



## Review Article

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



Nosa Idusuyi\*, John I. Olayinka

Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria

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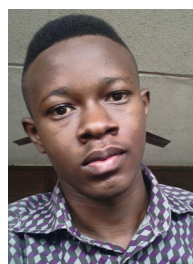
### ABSTRACT

Aluminium composites with reinforcements in the form of whiskers, particulates or continuous/discontinuous fibres are referred to as aluminium metal matrix composites (Al MMCs). These form of composites can be engineered to effectively provide tailored property combinations such as high strength to weight ratio, specific strength, specific stiffness, creep resistance and low density compared to conventional engineering materials. Al MMCs have become choice materials in applications such as aerospace, construction, marine and automotive. In some of these applications, dry sliding wear predominantly occurs. In this paper, attempt has been made to give a concise overview on how factors such as applied load, reinforcement particles, sliding distance and sliding speed affect the wear characteristics of different Al MMCs and reasons behind the wear patterns that are observed on the composite surfaces. A brief highlight of various wear types in relation to different reinforcement types, loading, speed and wear conditions have also been presented.

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Dr Idusuyi Nosa is a lecturer in the Department of Mechanical Engineering, University of Ibadan, Nigeria. My research interests are in the area of corrosion studies and metal matrix composites characterisation and testing.



John Iyanuoluwa Olayinka is a research student in the Department of Mechanical Engineering, University of Ibadan, Nigeria. His research interests include corrosion and tribology studies.

\* Corresponding author.

E-mail: [nosaidus@gmail.com](mailto:nosaidus@gmail.com) (N. Idusuyi).

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## 1. Introduction

Aluminium metal matrix composites (Al MMCs) account for about 69% by mass of metal matrix composites (MMCs) produced annually and used for industrial purposes [1]. This is so as a result of their outstanding physical, mechanical and tribological properties [1]. Al MMCs have been given preference over other frequently used aluminium alloys in recent times as a result of their excellent strength-to-weight ratio [2]. MMCs are designed to bring together the desirable metallic matrix characteristics and the properties of reinforcements particles [3]. Specifically, in the case of Al MMCs, the metallic matrix (aluminium) provides ductility, formability, toughness, electric and thermal conductivities while the reinforcements offer high hardness, modulus, strength, low thermal expansion and high temperature durability [4]. No monolithic material is yet to be a match for Al MMCs in terms of their combination of profile properties [5,6]. Al MMCs have become choice materials for construction and building purposes [2,7,8], structural, thermal management and mild steel bearing applications [9], for making components such as cylinder liners, rotating blade sleeves, brake drums, cylinder blocks, gear parts, piston crowns, crankshafts, disk brakes and drive shafts [10–17], aerospace and defence [18–22] and other fields have drawn even more attention [23]. Others are precision and optical instruments [24], rail transport [25], sporting equipment [8,21], air conditioner compressor pistons [26], energy [27]. These areas of application point to the fact that a substantial amount of components for which Al MMCs are developed are susceptible to high wear rates [11]. It is therefore pertinent to study the wear characteristics of these composites to enhance the understanding of their behaviour in service. It has been established that wear characteristics of materials are determined by a number of material and operational conditions in a complex manner [28]. In this paper, an overview is given on findings from several investigators concerning effects of  $x$  reinforcement, applied load, sliding distance and sliding speed on wear properties of Al MMCs.

## 2. Influence of reinforcement particles on wear characteristics of Al MMCs

The type, nature, shape and size of reinforcements are critical factors in the wear performance of Al MMCs and so careful selection is needed [21,29]. From an investigation on wear behaviour of hybrid Al2219/Gr/B<sub>4</sub>C composite [30], increase in sliding speed, sliding distance, applied load were found to lead to an increase in the wear rates of base alloy Al2219, Al2219 with 8%B<sub>4</sub>C and the hybridised composite (Al2219+8%B<sub>4</sub>C+3%Gr). However, the hybridised composite displayed better resistance to wear probably due to the action of the ceramic particle reinforcements which were present. The particles provided a considerable amount of resistance to the microcutting of the composite by the abrasive, leading to lessening of the rate at which material was being removed from the surface of the composite. Kumar et al. [3] investigated the wear behaviour and mechanical properties of a composite with AA430 matrix and a combination of SiC and

MgO reinforcement particles. They reported that as percentage reinforcement increased, volume loss of the composite samples decreased. At 600 rpm, volume loss reduced by 39% on addition of 2.5% reinforcement. The volume loss decreased by 46% when the reinforcement increased to 5% by weight and 92% when increased to 7.5%. Specific wear rates of the composite specimen were also observed to be less in comparison to that of the base alloy at various loads and speeds.

Sharma et al. [31] studied wear in an Al-Flyash reinforced composite. They observed that least wear loss and coefficient of 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 iron surface and MMC surface.

Vedrtnam and Kumar [32] investigated the wear behaviour of aluminium reinforced with silicon carbide and copper. From the work, it was shown that the most influential parameter on the rate of wear of the composite was weight percentage of the reinforcements. Load and sliding speed were second and third, respectively in the order of dominance while sliding distance had the least effect. Singh et al. [33] studied the friction and wear behaviour of aluminium alloy (Al 7075) and an Al MMC containing silicon carbide reinforcement particles under dry condition at different sliding distance. It was concluded from the work that wear rate of the silicon carbide based Al MMC was less than that of the aluminium matrix alloy by 30–40%. This is in line with the observation from another study by Hemanth et al. [34], Walczak et al. [12], on the tribological properties of Al MMC–SiC composites. The results from their work revealed that the resistance to wear by the SiC reinforced aluminium composite was higher by about 14% compared to that of the aluminium alloy. A natural mineral, rutile (TiO<sub>2</sub>) was used as reinforcement in a hybrid composite of aluminium base. Powder metallurgy was applied by Kumar and Rajadurai [35] to synthesise the composite. The effect of the rutile reinforcement on the microhardness properties and wear characteristics of the composites was studied. Results from the work are represented in Fig. 1. It was observed from the study that the wear resistance of the hybrid Al–SiC–TiO<sub>2</sub> was better than those of Al–SiC and the base alloy. As the rutile

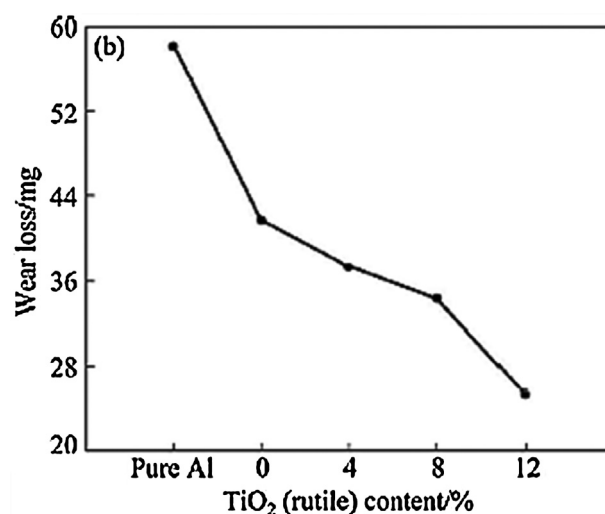


Fig. 1 – Influence of TiO<sub>2</sub> (rutile) reinforcement particles on wear of aluminium hybrid composites [35].

content increased, the wear resistance and hardness of the material also increased. The decrease in wear loss was found out to be due to the oxide phases formed as a result of the presence of  $\text{TiO}_2$ . These phases resisted the micromachining by the abrasives. The study also showed that adhesive wear and delamination were the main wear mechanisms present.

The wear and hardness properties of a hybrid Al MMC were investigated by Sarada et al. [36]. It was concluded from the study that hybrid reinforcement led to higher hardness and lower wear loss of the composite in comparison to single reinforcement. Over a period of 300 s, the hybrid composite (LM25/Active Carbon/Mica) was observed to have 5% less wear loss compared to the monocomposite (LM25/Active Carbon) while it had 10% less wear loss compared to LM25/Mica. It has been reported that the incorporation of reinforcements in Al MMCs restricts the flow of plastic deformation [11,37]. This is because the reinforcements form a protective layer between the abrasive opposing material and the counter faces in the composites [38–45]. An investigation by Sharma et al. [45] on the effects of size of particles on wear behaviour of aluminium matrix composites containing sillimanite reinforcement revealed that the presence of the sillimanite reinforcement considerably lowered the wear loss in comparison to the base alloy. Increase in the percentage of the reinforcement continued to enhance the wear resistance up to a certain level beyond which wear resistance started to reduce due to agglomeration of fine particles. Phanibhushana et al. [46] investigated the wear characteristics of hematite reinforced Al MMC. The study revealed that the addition of  $\text{Fe}_2\text{O}_3$  as reinforcement brought about improvements in wear resistance and mechanical properties of the composite such as hardness and ultimate tensile strength. Mistry and Gohil [26] studied the wear behaviour of AA7075/ $\text{Si}_3\text{N}_4$  MMC. Their study revealed that the average decrement in wear loss percentage of  $\text{Si}_3\text{N}_4$  reinforced MMC was 11.64%, 24.61% and 37.17% for 4%, 8% and 12% wt when compared with the matrix AA7075. They concluded that the hard ceramic reinforcement acted as a load bearing material and reduced the tendency for formation of a mixed mechanical layer on the composite surface.

### 3. Influence of applied load on wear characteristics of Al MMCs

As revealed by Sharma et al. [45], increase in applied load leads to increase in wear rate as a result of resistance that occurs due to friction between counter surfaces. According to Madhavarao et al. [47], load contributed as much as 85% to the wear of composites studied as frictional resistance leads to increase in temperature, causing the decrease in hardness of the material and ultimately, increase in the rate of wear. Kumar et al. [48] investigated the wear behaviour of an Al MMC made up of zinc aluminium alloy metal matrix and garnet particle reinforcement. The study showed that the rate of wear of both the aluminium alloy and the composite increased as the load increased from 50 N to 250 N in steps of 50 N. However, the rate of material removal of the base alloy was faster such that the 200 N was its transition load, where the wear mechanism suddenly changed to severe from mild wear. The composite

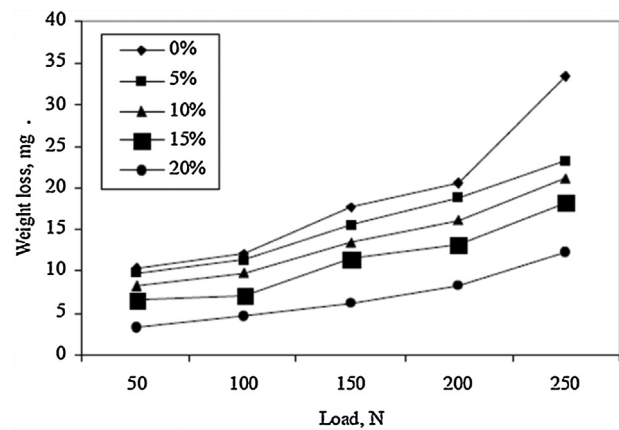


Fig. 2 – Variation of wear loss of zinc-aluminium based composites with load [48].

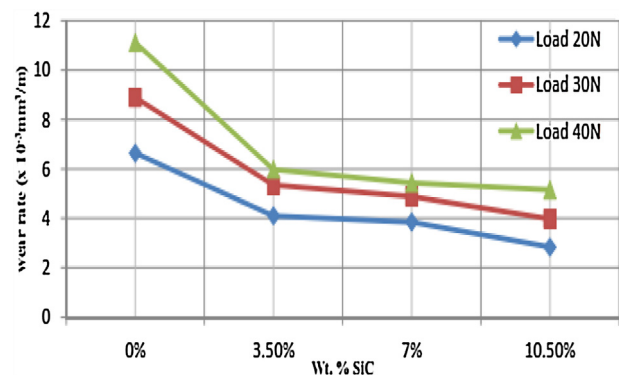


Fig. 3 – Wear rate for AA6063/SiC composite for different applied loads [50].

samples had their transition values delayed as a result of ceramic reinforcement present in them. This analysis is evident in the resulting plot as shown in Fig. 2. The results of the study also led to the conclusion that reinforcements in metal matrix composites are more beneficial to wear resistance at lower loads. A similar study by Dayanand et al. [19] on Al- $\text{AlB}_2$  composite also showed increased wear of composites with applied load. They also observed that the volumetric wear loss of unreinforced alloy was higher. According to Saravanakumar et al. [49], load contributed as much as 40.8% to the wear behaviour of AA2219/Gr MMC studied. They also observed that wear increased with load irrespective of speed and percentage of reinforcements in the matrix. In another study by Kaushika and Singhal [50], the volumetric wear rate of Al/SiC MMC decreased as the SiC particles increased and provided good interfacial bonding as shown in Fig. 3. A similar observation was made by Nieto et al. [27] and Celik and Seçilmiş [51] where they studied Al/ $\text{B}_4\text{C}$  MMC. A common observation from both studies was the formation of  $\text{B}_2\text{O}_3$  layer that limits friction and an increase in weight loss with increasing load.

From an investigation by Krishnamurthy et al. [52] on the wear properties of Al6063- $\text{TiB}_2$  composites, the specific rate of wear of the aluminium alloy was observed to increase

drastically at higher loads but decreases with addition of the  $\text{TiB}_2$  particles.

#### 4. Influence of sliding distance on wear characteristics of Al MMCs

In their work on the investigation of wear characteristics of Al-SiC composites, Singla et al. [53] submitted that at a fixed sliding velocity, the wear rate increased linearly as the sliding distance increased. Clustering of the reinforcing SiC particles and non-uniform blending with the aluminium matrix was said to have been the reason for the trend. The investigation of the tribological properties of Aluminium/Alumina/Graphite Al MMC, by Radhika et al. [54] gave a somewhat contrary result. The results from their work showed that as the sliding distance increased, the wear rate and coefficient of friction decreased. The inverse relationship was attributed to the abrasion resistance brought about by the presence of hard alumina particle and the reduction of wear due to a layer formed by graphite between the sliding pin surface and the composite. In another study by Saraswat et al. [14] on Al- $\text{B}_4\text{C}$  composite, they reported that as sliding distance increased the wear volume also increased. This increased wear volume has been related to increased coefficient of friction and temperature on the surface of the composites which softens the matrix materials [55]. Sharma et al. [45] carried out a study on how sliding distance affects sillimanite reinforced Al MMCs during sliding wear. It was observed that wear rate increased with increase in sliding distance (at 0–500 m) due to mechanical welding of pin with disc and fragmentation of asperities. Rate of wear was observed to decrease with increase in distance between 500 m and 2000 m due to the oxide film that was formed on surface of the pin. The film acted as a protective layer, reducing the area of contact between the two surfaces. The third zone was 2000–3000 m where the formation of mechanically mixed layer and its removal became simultaneous thereby leading to constant rate of wear loss as the sliding distance increased. A plot depicting the trend is shown in Fig. 4. Pramanik [56] studied the wear characteristics of an Al6061/ $\text{Al}_2\text{O}_3$  MMC. He observed

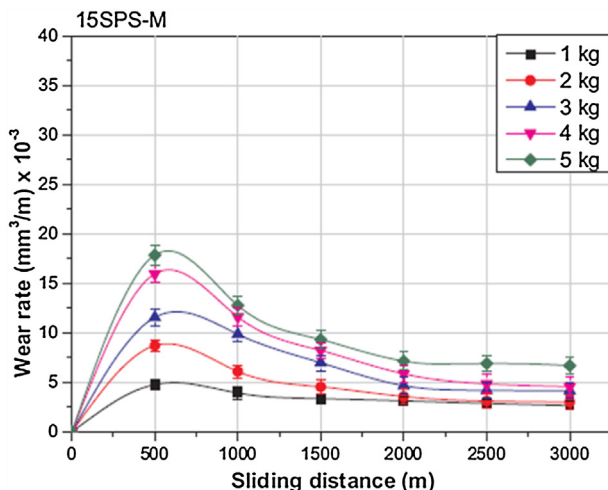


Fig. 4 – Variation of wear rate against sliding distance for 15% sillimanite reinforced Al MMC [45].

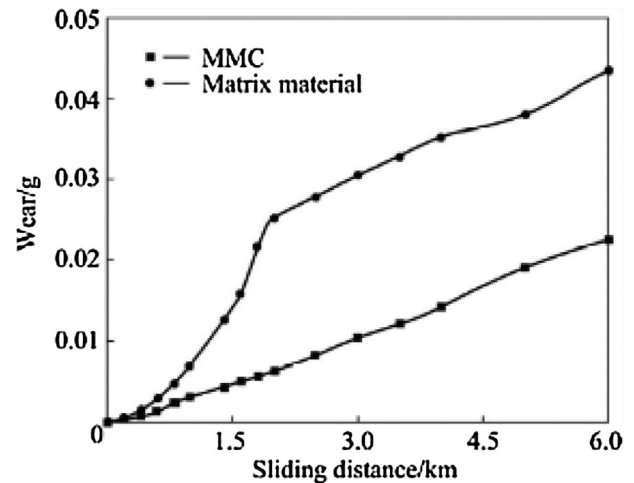


Fig. 5 – Wear of Al6061/ $\text{Al}_2\text{O}_3$  with increasing sliding distance [56].

a predictable linear relationship between the MMC and sliding distance (2 km) obeying closely the Archard law unlike the unreinforced alloy illustrated in Fig. 5.

#### 5. Influence of sliding speed on dry sliding wear characteristics of Al MMCs

Marigoudar and Sadashivappa [57] revealed in their work on ZA43 based Al MMC that at constant load of 40 N, the rate of wear of the Al MMC increased as the sliding speed increased. However, less loss of material due to wear was observed as the quantity of reinforcement increased. The trend is illustrated in Fig. 6. In a review on the prediction of tool wear during friction stir welding of Al MMC by Bist et al. [58], it was reported that the rate of wear of the tool was directly proportional to the tool rotation so that wear rate increased as the speed of rotation increased.

However, at much higher speeds, as the tool rotation increased, there was increase in thermal input which aided the improvement in flow properties of the composite and thus led to reduced tool wear. In their study of wear behaviour of Al6061-SiC composite that was hot extruded, Ramesh and Keshavamurthy [59] found out that as the speed of slurry

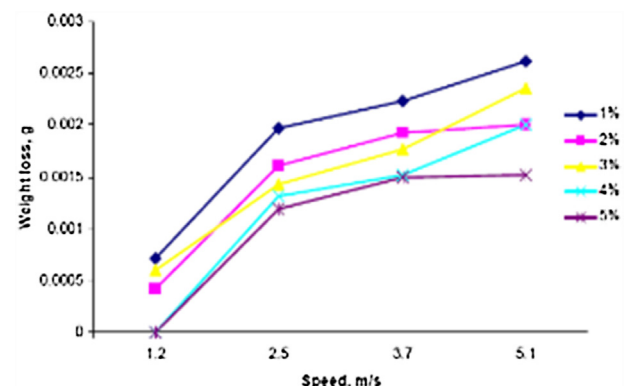


Fig. 6 – Effect of increasing speed on wear loss [57].



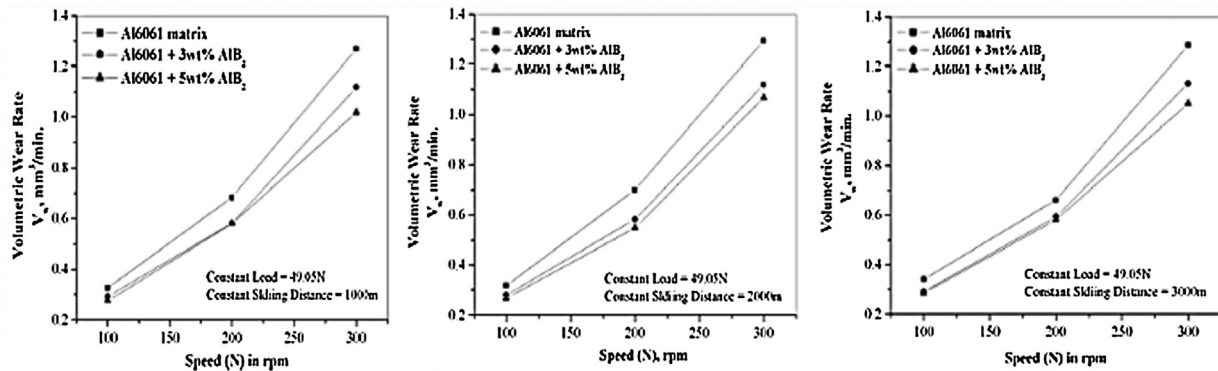


Fig. 7 – Variation of wear rate for Al–AlBr<sub>2</sub> composite at different sliding speeds [19].

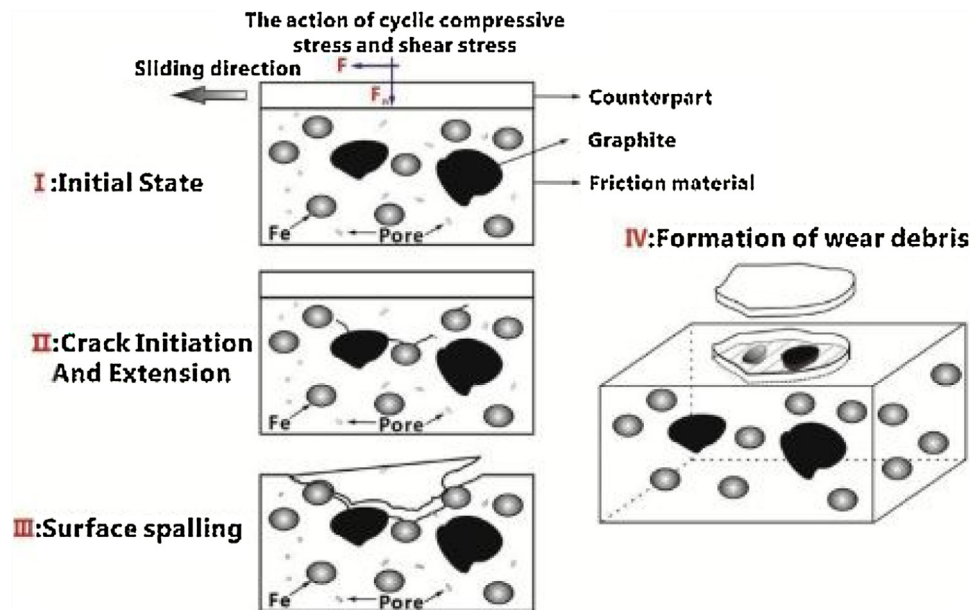


Fig. 8 – Schematic of a delamination wear process [61].

rotation increased, slurry erosive wear rate of the extruded and cast base alloy that was studied increased. However, in another study carried out by Gargatte et al. [11], the influence of sliding speed on the rate of wear of an Al-5083 was found to be inverse. At low speed, the rate of wear was high. As the speed 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 formed between the sliding surfaces [54]. This resulted in decrease in the wear rate. It was however revealed that at higher loads and increased sliding distance, the oxide film got removed, resulting in higher rate of material loss from the surface of the composite. As observed by Dayanand et al. [19], the effect of sliding speed follows a somewhat linear trend due to crack resistant AlBr<sub>2</sub> reinforcement as shown in Fig. 7.

## 6. Wear mechanisms

Wear mechanisms to which Al MMCs are susceptible include delamination, adhesive, abrasive and fretting. Interpretation

of surface morphology for each of the mechanisms is discussed here.

Delamination is characterised by excessive fracture of the material which results in the display of flake type debris [48], deep grooves, pits and craters [60]. As observed by Zhou et al. [61], in delamination wear, a series of interconnected cracks form due to poor particle bonding, surface contamination and oxidation as illustrated in Fig. 8. Adhesive wear is identified by the display of plastic deformation [62] and occurrence of pits and prowls [38]. The pits in adhesive wear are usually less, compared to those of delamination [60]. The presence of longitudinal or parallel grooves as an indication of microcutting or microploughing effect is what describes abrasive wear [63]. According to Mishra et al. [64], the grooves in abrasive wear are shallower when compared to those in delamination wear. Fretting wear is characterised by the display of minor scratches and loose fragments that result from oxide debris. It is usually as a result of the cyclic stress that occurs as a result of sliding between two surfaces [35]. Surface morphologies displaying

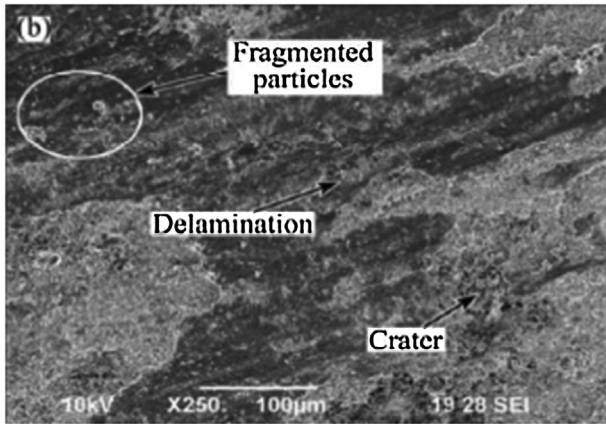


Fig. 9 – SEM image showing delamination wear of an Al matrix surface [35].

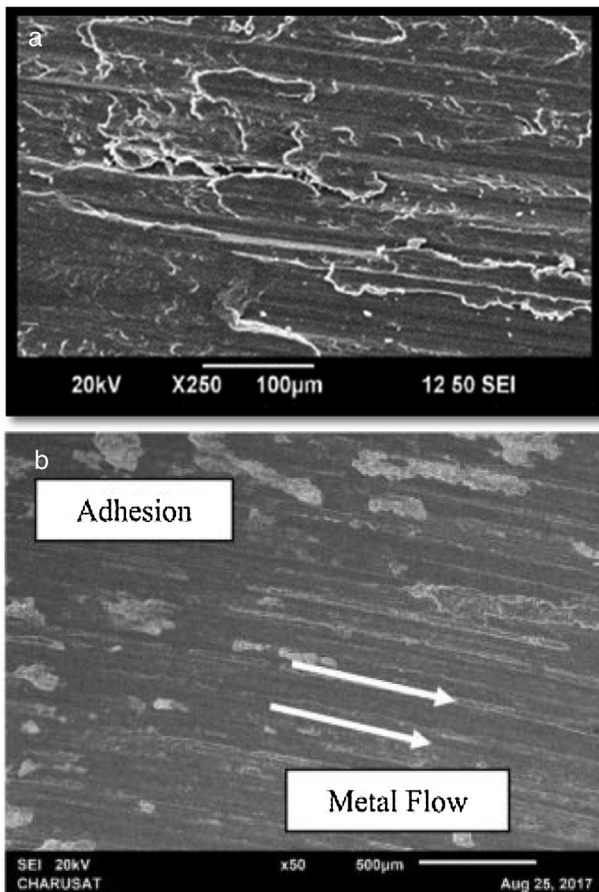


Fig. 10 – (a) SEM micrograph showing adhesive wear of an AA6061 surface [62]. (b) SEM micrographs displaying adhesive wear on (AA7075/Si<sub>3</sub>N<sub>4</sub>p) [26].

these wear mechanisms are shown in Figs. 9–12. A summary of various wear mechanisms with respect to different reinforcement types for selected Al MMCs is presented in Table 1.

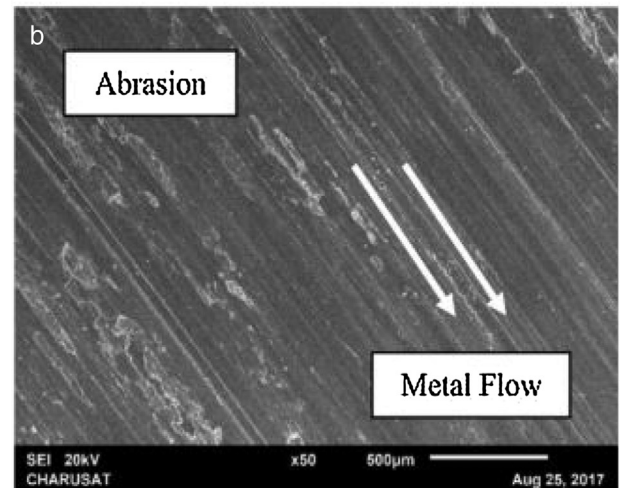
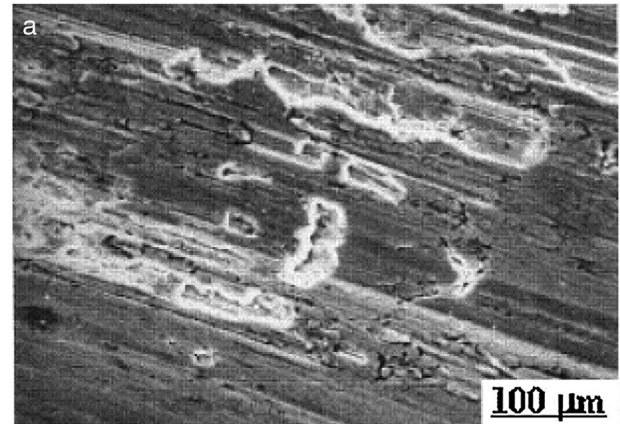


Fig. 11 – (a) SEM image showing abrasive wear mechanism in a zinc-aluminium based Al MMC [48]. (b) SEM micrographs displaying abrasive wear on (AA7075/Si<sub>3</sub>N<sub>4</sub>p) [26].

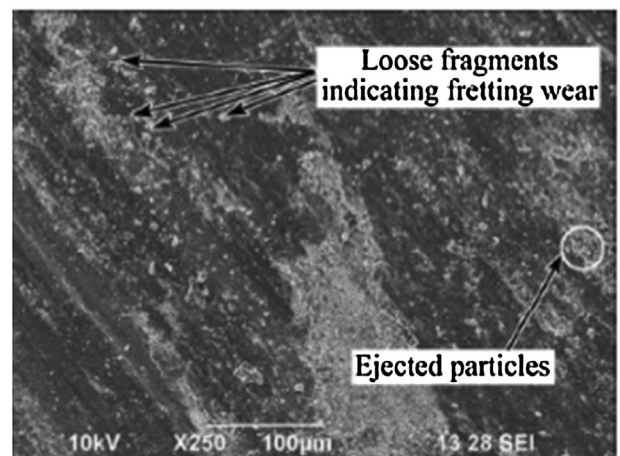


Fig. 12 – SEM image showing fretting wear of an Al-15%SiC-8%TiO<sub>2</sub> hybrid composite [35].

**Table 1 – Types of wear with respect to various wear conditions and reinforcement types of selected AlMMCs.**

Alloy/composite	Load (N)	Speed	Distance (m)	Predominant wear mechanism	Reference
Al/0wt%RHA Al/2wt%RHA Al/4wt%RHA Al/6wt%RHA Al/8wt%RHA	10–50	2 m/s	2000	Abrasive Adhesive Adhesive and abrasive	[62]
Al/5wt%SiC Al/7.5wt%SiC Al/10wt%SiC			–	Mostly abrasive, traces of adhesive	[63]
Zn–Al/5%garnet	30 50	2.45 m/s 2.45 m/s	– –	Abrasive Delamination	[48]
Al Al/15%SiC Al/15%SiC/4%TiO <sub>2</sub> Al/15%SiC/8%TiO <sub>2</sub> Al/15%SiC/12%TiO <sub>2</sub>	60	2.5 m/s	3000	Delamination Delamination and adhesive Abrasive Fretting Adhesive	[35]
Al/2%SiC Al/5%SiC	40	1.2 m/s 5.1 m/s	–	Delamination and abrasive	[57]
Al6061T6/15%SiC/15%Al <sub>2</sub> O <sub>3</sub>	30 35	2.25 m/s 2.00 m/s	1000 2000	Mostly abrasive. Traces of adhesive	[38]
Al6061 Al6061/4%TiB <sub>2</sub> Al6061/8%TiB <sub>2</sub> Al6061/12%TiB <sub>2</sub>		Abrasive	–	Delamination	[60]
Al2219 Al2219/8wt%B <sub>4</sub> C Al2219/8wt%B <sub>4</sub> C/3wt%Gr	30 –	600 rpm –	1500 –	Delamination, abrasive and adhesive	[30]
Al6061 Al6061/10%beryl	9.81 –	1.66 m/s –	Nil –	Delamination Abrasive	[43]
LM 25/activated carbon/mica LM 25/activated carbon LM 25/mica	–	–	–	Abrasive	[36]
Al6063 Al6063/10%WSD <sup>a</sup> Al6063/20%WSD	29.43	4.71 m/s	1000 2000 3000	Adhesive and abrasive	[65]
Al/3%SiC/0.5%Cu Al/6%SiC/0.75%Cu Al/9%SiC/1%Cu			–	Abrasive and a bit of adhesive	[32]

<sup>a</sup> WSD, wet grinder stone.

## 7. Conclusion

From the review presented, the following conclusions can be drawn:

- Hard reinforcement particles improve wear performance of Al MMCs.
- Increase in reinforcement particles increases wear resistance of Al MMCs.
- Reinforcement particles aid wear resistance by resisting the microcutting action of the rubbing abrasive and by the restriction of plastic deformation due to the protective oxide layer, formed between the composite and the opposing abrasive.

- Applied load is directly proportional to rate of material removal in dry sliding wear of Al MMCs.
- Sliding distance and sliding speed seem to exhibit predictable trends in their effects on wear rates of Al MMCs. Further research needs to be carried out in this regard.
- Wear mechanisms that can occur in Al MMCs include abrasive, adhesive, delamination and fretting wear. Delamination is predominant at high loads and in base alloys while abrasive is more probable in low load wear conditions and reinforced composites.

## Conflicts of interest

The authors declare no conflicts of interest.



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