tailored property combinations like high strength to weight ratio, specific strength, specific stiffness, creep resistance, and low density. Si MMCs are now preferred materials for use in the automotive, marine, aerospace, and construction industries. Among these applications, dry sliding wear is the most common type. This paper aims to provide a brief overview of the ways in which various Al MMCs' wear characteristics and the causes of wear patterns seen on composite surfaces are influenced by factors like applied load, reinforcement particles, sliding distance, and sliding speed. A succinct summary of the different wear kinds in connection to the different kinds of reinforcement, loading, speed, and wear conditions has also been provided.

1. Introduction

Silicon metal matrix composites (Si MMCs) account forabout 69% by mass of metal matrix composites (MMCs) pro-duced annually and used for industrial purposes [1]. This is soas a result of their outstanding physical, mechanical and tri-bological properties [1]. Si MMCs have been given preferenceover other frequently used aluminium alloys in recent times asa result of their excellent strength-to-weight ratio [2]. MMCsare designed to bring together the desirable metallic matrixcharacteristics and the properties of reinforcements particles[3]. Specifically, in the case of Al MMCs, the metallic matrix(aluminium) provides ductility, formability, toughness, elec-tric and thermal conductivities while the reinforcements offerhigh hardness, modulus, strength, low thermal expansion andhigh temperature durability [4]. No monolithic material is yetto be a match for Al MMCs in terms of their combination ofprofile properties [5,6]. Al MMCs have become choice materi-als for construction and building purposes [2,7,8], structural,thermal management and mild steel bearing applications[9], for making components such as cylinder liners, rotatingblade sleeves, brake drums, cylinder blocks, gear parts, pis-ton crowns, crankshafts, disk brakes and drive shafts [10–17],aerospace and defence [18–22] and other fields have drawneven more attention [23]. Others are precision and opticalinstruments [24], rail transport [25], sporting equipment [8,21],air conditioner compressor pistons [26], energy [27]. Theseareas of application point to the fact that a substantial amountof components for which Al MMCs are developed are suscep-tible to high wear rates [11]. It is therefore pertinent to studythe wear characteristics of these composites to enhance theunderstanding of their behaviour in service. It has been estab-lished that wear characteristics of materials are determined bya number of material and operational conditions in a complexmanner [28]. In this paper, an overview is given on findingsfrom several investigators concerning effects of *x* reinforce-ment, applied load, sliding distance and sliding speed on wearproperties of Al MMCs.

2. Influence of reinforcement particles onwear characteristics of Al MMCs

The type, nature, shape and size of reinforcements are crit-ical factors in the wear performance of Al MMCs and socareful selection is needed [21,29]. From an investigationon wear behaviour of hybrid Al2219/Gr/B4C composite [30],increase in sliding speed, sliding distance, applied load werefound to lead to an increase in the wear rates of base alloyAl2219, Al2219 with 8%B4C and the hybridised composite(Al2219 + 8%B4C + 3%Gr). However, the hybridised compositedisplayed better resistance to wear probably due to the actionof the ceramic particle reinforcements which were present.The particles provided a considerable amount of resistance tothe microcutting of the composite by the abrasive, leading tolessening of the rate at which material was being removedfrom the surface of the composite. Kumar et al. [3] inves-tigated the wear behaviour and mechanical properties of acomposite with AA430 matrix and a combination of SiC and MgO reinforcement particles. They reported that as percent-age reinforcement increased, volume loss of the compositesamples decreased. At 600 rpm, volume loss reduced by 39%on addition of 2.5% reinforcement. The volume loss decreasedby 46% when the reinforcement increased to 5% by weight and92% when increased to 7.5%. Specific wear rates of the com-posite specimen were also observed to be less in comparisonto that of the base alloy at various loads and speeds.Sharma et al. [31] studied wear in an Al-Flyash reinforcedcomposite. They observed that least wear loss and coefficientof friction values of 0.32 g and 0.12 were obtained at 6 wt%and 4 wt% flyash content between the tribo-pairs of cast ironsurface and MMC surface.Vedrtnam and Kumar [32] investigated the wear behaviourof aluminium reinforced with silicon carbide and copper. Fromthe work, it was shown that the most influential parameteron the rate of wear of the composite was weight percentageof the reinforcements. Load and sliding speed were secondand third, respectively in the order of dominance while slid-ing distance had the least effect. Singh et al. [33] studied thefriction and wear behaviour of aluminium alloy (Al 7075) andan Al MMC containing silicon carbide reinforcement particlesunder dry condition at different sliding distance. It was con-cluded from the work that wear rate of the silicon carbidebased Al MMC was less than that of the aluminium matrixalloy by 30–40%. This is in line with the observation fromanother study by Hemanth et al. [34], Walczak et al. [12], on thetribological properties of Al MMC–SiC composites. The resultsfrom their work revealed that the resistance to wear by theSiC reinforced aluminium composite was higher by about 14%compared to that of the aluminium alloy. A natural mineral,rutile (TiO2) was used as reinforcement in a hybrid compositeof aluminium base. Powder metallurgy was applied by Kumarand Rajadurai [35] to synthesise the composite. The effect ofthe rutile reinforcement on the microhardness properties andwear characteristics of the composites was studied. Resultsfrom the work are represented in Fig. 1. It was observed fromthe study that the wear resistance of the hybrid Al–SiC–TiO2was better than those of Al–SiC and the base alloy.

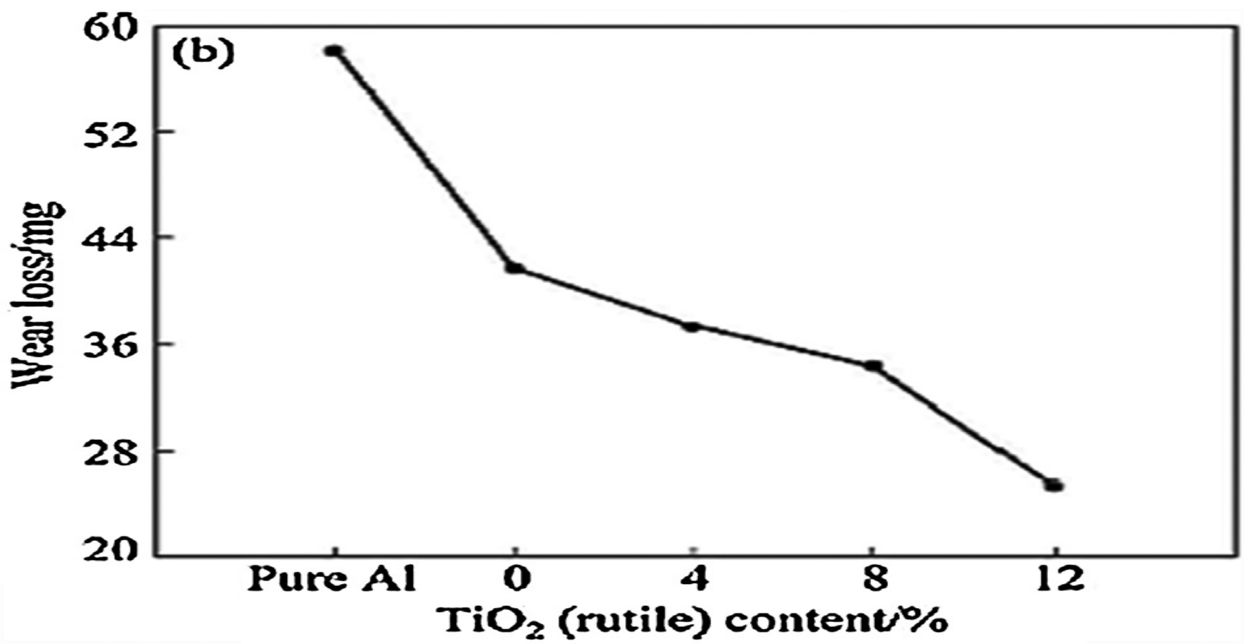

Fig. 1 – Influence of TiO2(rutile) reinforcement particles onwear of aluminium hybrid composites [35].

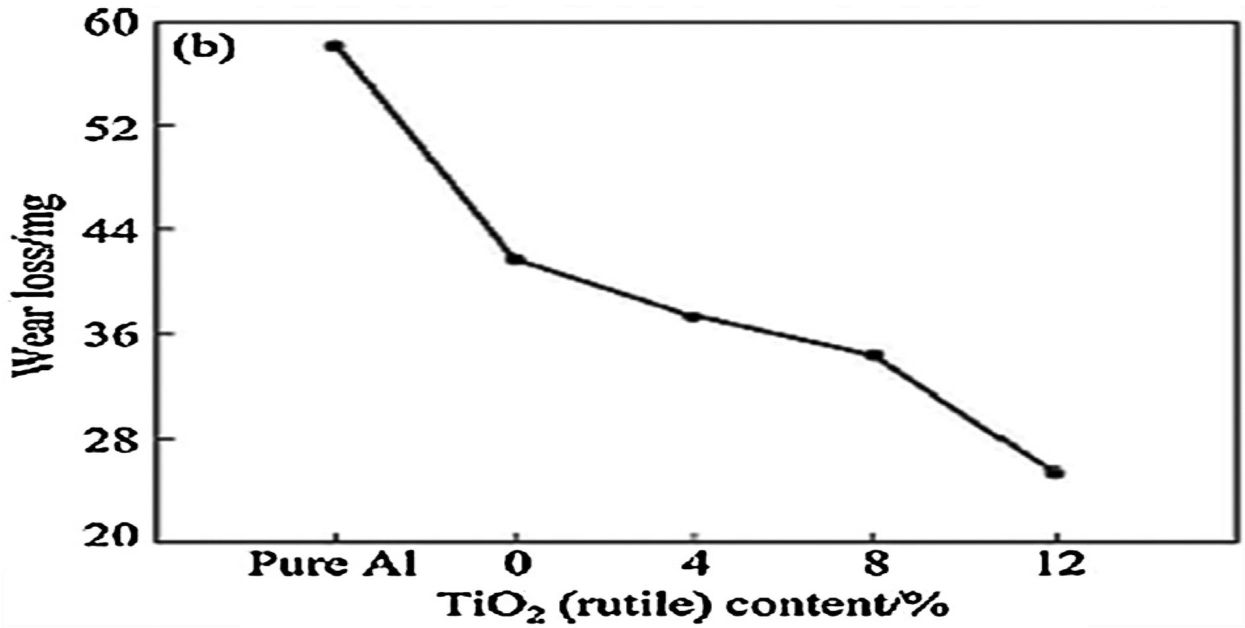

Fig. 2 – Variation of wear loss of zinc–aluminium basedcomposites with load [48].

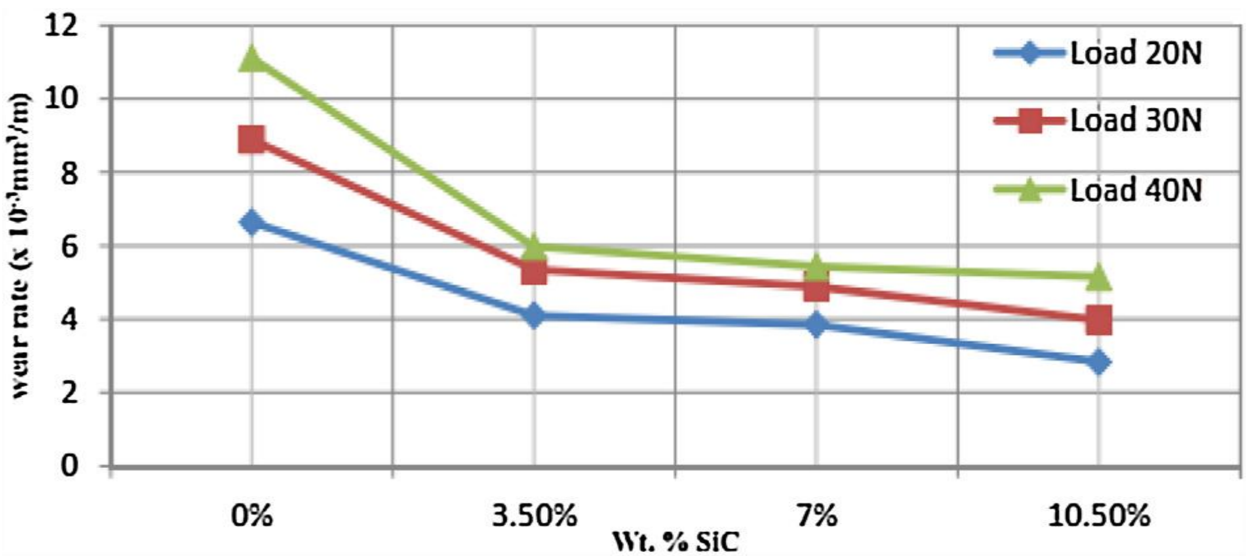

Fig. 3 – Wear rate for AA6063/SiC composite for differentapplied loads [50].

As the rutile content increased, the wear resistance and hardness of thematerial also increased. The decrease in wear loss was foundout to be due to the oxide phases formed as a result of thepresence of TiO_2. These phases resisted the micromachiningby the abrasives. The study also showed that adhesive wearand delamination were the main wear mechanisms present.The wear and hardness properties of a hybrid Al MMC wereinvestigated by Sarada et al. [36]. It was concluded from thestudy that hybrid reinforcement led to higher hardness andlower wear loss of the composite in comparison to singlereinforcement. Over a period of 300 s, the hybrid compos-ite (LM25/Active Carbon/Mica) was observed to have 5% lesswear loss compared to the monocomposite (LM25/Active Car-bon) while it had 10% less wear loss compared to LM25/Mica.It has been reported that the incorporation of reinforce-ments in Al MMCs restricts the flow of plastic deformation[11,37]. This is because the reinforcements form a protec-tive layer between the abrasive opposing material and thecounter faces in the composites [38–45]. An investigation bySharma et al. [45] on the effects of size of particles on wearbehaviour of aluminium matrix composites containing silli-manite reinforcement particles revealed that the presence ofthe sillimanite reinforcement considerably lowered the wearloss in comparison to the base alloy. Increase in the per-centage of the reinforcement continued to enhance the wearresistance up to a certain level beyond which wear resis-tance started to reduce due to agglomeration of fine particles.Phanibhushana et al. [46] investigated the wear character-istics of hematite reinforced Al MMC. The study revealedthat the addition of Fe_2O_3as reinforcement brought aboutimprovements in wear resistance and mechanical proper-ties of the composite such as hardness and ultimate tensilestrength. Mistry and Gohil [26] studied the wear behaviour ofAA7075/Si_3N_4p MMC. Their study revealed that the averagedecrement in wear loss percentage of Si_3N_4p reinforced MMCwas 11.64%, 24.61% and 37.17% for 4%, 8% and 12% wt whencompared with the matrix AA7075. They concluded that thehard ceramic reinforcement acted as a load bearing materialand reduced the tendency for formation of a mixed mechani-cal layer on the composite surface.

3. Influence of applied load on wearcharacteristics of Al MMCs

As revealed by Sharma et al. [45], increase in applied loadleads to increase in wear rate as a result of resistance thatoccurs due to friction between counter surfaces. Accordingto Madhavarao et al. [47], load contributed as much as 85% tothe wear of composites studied as frictional resistance leadsto increase in temperature, causing the decrease in hardnessof the material and ultimately, increase in the rate of wear.Kumar et al. [48] investigated the wear behaviour of an Al MMCmade up of zinc aluminium alloy metal matrix and garnet par-ticle reinforcement. The study showed that the rate of wear ofboth the aluminium alloy and the composite increased as theload increased from 50 N to 250 N in steps of 50 N. However, therate of material removal of the base alloy was faster such thatthe 200 N was its transition load, where the wear mechanismsuddenly changed to severe from mild wear. The composite samples had their transition values delayed as a result ofceramic reinforcement present in them. This analysis is evi-dent in the resulting plot as shown in Fig. 2. The results of thestudy also led to the conclusion that reinforcements in metalmatrix composites are more beneficial to wear resistance atlower loads. A similar study by Dayanand et al. [19] on Al–AlB2composite also showed increased wear of composites withapplied load. They also observed that the volumetric wear lossof unreinforced alloy was higher. According to Saravanaku-mar et al. [49], load contributed as much as 40.8% to the wearbehaviour of AA2219/Gr MMC studied. They also observedthat wear increased with load irrespective of speed and per-centage of reinforcements in the matrix. In another study byKaushika and Singhal [50], the volumetric wear rate of Al/SiCMMC decreased as the SiC particles increased and providedgood interfacial bonding as shown in Fig. 3. A similar obser-vation was made by Nieto et al. [27] and Celik and Sec¸ilmis[51] where they studied Al/B4C MMC. A common observationfrom both studies was the formation of B2O3layer that limitsfriction and an increase in weight loss with increasing load.From an investigation by Krishnamurthy et al. [52] on thewear properties of Al6063–TiB2composites, the specific rateof wear of the aluminium alloy was observed to increase drastically at higher loads but decreases with addition of theTiB2particles.

4. Influence of sliding distance on wearcharacteristics of Al MMCs

MMCsIn their work on the investigation of wear characteristics ofAl–SiC composites, Singla et al. [53] submitted that at a fixedsliding velocity, the wear rate increased linearly as the slidingdistance increased. Clustering of the reinforcing SiC particlesand non-uniform blending with the aluminium matrix wassaid to have been the reason for the trend. The investigationof the tribological properties of Aluminium/Alumina/GraphiteAl MMC, by Radhika et al. [54] gave a somewhat contraryresult. The results from their work showed that as the slid-ing distance increased, the wear rate and coefficient of frictiondecreased. The inverse relationship was attributed to the abra-sion resistance brought about by the presence of hard aluminaparticle and the reduction of wear due to a layer formed bygraphite between the sliding pin surface and the composite.In another study by Saraswat et al. [14] on Al–B4C compos-ite, they reported that as sliding distance increased the wearvolume also increased. This increased wear volume has beenrelated to increased coefficient of friction and temperature onthe surface of the composites which softens the matrix mate-rials [55]. Sharma et al. [45] carried out a study on how slidingdistance affects sillimanite reinforced Al MMCs during slidingwear. It was observed that wear rate increased with increase insliding distance (at 0–500 m) due to mechanical welding of pinwith disc and fragmentation of asperities. Rate of wear wasobserved to decrease with increase in distance between 500 mand 2000 m due to the oxide film that was formed on surfaceof the pin. The film acted as a protective layer, reducing thearea of contact between the two surfaces. The third zone was2000–3000 m where the formation of mechanically mixed layerand its removal became simultaneous thereby leading to con-stant rate of wear loss as the sliding distance increased. A plotdepicting the trend is shown in Fig. 4. Pramanik [56] studiedthe wear characteristics of an Al6061/Al2O3MMC. He observed a predictable linear relationship between the MMC and slid-ing distance (2 km) obeying closely the Archard law unlike theunreinforced alloy illustrated in Fig. 5.

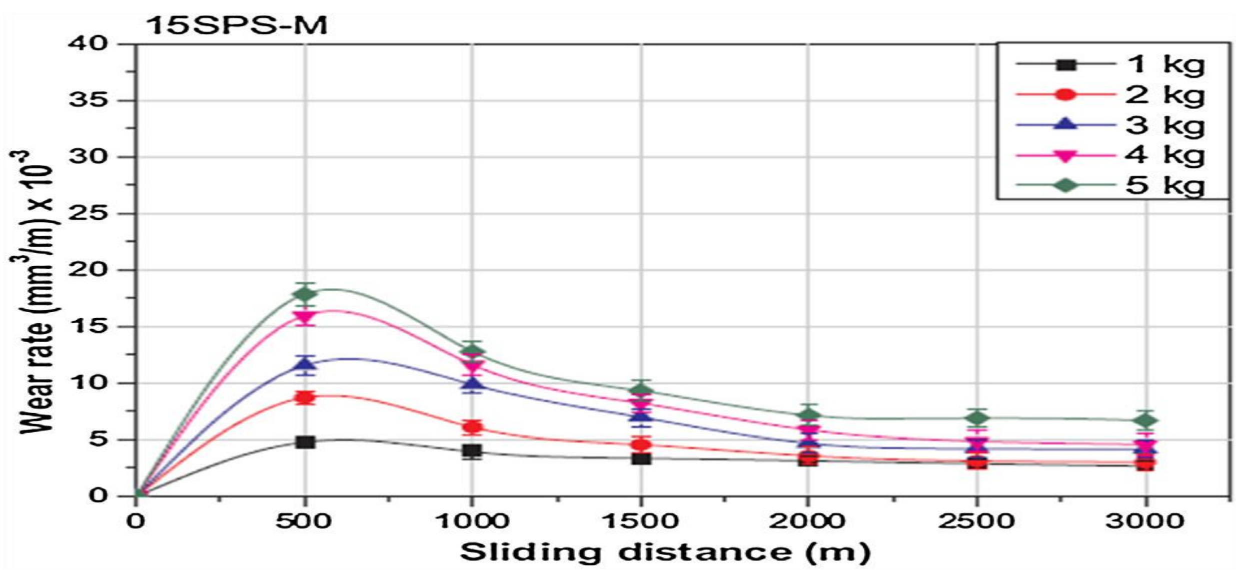

Fig. 4 – Variation of wear rate against sliding distance for15% sillimanite reinforced Al MMC [45].

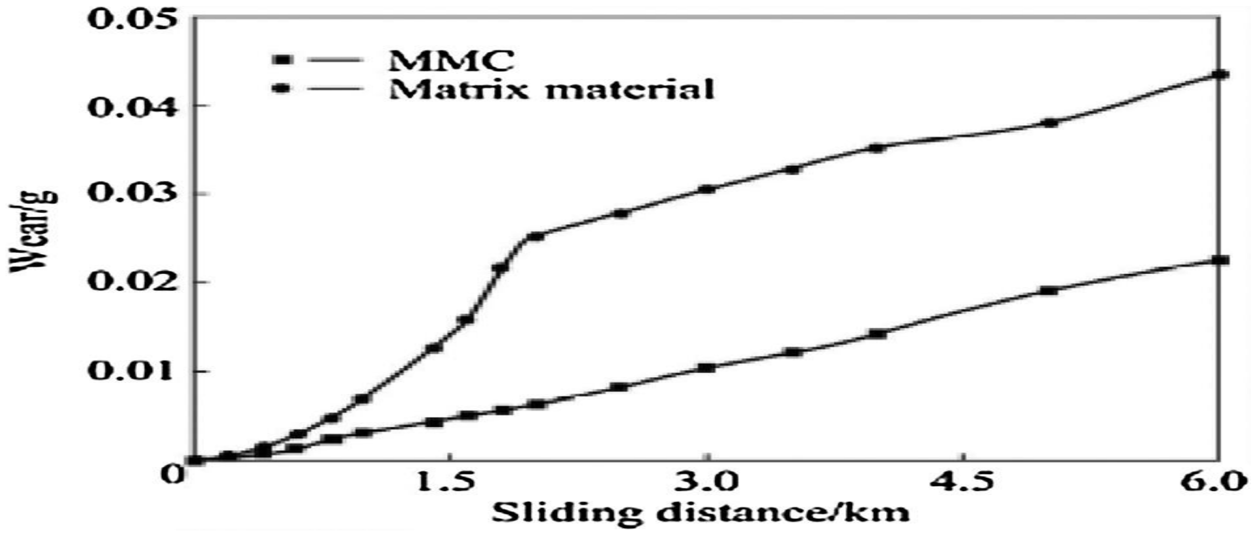

Fig. 5 – Wear of Al6061/Al2O3with increasing slidingdistance [56].

.5. Influence of sliding speed on dry slidingwear characteristics of Al MMCs

Marigoudar and Sadashivappa [57] revealed in their work onZA43 based Al MMC that at constant load of 40 N, the rate ofwear of the Al MMC increased as the sliding speed increased.However, less loss of material due to wear was observedas the quantity of reinforcement increased. The trend isillustrated in Fig. 6. In a review on the prediction of tool wearduring friction stir welding of Al MMC by Bist et al. [58], itwas reported that the rate of wear of the tool was directlyproportional to the tool rotation so that wear rate increasedas the speed of rotation increased.However, at much higher speeds, as the tool rotationincreased, there was increase in thermal input which aidedthe improvement in flow properties of the composite and thusled to reduced tool wear. In their study of wear behaviourof Al6061–SiC composite that was hot extruded, Ramesh andKeshavamarthy [59] found out that as the speed of slurry rotation increased, slurry erosive wear rate of the extrudedand cast base alloy that was studied increased. However, inanother study carried out by Gargatte et al. [11], the influenceof sliding speed on the rate of wear of an Al-5083 was foundto be inverse. At low speed, the rate of wear was high. As thespeed increased, the rate of wear was observed to decrease.This trend was observed because as sliding wear progressed,coefficient of friction decreased and a thin oxide film formedbetween the sliding surfaces [54]. This resulted in decrease inthe wear rate. It was however revealed that at higher loadsand increased sliding distance, the oxide film got removed,resulting in higher rate of material loss from the surface ofthe composite. As observed by Dayanand et al. [19], the effectof sliding speed follows a somewhat linear trend due to crackresistant AlBr2reinforcement as shown in Fig. 7.

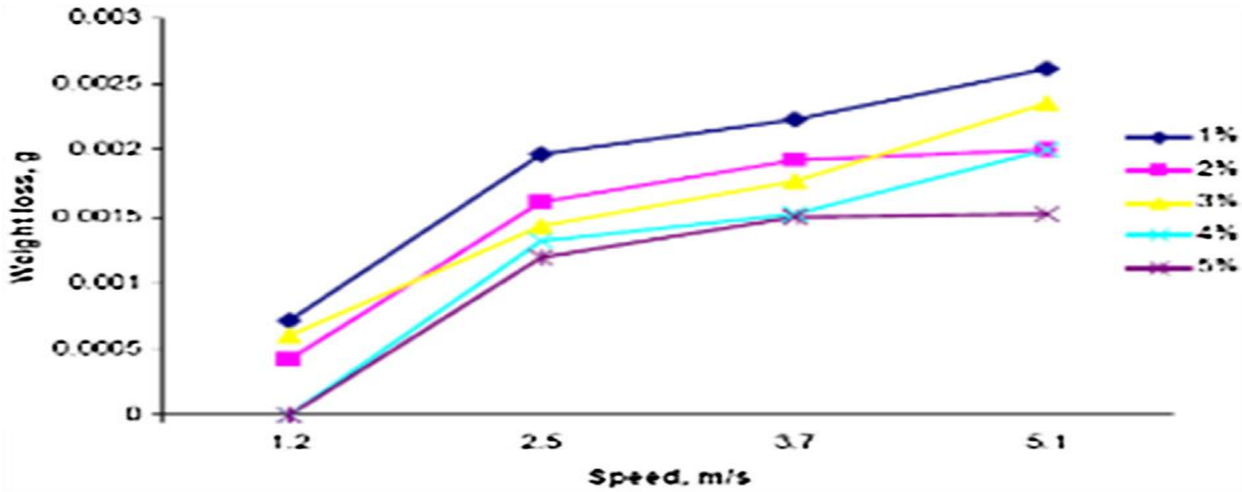

Fig. 6 – Effect of increasing speed on wear loss [57].

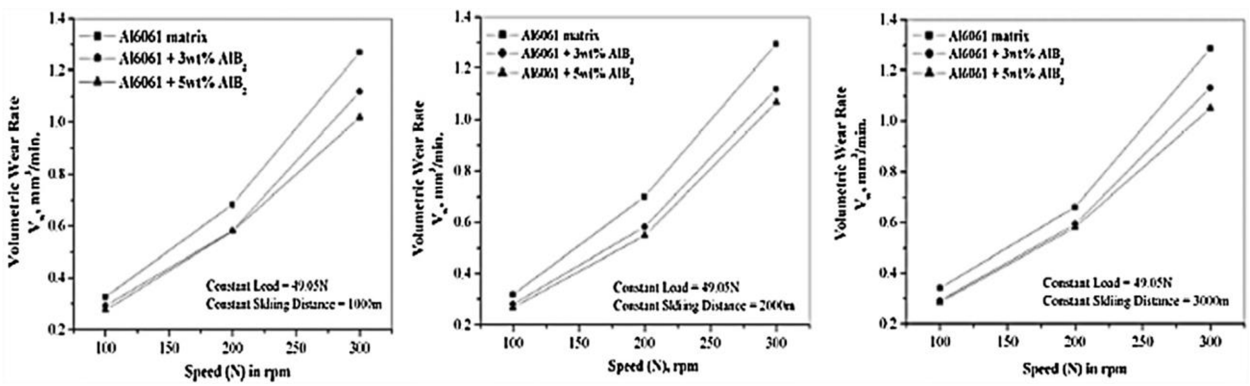

Fig. 7 – Variation of wear rate for Al–AlBr2composite at different sliding speeds [19].

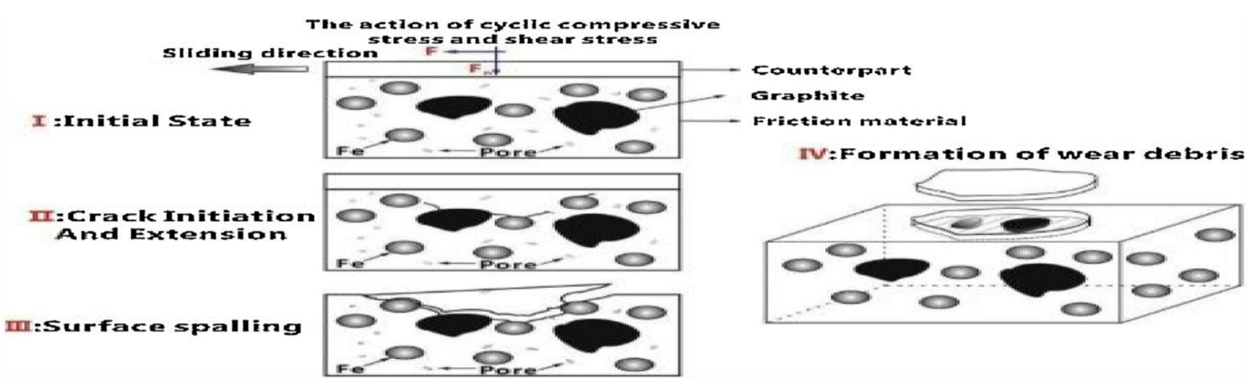

Fig. 8 – Schematic of a delamination wear process [61].

6. Wear mechanisms

Wear mechanisms to which Al MMCs are susceptible includedelamination, adhesive, abrasive and fretting. Interpretation of surface morphology for each of the mechanisms is dis-cussed here.Delamination is characterised by excessive fracture of thematerial which results in the display of flake type debris[48], deep grooves, pits and craters [60]. As observed byZhou et al. [61], in delamination wear, a series of intercon-nected cracks form due to poor particle bonding, surfacecontamination and oxidation as illustrated in Fig. 8. Adhe-sive wear is identified by the display of plastic deformation[62] and occurrence of pits and prows [38]. The pits inadhesive wear are usually less, compared to those of delami-nation [60]. The presence of longitudinal or parallel groovesas an indication of microcutting or microploughing effectis what describes abrasive wear [63]. According to Mishraet al. [64], the grooves in abrasive wear are shallower whencompared to those in delamination wear. Fretting wear ischaracterised by the display of minor scratches and loosefragments that result from oxide debris. It is usually as aresult of the cyclic stress that occurs as a result of slidingbetween two surfaces [35]. Surface morphologies displaying these wear mechanisms are shown in Figs. 9–12. A sum-mary of various wear mechanisms with respect to differentreinforcement types for selected Al MMCs is presented.

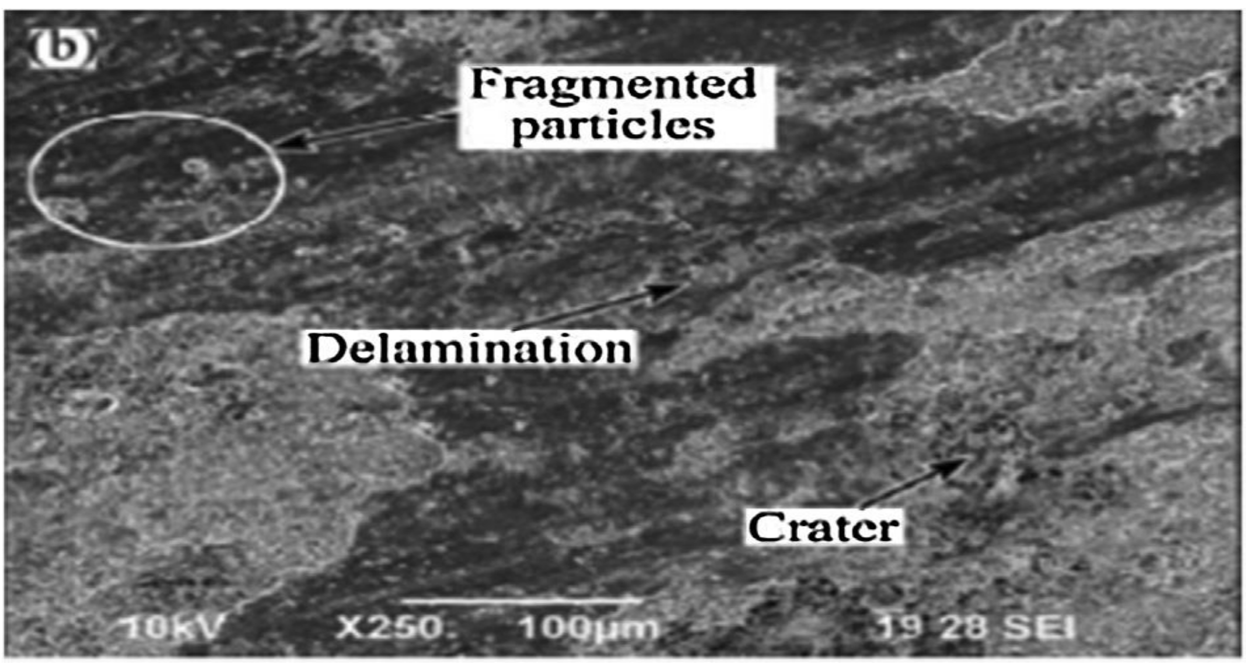

Fig. 9 – SEM image showing delamination wear of an Almatrix surface [35].

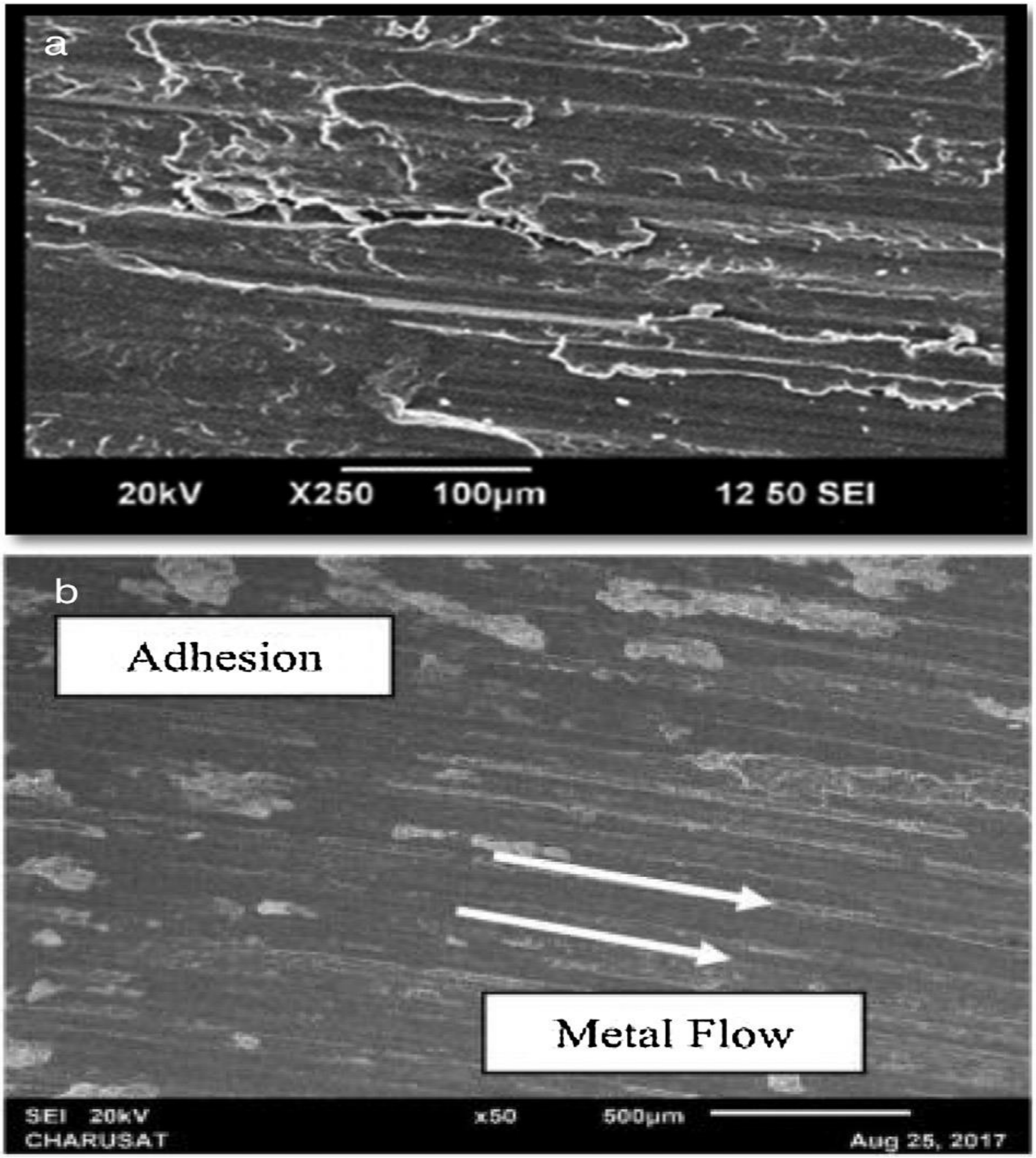

Fig. 10 – (a) SEM micrograph showing adhesive wear of anAA6061 surface [62]. (b) SEM micrographs displayingadhesive wear on (AA7075/Si3N4p) [26].

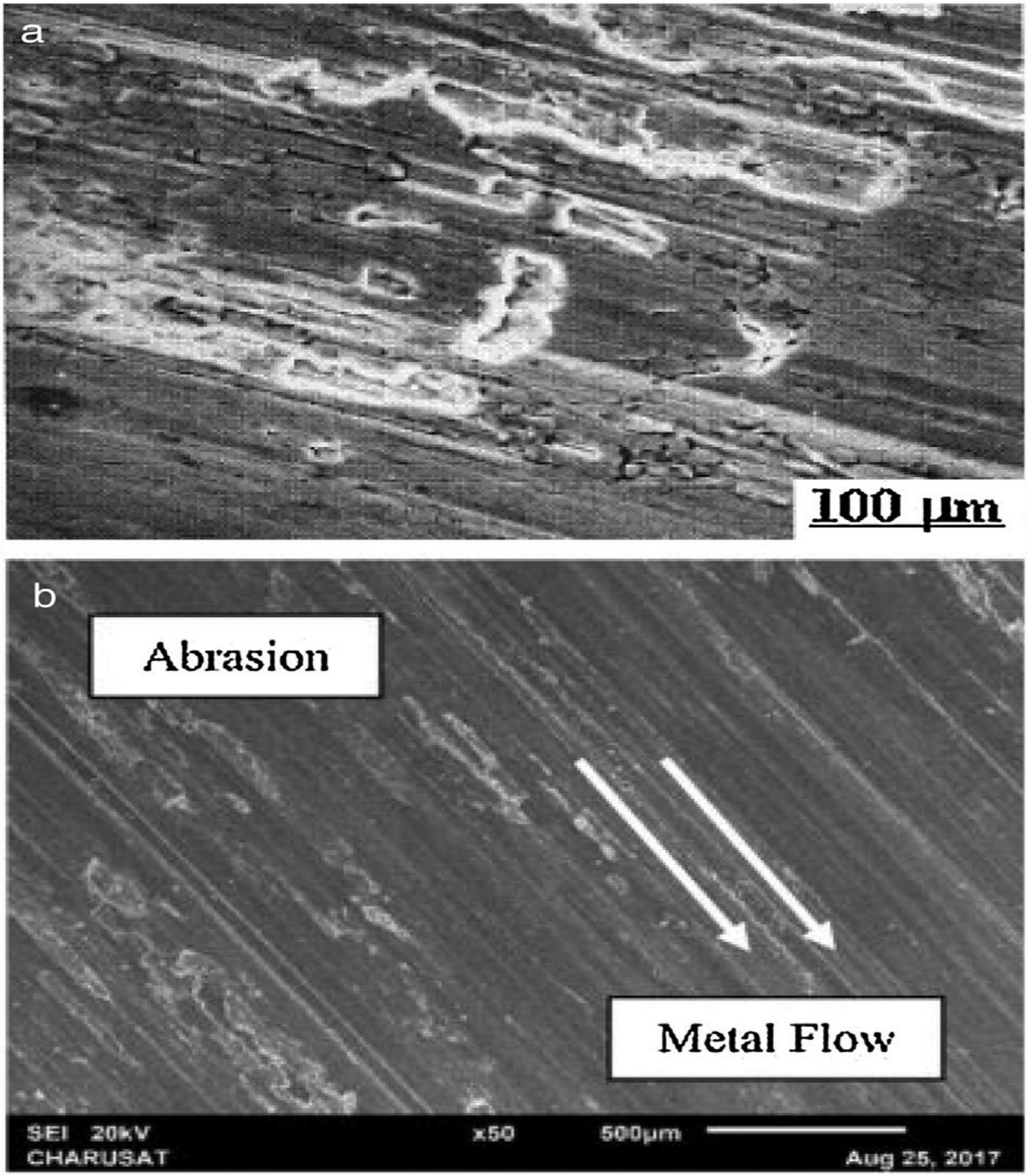

Fig. 11 – (a) SEM image showing abrasive wear mechanismin a zinc–aluminium based Al MMC [48]. (b) SEMmicrographs displaying abrasive wear on (AA7075/Si3N4p)[26].

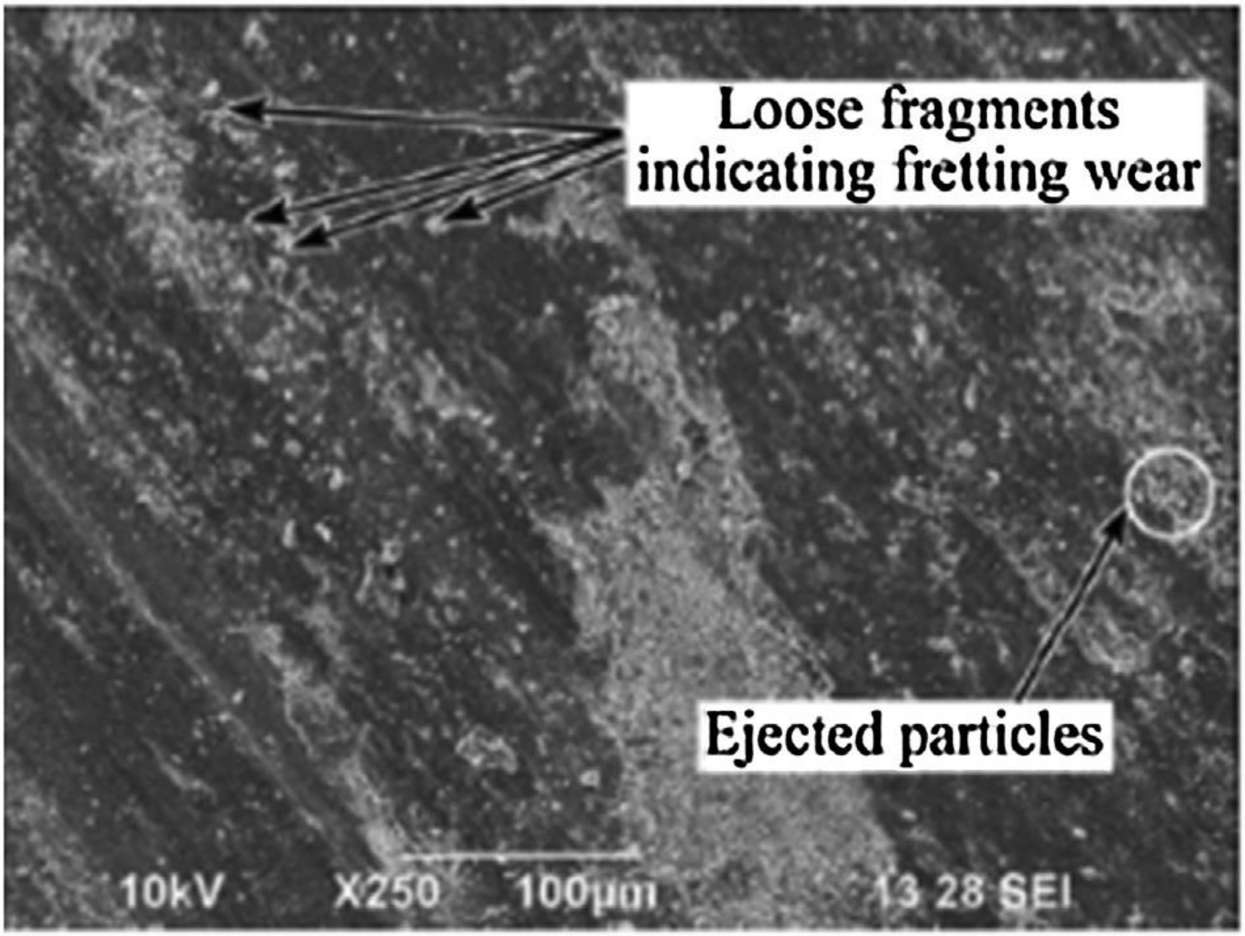

Fig. 12 – SEM image showing fretting wear of anAl–15%SiC–8%TiO2hybrid composite [35].

7. Conclusion

- From the review presented, the following conclusions can be drawn:
- The wear performance of Al MMCs is enhanced by hard reinforcement particles.
- Wear resistance of Al MMCs is increased by an increase in reinforcement particles.
- The protective oxide layer that forms between the composite and the opposing abrasive prevents wear by impeding the microcutting action of the rubbing abrasive and by limiting plastic deformation.
- When it comes to the dry sliding wear of Al MMCs, applied load is directly correlated with material removal rate.
- The effects of sliding distance and speed on the wear rates of Al MMCs appear to follow predictable trends.In this regard, more research needs to be done.

- Al MMCs are susceptible to fretting, adhesive, delamination, and abrasive wear mechanisms. Abrasive wear is more likely in low load wear conditions and reinforced composites, whereas delamination is more common at high loads and in base alloys.

Conflicts of interest

The authors declare no conflicts of interest

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