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TOPICAL REVIEW

Inspiration of reinforcements, manufacturing methods, and microstructural changes on wear behavior of metal matrix composites—a recent review

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Abstract

The Metal Matrix Composites (MMCs) are increasingly replacing the commercial alloys in engineering components and undergoing intense analysis in the development of advanced composite structures. The metal matrix composites exhibit superior mechanical and tribological behavior than alloys in wear critical applications. Profound research works have been carried out in manufacturing the MMCs for improved friction and wear behavior. This study highlights the recent investigations from the perspective of wear behavior of MMCs. The effect of reinforcements and manufacturing processes of composites on wear behavior is elaborated. The significance of mechanical factors such as normal load, sliding speed and sliding distance is explained. The wear mechanisms observed in MMCs and studies on sub surface damages of composites are reported.

Introduction

Aluminum Metal Matrix Composites (Al-MMC’s) are now extensively used in automobile and aircraft industries. With the high desire for precision and dimensionally stable aircraft structure, the Al-MMC’s have driven the development of new combinations of composites with more specific strength and wear resistance [1, 2]. The first successful application of continuous fiber reinforced Boron-Al composite was developed in the form of tubular struts for the frame and rib truss member in the mid-fuselage section and the drag link of the space shuttle Orbiter. The Graphite reinforced Al 6061 tubes have been used in the structural antenna support boom for the Hubble space telescope because of the high mechanical and thermo-physical properties of Graphite(P100)/Al6061 flat panels and tubes [3]. The morphology of reinforcements play significant role in deciding the fracture behavior of Al-hybrid composites [4]. The failure of automotive and aircraft parts which are in relative motion is mainly occurred due to surface failure. The abrasion and erosion type of surface failure are noted in the first stage of compressor blades of gas turbine. The turbine blades exhibited different mode of wear in different regions based on the contact pressure distribution of incoming air flow [5]. The surface degradation of gas turbine blades are mainly affected by the solid foreign particles mixed in the air which are confirmed by trajectory of eroding particles on the surface [6]. In case steam turbine blades, the erosion occurs due to the magnetic particles formed in the boiler and passes through steam. The erosive wear life of the materials can be enhanced through hard coatings on the surfaces [7]. In the assembly of hub and plunger, the friction due to the contact of surface asperity during operation determines the rate of wear. This surface micro geometry varies during the course of wear [8]. Hence, it is essential to understand the wear behavior of Al-MMC’s in order to enhance the applications of such advanced materials in automobile components. Widespread research work has been carried out in Al-MMC’s in order to understand the surface behavior of Aluminum alloys. The studies have been carried out by reinforcing aluminum alloys with several ceramic particles like SiC, Al2O3, B4C, h-BN, ZrO2, etc [9, 10]. The components like piston, cylinder head, etc, which are widely used in automotive industries, have been slowly manufactured using SiC or Al2O3 reinforced Al-MMC’s.
Ceramic particles are embedded in Al-MMCs to procrastinate the transition of mild wear to severe wear [11]. Synthetic ceramics (Al₂O₃, B₂C, WC, etc), ceramics from industrial (Fly ash, Red mud, etc) and agricultural wastes (Rice husk ash, Bamboo leaf ash, etc) are three major types of ceramics used for dispersion in Al-based matrix [13]. The reinforcements from industrial and agricultural wastes are inexpensive and they comparatively offered lesser protection to the matrix. More investigations need to be triggered towards exploring the potential of these low-cost ceramics in Al-MMC’s.

The Archard’s equation clearly explained the role of mechanical factors and material property in deciding the wear loss and wear mechanism of the material. The property of the material strongly depends on the manufacturing route of the composites. The mechanical and tribological properties of MMC is intensely are governed by reinforcement, the morphology of reinforcement, manufacturing method of composites. Archard equation also holds good for composite materials. The dependency of wear behavior and wear mechanism of the material on above said control factors (i.e. material property and mechanical factors) was further confirmed by [10, 16]

\[
V_c = \frac{g_i P}{g_r H_c} \frac{d}{f_r} \left[1 - e^{-\frac{K_w f_r d}{H_c (1 - f_r)}}\right]
\]

(2)

\[
V_c — volume loss of composites (mm³), g_i and g_r — constants derived from wear loss of mating surfaces, P — Normal load (N), H_c — hardness of the composite (Brinell hardness), f_r — volume fraction of reinforcement, d — particle size of reinforcement.

Wear coefficient (K_w) as shown in figure 9b, is another dimensionless parameter, that can be calculated from Archard’s equation [15] for steady-state wear rate and another equation predicted by Zhang [16] for transient wear rate. Wear coefficient is defined as the probability of the formation of wear particles during wear [17]. It is required to conduct the sliding wear test for the sliding distance more than 3 km in order to find the transition from mild to severe wear. Yang [10, 17] derived a novel equation to determine wear-coefficient for AA6061/Al₂O₃—Steel tribosystem which is applicable in both transient and steady-state wear.

\[
K_w = \frac{3Hc d (1 - f_r)}{PL g_i f_r} \left[1 - \left(\frac{f_r G_L}{H_c (1 - f_r)}\right)\right]
\]

(3)

K_w — wear coefficient, Hc — hardness of the composite, f_r — volume fraction of reinforcement and d — particle size of reinforcement.

It is important to understand the influence of these factors on wear behavior in order to further broaden and deepen the research work in the field. In this perspective, a review work has been accelerated and the interesting results were compiled in this article. The review work was focused on the literature published in last two decades. As Aluminum-based MMC’s are widely used in auto components, the review focused on the wear studies of Al-MMC’s. This review work emphasizes the role of manufacturing processes, reinforcements, mechanical factors in deciding the wear mechanisms of Al-MMC’s.

**Influence of manufacturing processes**

Al-MMC’s are manufactured in several ways. Stir casting (liquid metallurgy), Powder metallurgy, Particle squeeze infiltration techniques were much used by investigators. Major problems faced by the researchers during the manufacturing of MMC’s are dispersion of reinforcement and bonding of reinforcement with matrix. The microstructure of the composite material greatly depends on the route of manufacturing process of the material. Henceforth, the processing route must be chosen based on the nature of matrix, reinforcement and the ability to bind them together. Singla et al [18] expressed that the ball milling process ensures proper dispersion when optimum milling time is followed. They also reported that the over milling lead to the damage
of reinforcements and reduced their potential. Similarly in stirring process, Stirring time is an essential parameter. Over stirring of the mixture would lead to the porosity by agitation. Apart from stirring time, the speed and the position of the stirrer, angle of stirrer blade are known as other process parameters that control the quality of microstructure in MMC fabrication. Akbari et al [19] have revealed that the ideal stirring time of A356/Al2O3 nano-composite is 4 and 8 min. The porosity of the matrix due to over agitation may support the wear resistance of the material in wet sliding conditions as these pores would act as carriers of lubricants. In case of dry sliding condition, it was reported reversely. The amount of porosity affects the hardness of the composites. It can be understood from Archard’s equation that the hardness is inversely proportional to the wear loss. Consequently, the wear loss of the composites was observed to increase when porosity content was increased as shown in figure 1.

The entrapment of gases during addition and mixing process of reinforcement was identified as another reason for poor distribution. Two-stage stirring (stir the composite slurry again by heating to liquid state) break the gas layer formed around the reinforcement particles which block the bonding between matrix and reinforcements. In another way, reinforcement particles can be ball milled to avoid cluster formation and mixed with melt for improved dispersion. In some articles, it is observed that the Al-MMC’s were heat-treated by solutionizing followed by aging. The impact of heat treatment on microstructure of constituents was studied and it was found that the heat treatment offered better wear resistance and lesser subsurface plastic deformation [20]. Mismatch of Coefficient of Thermal Expansion (CTE) and physical and mechanical properties between matrix and reinforcement drive them to behave differently in cooling process. This contrasting behavior develops stress in the interface which is accommodated by plastic deformation in the vicinity. When the material is brittle and could not undergo plastic deformation, it promotes crack through the pores around the reinforcement to relieve the interfacial stress [21]. There are some novel techniques identified by the researchers to avoid unwanted reactions and uniform distribution of reinforcement in the melt. Paramsothy et al [22] have wrapped the Al2O3 nano-particles in aluminum foil and introduced into the melt. This showed improved dispersion and betterment in mechanical properties. Poovazhagan et al [23] have dealt with ultrasonic cavitation technique for degassing and improved dispersion of reinforcement in melt. This technique further helped in reducing the agglomeration when nano-sized particles are used as reinforcement [24]. Gladston et al [25] reported improved interfacial bonding between rice husk ash and AA6061 matrix when the composite was manufactured using compo-casting technique. In this technique, the reinforcements are added in slurry stage of melt. It was also reported in other pieces of literature that this may be the suitable process route for Mg alloys which are highly reactive [26].

Powder metallurgy (P/M) is an excellent method to reinforce more volume fraction of nano-sized objects in Al matrix as possibility for agglomeration is high in liquid metallurgy processes [27, 28].

![Figure 1. Change in hardness with stirring time (due to porosity) versus wear rate. Reprinted from [19], Copyright (2013), with permission from Elsevier.](image-url)
Cold Isostatic Pressing (CIP) followed by pressure-less sintering generated pores in microstructure of the composites which led to the segregation of particles as clusters. This porous microstructure is undesirable while enriching the mechanical and tribological properties of materials in dry sliding conditions. The porosity of P/M composites increases with volume fraction of reinforcement [29]. It has been reported by Ray et al [30] that hot pressing after sintering closes the pores in sintered components. They also observed that the second phase particles present in the grain boundary restricted the mass flow across the boundary during sintering which reduced the densification of preforms. Composites formed by P/M technique present less anisotropy and comparatively the process is simple to automate [27]. The effective sintering of the MMC’s is influenced by the size of the reinforcement. Rahimian et al [31] have reported that the relative density of the composites increased when the size of the reinforcement (Al₂O₃) was increased from 3 μm to 12 μm due to the reduction in surface area of coarse particles. The relative density was found to be reduced when the size was further increased to 48 μm as shown in figure 2. This was predicted as lack of pressure distribution among the particles due to the above-said reason of reduction in specific surface area. Further, the sintering was found to be active when the weight fraction of reinforcement was low.

In order to enhance the surface properties of Al-MMC’s, it is necessary to disperse the reinforcements on the surface of the composites. These surface composites are achieved by thermal spraying and laser beam based processes. As the matrix and reinforcements are taken to high temperatures during these processes, there is formation of some deleterious compounds on the surface. Devaraju et al [32] have experimented Friction Stir Process (FSP) to manufacture hybrid surface composites in AA6061. They observed superior microstructure and wear resistance of the composite. The grain refinement and proper grain orientation in these composites are achieved by mechanical force and friction heat due to the process.

In all the above-said processes, the reinforcements are added externally in the form of particles, fibers, tubes, platelets. In these ex situ synthesis process, the surface of the reinforcements are easily getting contaminated and reacted adversely with atmospheric elements. This contamination affects the interfacial reaction between reinforcements and the matrix. Also, high porosity and inhomogeneous distribution of the reinforcement particles lead to the agglomeration and deterioration of mechanical and tribological properties. In situ manufacturing technique is a suitable fabrication method to overcome all the above-said constraints of common manufacturing techniques of Al-MMC’s. Several researchers [33–38] have been carried out using this fabrication method and the outcome was found to be successful. Al-Si alloys, which are widely used in auto components, are not serving the purpose effectively at high temperatures as the properties diminish. Al-MMC’s with SiC, Al₂O₃ as reinforcements in many forms (particles, whiskers, and fibers) were studied intensely in last two decades. It is still required to conduct further studies on in situ manufacturing of composites and the effect of superheating the composite melt on morphology of nucleated grains. The outcome of this study will be fruitful to find a solution for high-temperature property enhancement of existing Al-Si alloy.

Effect of reinforcements

Mostly used Aluminum alloys are reinforced with several particles and fibers to enhance their properties. The size and shape of the reinforcement play a vital role in deciding the response of the material. The full potential of the reinforcement comes out when the interfacial bonding with matrix is perfectly established. The Al₂O₃ and SiC are widely exercised by the researches to improve the tribological properties of Al-based alloys. Al₂O₃
possesses hexagonal close pack (hcp) molecular structure which provides the self-lubricating tendency and SiC is an abrasive particle. Aluminum carbide (Al₄C₃), a deleterious compound, forms at around 720 °C when Al reacts with SiC [27]. Al₄C₃ provides poor mechanical and tribological properties to the composites. The formation of Al₄C₃ and dissolution of SiC in Al matrix can be averted by controlling the stirring time of stir casting process [29]. Low volume of SiC in A356 matrix devised clusters that were loosely packed with matrix and pulled out easily in intermediate load that causes steep wear loss. Inferior mechanical locking in low volume reinforcement was noted as prime reason for the damage. Increased sizes of alumina (in the range of microns) in AA 2024 matrix revealed higher wear resistance than pure matrix. In Al-based matrix, micron-sized particles of ceramics perform better in lower loads and nano-particles act well in higher loads [39]. Nano-particles of SiC reportedly increased the wear resistance as they offer much constraints for the dislocation of particles in turns also increased the hardness by this work hardening effect. Hard SiC reinforcements protect soft matrix by reducing the extent of penetration of counter face [29]. The possibility for the nucleation of crack associated with wear is lesser in nano-sized reinforcement whereas particles of size more than 1 microns are more vulnerable [19]. Micro crack followed by fragmentation observed when micron-sized SiC reinforced with Al–Si alloy matrix at lower loads [39]. Carbon nano tubes of diameter more than 140 nm dispersed well in Aluminum matrix. Clusters formed when 40 nm diameter particles were reinforced. The type and volume of CNT are also significant in wear resistance [18]. Devaraju et al [32] have investigated the effect of graphite and Al₂O₃ in AA6061/SiC hybrid composites manufactured by friction stir processing (FSP). They found that the graphite reinforced hybrid composites exhibited improved wear resistance than Al₂O₃ reinforced hybrid composites as shown in figure 3. This was predicted due to the formation of mechanically mixed layer which contained graphite and offered solid lubricating effect. This lubricating effect of graphite is caused due to the week Vander-Waals force between molecular layers of graphite.

Metal mixed ceramic particles deliver exceptional hardness and wear resistance when reinforced with Al alloy matrix. Nano Al₂O₃ milled with Cu particles accord superior hardness and wear resistance than base alloy [19]. The volume fraction of reinforcement affects the wear resistance of the matrix. The optimum volume fraction of reinforcement varies with respect to the matrix composition. 20% and 12% of Alumina were reported as optimum volume for AA 6061 and Al-12Si matrix respectively to provide improved wear properties [12]. Rice Husk Ash and Fly ash delivered better wear properties when hybridized with SiC in Al-based composites than separately reinforced [40]. The Fly ash contains SiO₂ which empowered FA to offer lubrication in the interface of mating surfaces. Baradeswaran and Elayaperumal [41] have confirmed that Al₂O₃ and 5% graphite picked up the collective responsibility with AA 7075 to enhance the wear resistance by forming a tribo layer in contact pin surface. Despite the protection offered to the matrix by increased volume of Al₂O₃ hard particles, the crack nucleation and propagation in grain boundaries of Al₂O₃ led to the increment in wear rate. The presence of Zircon particles in Al matrix improved the hardness, wear resistance as the volume increased [40]. Zhiqiang et al [42] have revealed that coefficient of friction of 9 vol% of Si added to Al–Cu–Mg was increased more than base matrix after a critical load, but the wear rate was found to be lesser than Al alloy. When, Al₂O₃, B₄C, Ti₃Al, B₇Ti were reinforced with AA 6061 till 15 vol%, the authors observed no considerable influence of any particular type of reinforcements and their volume in wear resistance of the material [43].

Figure 3. Wear rate of Hybrid composites. Reprinted from [32], Copyright (2013), with permission from Elsevier.
Complex Metallic Alloys (CMA) are intermetallic compounds characterized by the presence of well-defined cluster of atoms. Limited articles were published in analyzing the tribological characteristics of aluminum alloy reinforced with CMA. Intermetallic compounds are highly brittle in nature and easily fragmented with combined effect of shear and compression during wear which was witnessed by Zhu with Al$_3$Zr formed during milling [44]. Fragmentation of particles observed at higher load which enhances third body wear with severe volume loss [19]. Pre-milled Al$_2$O$_3$, along with Cu metal particles contributed better wear resistance as Cu strengthen Al matrix. The extensive reaction of intermetallic compounds with matrix was found to be decreased with Powder Metallurgical route [45]. Exceptional support was provided by intermetallic compounds to Al matrix at lower loads and high temperatures. It is observed while coming across these works of literature that the hybrid MMC’s offered improvement in tribological properties of the material than conventional MMC’s. The research works on wear characterization and wear mechanics of hybrid MMC’s can be intensified for further exploration.

**Significance of mechanical factors**

The mechanical factors that influence the friction and wear behavior of material are known as normal load, sliding speed, and sliding distance. The transition of wear from mild to severe depends on the values of these control factors. The transition point of these values varies or increased when the metals are reinforced with other materials [12].

**Normal load**

The variation of normal load in test normally shows the transition of mild wear to severe wear. The normal load at which this changeover occurs is called transition load or critical load. Critical load (Transition load) of Al-MMC independent of bulk hardness of the material and it controls the maximum thickness of the Mechanically Mixed layer (MML), which is usually formed on the surface of the sliding material due to transfer of material from both the surfaces during wear. When the magnitude of normal load is greater than transfer load, it would lead to an increase in rate fracture of MML. This rate of fracture of MML would be greater than rate of formation of MML, in turn, it increases the wear rate [14] as shown in figure 4.

Transfer load in Al-based materials can be increased by incorporating the ceramic reinforcement. Wear rate of reinforced matrix was observed in mild regime while unreinforced alloy experienced severe wear at the same normal load [12] as shown in figure 5. The transfer load of AA6061 improved to 230 N by introducing Al$_2$O$_3$ in the matrix. Hybrid nano-composites fabricated along with Carbon (graphite) as one of the reinforcements, contributed extraordinarily to delay the transfer load to 294 N in Al-12Si alloys [12] as shown in figure 6.

Hard and sharp asperities of Zircon (ZrSiO$_4$) delayed the transition load of Aluminum by forming MML with the counter face [46]. The tendency of cracking during wear phenomena was discovered to be more at low normal load conditions [20]. The pores and cracks formed during fabrication processes were closed by plastic flow of matrix material at higher normal load. This plastic deformation increased the wear resistance through work hardening the worn surface [47] and subsurface.

The hard reinforcement in the composites offer support to low magnitude of normal load [48]. The asperities of hard reinforcement sheared-off when normal load is increased. The fragmented asperities formed a layer on the surface of the composites. The layer may contain the asperities of composites or counter-face material. The counter-face surface get cut out due to the hard reinforcements in soft matrix. This may also happen in reverse way that the asperities of counter-face may penetrate into the soft matrix [49]. This layer is called as transfer layer or tribo layer, which reduces the wear rate of the material [50]. The transfer layer is formed when the local stress at the interface is greater than the fracture stress of the particle [51]. This fracture stress of the particle depends on the normal load and the fracture is governed by the interfacial bonding between the matrix and reinforcement and nature of reinforcement. The fracture stress occurred at normal load greater than 50 N in AA7075/Al$_2$O$_3$ composite [51]. The transfer layer gets compacted at higher magnitude of normal loads. The compacted tribo layer formation reported to be beneficial as it reduces the wear rate [52]. On continuous exposure of high magnitude normal load or increased sliding speed at higher normal load would lead to the increment in interfacial temperature. This rise in temperature at the interface softens the compacted tribo layer and confirms the subsequent fracture of the layer [52]. The interface temperature also create oxide layer of matrix on the wear surface [53, 54]. Show et al [54] have expressed that contact surface temperature is high at higher normal load. Apart from interface temperature, the contact area also influences the oxide layer formation [55]. The oxide layer fractures at certain higher magnitude of load and lead to third body wear if the fractured particles trapped in between the mating surfaces [56].
The low and high magnitude of normal load depends on factors like morphology and the amount of the reinforcement in the composites. The interaction between the particle size and normal load reported as a significant factor in wear phenomena [57]. The post fabrication heat treatment processes considerably affect the
transition load of the composite material. The wear mechanism changes from abrasive wear to adhesion and delamination while increasing the normal load. Vivekananda and Balasivanandha Prabu [58] expressed that the severity of abrasive wear depends mainly on the normal load.

Generally, the coefficient of friction of the Al-MMC is decreasing with increasing normal load. Al-Si$_3$N$_4$ nano composites developed were investigated for its friction and wear performance by Ambigai et al [59]. The coefficient of friction of the Al-Si$_3$N$_4$ nano composites experienced reduction with increase in the normal load. The probable cause for the reduction in the CoF is the increased interface temperature cause the tribo-oxidation and weakens the friction layer and reduces the bonding property of the layer. Similarly, Du Jun et al [12] have evaluated the hybrid composite using Al–Si alloy reinforced with Al$_2$O$_3$ and short carbon fiber. The increase in the carbon fiber reduced the CoF but the normal load has the same behavior in the hybrid Al MMCs. Irrespective of the composition, the CoF reduced with increase in the normal Load.

**Sliding speed**

The sliding velocity of the wear process is a function of revolution of the disc and the contact point of the pin from the center of the disc (in case of Pin-on-Disc equipment). Sliding velocity kept as a variable in some studies. Basavarajappa et al [60] concluded that the sliding speed is the most significant mechanical factor in affecting wear behavior followed by normal load and sliding distance. Abouelmagd G [27] have found that Al/1.5vol% Al$_2$O$_3$/4vol%Al$_4$C$_3$ (Aluminum Carbide in needle-like phase) hybrid composite showed less wear rate at lower sliding speed. An increase in wear rate at high speed was noticed due to the rise of friction in tribosystem. Friction raised the temperature at contact surfaces, which soften the matrix (thermal softening) and reduced the shear strength to cause severe wear. In extension, the temperature rise at the interface of mating surfaces also leads to faster oxidation which helps to reduce the wear by forming oxide layer of base matrix [44] as shown in figure 7. The sliding interfaces are protected by this oxide layer and reduces the wear rate [60].

The addition of ceramic particles adjoined the transition temperature at which thermal softening occurs. The transition temperature of AA6061/20 vol% Al$_2$O$_3$ and A356/20 vol% SiC composites, was prolonged to the range of 310 °C–350 °C and 440 °C–450 °C respectively. These composites exhibited mild wear in the above-said range of temperatures. Inclusion of 10 vol% graphite with 20 vol% SiC as part of hybridization, further increased the temperature to 460 °C. This shows that the thermal stability of MMC’s can be increased by hybridization. Increased wear rate due to thermal softening at high sliding speed was not observed in A 7075/Al$_2$O$_3$/graphite hybrid composite as pin surface was protected by a layer of pulled out particles of graphite [41]. Even though the graphite provided the self-lubricating tendency to the material, it reduced the hardness, ductility, and strength of the material. The material of wear surface plastically deforms severely at higher sliding speeds due to frictional heat produced [61]. The rate of formation of wear debris found to be higher when the sliding speed is increased. The flake shaped wear debris formed at higher sliding speed explains the severe rubbing in the interface [62]. Due to high frictional heat and shear force, the bonding between the matrix and the reinforcement get weakened, and the reinforcement subsequently pulled out [55]. In the perspective of wear mechanism, at low sliding speed, abrasion and mild plastic deformation were noted to be effective wear mechanisms. Whereas at high sliding speed, oxidation, delamination, severe plastic deformation, surface
melting and adhesion were found operative in AA2014/B_4C fiber-reinforced composites [11]. In certain cases, the ultra-severe wear, at high sliding speed such as 5 m s\(^{-1}\), lead to the seizure of contact material [60]. The sliding speed shows the impact on the coefficient of friction. The increase in the sliding speed reduces the coefficient of friction irrespective of the applied load conditions. The increasing sliding speed of the rotor weakens the tribo-interface which causes the reduction in the coefficient of friction [48].

**Sliding distance**

Ekka *et al* [63] have identified that the sliding distance is one of the influencing mechanical factors followed by normal load and sliding speed. The run-in period of wear commonly observed until few hundred meters then the steady-state linear wear behavior of material are noticed with materials. The unstable and fluctuating wear is commonly noted in the initial run-in period as shown in figure 9a [64]. During the run-in period, the mating surfaces maintain direct contact between them, and newer surfaces are formed after sliding to certain distance [55].

In many pieces of literature, it was reported that the transition from run-in period to steady state is quickened in composites. Yang [65] has developed a mathematical model for obtaining the transient and steady-state wear loss of AA6061/20 vol% Al_2O_3 particles against steel disc. Yang [10] expressed that 6 km, 9 km and 12 km are identified as the best sliding distances in order to effectively calculate the steady-state wear coefficient for the material. The interfacial temperature of the mating surfaces increases with increasing sliding distance and saturates at around 8 km to the temperature of 40 °C–45 °C. This interface temperature increases when contact pressure of the specimen is increased as shown in figure 8.

Khoushik *et al* [57] have reported that the sliding distance is one of the significant mechanical factors to affect the wear parameters of AA6063/SiC composites. The influence of sliding distance was further confirmed to be the most prominent control factor in wear performance of AA7075/Ni composites [61]. Kumar *et al* [52] have expressed that the cumulative wear volume of Al/TiC composites varies linearly with respect to sliding distance. The wear rate of the composites is found to be lower than the unreinforced material [67]. Jojith *et al* [68] have fabricated the hybrid composites of MoS_2 and TiO_2 reinforced in LM13 alloy. They found that the hybrid composites with MoS_2 performed better in long sliding distance due to its self-lubricating property. Hariharasakthisudhan *et al* [38] have examined the steady state wear behavior of multi-scale hybrid composites. They identified that the scale and morphology of the reinforcements in hybrid composites affect the wear performance in long sliding distance up to 12 km.

In general, the CoF increase with sliding distance because of the increment in the contact area (due to wear of the sample) of the tribo surface. The increase in the contact area increases the direct contact exposure of the reinforcement asperities. After a certain distance the CoF starts decreasing due to the formation of the tribo-layer which reduce the direct contact of the asperities between the tribo couple [69].
Figure 8. Change in interface temperature with respect to sliding distance for contact pressure (a), (b) – 0.5 MPa and (c), (d) – 2 MPa. Reprinted from [66], Copyright (2015), with permission from Elsevier.

Figure 9. Variation of standard wear coefficient and wear volume with respect to sliding distance. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Tribology Letters [17].
Wear mechanisms

Wear Mechanisms of developed composite materials can be better understood by conducting microstructure analysis on worn surfaces, subsurface of worn surface (vertical cut section of the specimen) to the depth of few microns, wear tracks, and wear debris formed during wear process. Successive topics explain the most commonly observed wear mechanisms in Al-MMC’s.

Abrasive wear

Grooves and scratches on the micrograph indicate abrasive wear as shown in figure 10. These grooves are generally formed by ploughing of asperities of reinforcement particles during initial period of sliding. The broken asperities during run-in wear are pulled out and cut the counter faces in contact if they are entrapped between mating surfaces. Composites with larger volume fraction of reinforcement sustained abrasive wear at the time of sliding [46]. The abrasion may become severe when the normal load and sliding speed are increased more than certain value. Al-MMC’s under lower load of wear course commonly went through abrasive wear [40]. Bamboo leaf Ash particle used along with Al–Si–Mg/SiC composite displayed abrasive wear with low debris on composite. The severe abrasion can be identified with deep grooves on the wear surface. The deep abrasive grooves indicate massive plastic deformation in the material. Sometimes, the exposure of soft matrix material to counter face, due to lack of dispersion of reinforcement, may cause severe abrasion even at low normal loads. Unreinforced AA 7075 exhibited deep grooves in lower loads [41]. Abrasive wear dominated when Al reinforced with micron size particles of intermetallic compounds [70].

Adhesive wear

In MMC’s the matrix usually a soft and ductile material like Al, Cu, Zn, and Mg. When these soft metal parts of the composite come into the contact with counter-face material during wear process, it undergoes plastic deformation due to shear force. This type of surface change is indicated as adhesive wear [72]. This plastic deformation not only exists on the worn surface also is transferred to the subsurface of the material. The plastic deformation of matrix is controlled or reduced by the presence of reinforcements in MMC’s [73]. The normal load is identified as much influencing factor to increase the plastic deformation and subsequent work hardening in the subsurface of the material as shown in figures 11 and 12. Al-qutub et al [48] found adhesive wear as primary wear mechanism in Al/Al₂O₃ composite at higher sliding speeds. The adhesions at high sliding speed are mostly combined with delamination. In some cases, the adhesion of aluminum composites on rotating disc appeared. Due to micro cutting and adhesion, a new surface that comprised wear debris and oxide debris, is developed on the composites [61].

Figure 10. Extensive grooving of AA 2024/Al₂O₃. Reprinted from [71], Copyright (2006), with permission from Elsevier.
Mechanically mixed layer (MML)

Mechanically Mixed Layer (MML) forms during the course of wear test by the mechanical alloying between the wearing surfaces after a period. MML often observed with Al-MMC’s. Irrespective of the value of the coefficient of friction, MML offers better wear resistance in Al-MMC’s [14]. The thickness, hardness, and composition of MML control the resistance endeavored for wear. The formation of MML involves a sequence of processes. The process starts with particle fragmentation of subsurface closer to the worn surface followed by nucleation of crack in grain boundaries, coalescence of crack, and shear instability of particles. The configuration of MML and subsurface changes are schematically represented in figure 13. Plastically Deformed Region (PDR) just beneath the MML as shown in figure 14, releases the material continuously to keep up the thickness of the MML in the course of wear [43]. As steel was used as counterface material for most of the tribological study of Al-MMCs, Fe reported taking part in the composition of MML, which can be observed in Energy Dispersive Spectroscopy (EDS) results to validate the presence of MML. The EDS spectrum results of AA 7075/Al₂O₃/5 vol% graphite proved the presence Fe particle from counter face which came out by Mechanical Alloying [41].

Figure 11. Adhesive wear of Al-10FeSiCrC at normal load 30N [67] (Arrows indicate plastic deformation and Circles indicate voids/pores). [67] [2006], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).

Figure 12. Adhesive wear of Al-10FeSiCrC at normal load 70N [67] (Arrows indicate plastic deformation). [67] [2006], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).
Delamination

Another commonly noted wear mechanism with Al - MMC’s is delamination. This phenomenon is a serious surface deformation. Large flake shape morphology of worn-out surface indicates the delamination as shown in figure 15 [41]. It is mostly observed along with adhesive wear of the composites in severe regime of wear [12]. Adhesive wear results from plastic shear instability at the junction of the contact materials due to high magnitude of normal loads. Wear resistance of the material is severely affected by delamination. The large volume fraction of reinforcement led to the formation of long continuous crack on the surface. Particle fracture or cracks/voids in matrix or in the interface of matrix and reinforcement subsequently forms the delamination. Fracture toughness, shape and size of the particles greatly influence the maximum load that can be supported by the reinforcement [21]. The developed cracks provoke the delamination. The encrusted reinforcement got removed when the sliding speed of test was increased. As the layer got broken, load transferred to matrix and caused subsequent ploughing, crack initiation and propagation to delamination. Improved plastic properties and bonding ability of ultra-fine nano particles provide better wear resistance [39]. High stressed particles get fragmented when the stress exceeded the particle’s fracture strength [70].

Boundary (metal oxide layer, moisture layer, and graphite layer) friction mechanism was encountered with Sb/graphite composites when reinforced with micron and nano-sized fillers [74]. Micron level fillers influenced tribological behavior, where mechanical and physical behavior dominated by nano level fillers.
Summary

This article summarizes a few interesting findings of the dry sliding wear behavior of Al-MMC’s in last two decades. The following conclusions have arrived from the study.

a. Manufacturing process plays essential role to control the microstructure of Al-MMC’s. In-situ manufacturing process of Al-MMC’s offered comparatively improved microstructure and tribological performances than the composites fabricated through Ex-situ processes.

b. Complex Metallic Alloys (CMA) and intermetallic compounds formed with in situ manufacturing process provided superior wear properties. Further research work can be intensified to investigate the friction and wear behavior of such composites in order to find suitable material for high temperature wear resistance.

c. Sliding speed and normal load are the most significant mechanical factors, which affect the wear phenomena of Aluminum metal matrix composites.

d. Abrasive wear is commonly found in the lower normal load and sliding speed. Severity of abrasion increases when values of above-said factors increased. Adhesive wear along with delamination observed in the higher loading configuration. The extreme cases also reported oxidative wear, surface melting, and seizure of mating surfaces.

e. Hybrid MMC’s are reported to show improved tribological behavior than conventional MMC’s with single reinforcement. Hybrid composites with one of the reinforcement as a lubricant (i.e. MoS₂, graphite, Zinc Stearate) may further be studied for improved tribological behavior.

f. Wear mechanics and wear characterization for hybrid MMC’s can be further explored for better understanding and to find suitable material long term wear resistance.

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References

[1] Zhang X, Chen Y and Hu J 2018 Recent advances in the development of aerospace materials Prog. Aerosp. Sci. 97 22–34
[2] Rawal S P 2001 Metal-matrix composites for space applications JOM 53 14–7
[3] Rawal S P et al 1990 Composite materials for space applications Nasa Contract Rep 187472
[4] Logesh K et al 2019 Mechanical properties and microstructure of A356 alloy reinforced AlN/MWCNT/graphite/Al composites fabricated by stir casting Mater. Res. Express 7 015004
[5] Laguna-Camacho J R et al 2016 A study of the wear damage on gas turbine blades Eng. Fail. Anal. 61 88–99
[6] Lee K et al 2019 Engineering Design Applications. (Cham: Springer International Publishing) Epub ahead of print (https://doi.org/10.1007/978-3-319-79005-3)

[7] Garg D and Dyer P N 1993 Erosive wear behavior of chemical vapor deposited multilayer tungsten carbide coating Wear 162–164 552–7

[8] Mirlilimov V M and Akhundova P E 2018 Minimization of stress state of a hub of friction pair Adv Math Phys 2018 1–10

[9] Kato K 2000 Wear in relation to friction—a review Wear 241 151–7

[10] Yang L J 2003 The transient and steady wear coefficients of Al6061 aluminium alloy reinforced with alumina particles Compos. Sci. Technol. 63 575–83

[11] Sahin Y 2003 Wear behaviour of aluminium alloy and its composites reinforced by SiC particles using statistical analysis Mater. Des. 24 95–103

[12] Jun D et al 2004 Dry sliding wear friction and wear properties of Al2O3 and carbon short fibres reinforced Al–12Si alloy hybrid composites Wear 257 930–40

[13] Bodunrin M O, Alaneke K K and Chown L H 2015 Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics J. Mater. Res. Technol. 4 434–45

[14] Venkataraman B and Sundararajan G 2000 Correlation between the characteristics of the mechanically mixed layer and wear behaviour of aluminium, Al–7075 alloy and Al–MMC’s Wear 245 22–38

[15] Archard J F 1953 Contact and rubbing of flat surfaces J. Appl. Phys. 24 981–8

[16] Zhang Z, Zhang L and Mai Y W 1996 The running-in wear of a steel/SiCp–Al composite system Wear 194 38–43

[17] Yang L J 2004 Prediction of net steady-state wear coefficient in an Al–Al2O3 (P)/Steel system with an integrated wear model Tribol. Lett. 17 105–18

[18] Singla D, Amulya K and Murtaza Q 2015 CNT reinforced aluminium matrix composite—a review Mater Today Proc 2 2886–95

[19] Akbari M K, Baharvandi H R and Mirzaee O 2013 Nano-sized aluminum oxide reinforced commercial casting A356 alloy matrix: evaluation of hardness, wear resistance and compressive strength focusing on particle distribution in aluminium matrix Compos Part B Eng 52 262–8

[20] Sawla S and Das S 2004 Combined effect of reinforcement and heat treatment on the two body abrasive wear of aluminum alloy and aluminum composite Wear 257 555–61

[21] Ted Guo M L and Tsao C Y A 2002 Tribological behavior of aluminum/siC/nickel-coated graphite hybrid composites Mater. Sci. Eng. A 333 134–45

[22] Paramsothy M et al 2009 Enhancing tensile/compressive response of magnesium alloy AZ31 by integrating with Al2O3 nanoparticles Mater. Sci. Eng. A 527 162–8

[23] Poovazhahan L, Kalaielvans K and Sornakumar T 2016 Processing and performance characteristics of aluminum–nano boron carbide metal matrix nanocomposites Mater Manuf Process 31 1275–85

[24] Tjong S C 2013 Recent progress in the development and properties of novel metal matrix nanocomposites reinforced with carbon nanotubes and graphene nanosheets Mater Sci Eng R Reports 74 281–350

[25] Gladston J A K et al 2015 Production and characterization of rich husk ash particulate reinforced AA6061 aluminum alloy composites by compocasting Trans Nonferrous Met Soc China English Ed 25 683–91

[26] Bahrami A et al 2016 Development of metal–matrix composites from industrial/agricultural waste materials and their derivatives Crit Rev. Environ Sci Technol 46 143–207

[27] Abouelmagd G 2004 Hot deformation and wear resistance of P/M aluminium metal matrix composites J. Mater. Process. Technol. 155–156 1395–401

[28] Harinarasakthisudhan P, Jose S and Manisekar K 2019 Dry sliding wear behaviour of single and dual ceramic reinforcements premixed with Al powder in AA6061 matrix J. Mater. Res. Technol. 8 275–83

[29] Bindumadhavan P N et al 2001 Effect of particle-porosity clusters on tribological behavior of cast aluminum alloy A356–SiCp metal matrix composites Mater. Sci. Eng. A 315 217–26

[30] Ray A K et al 2002 Fabrication of TiN reinforced aluminium metal matrix composites through a powder metallurgical route Mater. Sci. Eng. A 338 160–5

[31] Rahimian M, Parvin N and Ehsani N 2010 Investigation of particle size and amount of alumina on microstructure and mechanical properties of Al matrix composite made by powder metallurgy Mater. Sci. Eng. A 527 1031–8

[32] Devaraju A, Kumar A and Kotriverezhachiri K 2013 Influence of addition of Grp / Al2O3-p with SiCp on wear properties of aluminum alloy 6061-T6 hybrid composites via friction stir processing Trans. Nonferrous Met. Soc. China English Ed. 23 1275–80

[33] Harinarasakthisudhan P and Jose S 2018 Influence of metal powder premixing on mechanical behaviour of dual reinforcement (Al2O3 (μm)/Si3N4 (nm)) in AA6061 matrix J. Alloys Compd. 731 100–10

[34] Mandal A, Murty B S and Chakraborty M 2009 Sliding wear behaviour of T6 treated A356–TiB2 in situ composites Wear 266 865–72

[35] Gautam G, Ghose A K and Chakraborty I 2015 Tensile and dry sliding wear behaviour of in-situ Al2O3 + Al2O3-reinforced aluminum metal matrix composites Metall. Mater. Trans. A, Phys. Metall.Mater. Sci. 46 5952–61

[36] Everton S K et al 2016 Review of in situ process monitoring and in situ metrology for metal additive manufacturing Mater. Des. 95 431–45

[37] Pavitra K and Mitra R 2012 Effect of age-hardening on dry sliding wear of mushy state rolled in situ Al-4.5Cu-5TiB2 composites Mater. Sci. Eng. A 557 84–91

[38] Harinarasakthisudhan P et al 2020 Steady-state wear behaviour of multi-scale hybrid composite—AA6061/Al2O3 (μm)/Si3N4 (nm)/ graphite—EN31 steel tribio system J. Tribol. 142 1–23

[39] Mozami-Goudarzi M and Akhlaghi F 2016 Wear behavior of Al 5252 alloy reinforced with micrometric and nanometric SiC particles Tribol. Int. 102 28–37

[40] Kala H, Mis K K S and Kumar S 2014 A review on mechanical and tribological behaviours of stir cast aluminium matrix composites Procedia Mater Sci 6 1951–60

[41] Baradswaran A and Elaya Perumal A 2014 Study on mechanical and wear properties of Al 7075/Al2O3/graphite hybrid composites Compos Part B Eng 56 164–71

[42] Zhiqiang S, Di Z and Guobin L 2005 Evaluation of dry sliding wear behavior of silicon particles reinforced aluminum matrix composites Mater. Des. 26 454–8

[43] Rosenberger M R, Schvezov C E and Forlerer E 2003 Wear of different aluminum matrix composites under conditions that generate a mechanically mixed layer Wear 259 590–601

[44] Zhu H G et al 2010 Dry sliding wear behavior of Al-based composites fabricated by exothermic reaction in an Al-ZrO2-C system Wear 268 1465–71
[45] Scudino S et al 2009 Powder metallurgy of Al-based metal matrix composites reinforced with β-Al4Mg3 intermetallic particles: analysis and modeling of mechanical properties Acta Mater. 57 4529–38
[46] Mazahery A and Shabani M O 2012 Study on microstructure and abrasive wear behavior of sintered Al matrix composites Ceram. Int. 38 4263–9
[47] Tan Z H et al 2008 The compressive properties of 2024Al matrix composites reinforced with high content SiC particles at various strain rates Mater. Sci. Eng. A 489 302–9
[48] Al-Qutub A M, Allam I M and Abdul Samad M A 2008 Wear and friction of Al-Al2O3 composites at various sliding speeds J. Mater. Sci. 43 5797–803
[49] Ghandvar H, Farahany S and Idris M H 2018 Effect of wettability enhancement of SiC particles on impact toughness and dry sliding wear behavior of compocasted A356/20SiCp composites Tribol. Trans. 61 88–99
[50] Ambigai R and Prabhu S 2019 Experimental and ANOVA analysis on tribological behavior of Al/β, C micro and nanocomposite Aust J Mech Eng 17 53–63
[51] Daoud A, Abou El-Khair M T and Abdel-Azim A N 2004 Effect of Al2O3 Particles on the microstructure and sliding wear of 7075 Al alloy manufactured by squeeze casting method J. Mater. Eng. Perform. 13 135–43
[52] Kumar A, Gautam R K and Tyagi R 2016 Dry sliding wear characteristics of in situ synthesized Al-6063/TiC composites Compos. Interfaces 23 469–80
[53] Mondal M K, Biswas K and Maity J 2016 Dry sliding wear behaviour of a novel 6351 Al-6Al4SiC4 composite at high loads Can. Metall Q 55 75–93
[54] Show B K, Mondal D K and Maity J 2014 Dry sliding wear behavior of a novel 6351 Al-(Al6SiC4 + SiC) hybrid composite J. Mater. Eng. Perform. 23 875–97
[55] Singh R et al 2019 Characterization of dry sliding wear mechanisms of AA5083/β, C metal matrix composite J. Brazilian Soc. Mech. Sci. Eng. 41 98
[56] Mohan S et al 2016 Dry sliding wear behavior of Al-SiO2 composites Compos. Interfaces 23 493–502
[57] Kuashik N and Singhal S 2018 Hybrid combination of Taguchi-GRA-PCA for optimization of wear behavior in AA6063/SiCp matrix composite Prod. Manuf. Res. 6 171–89
[58] Vivekananda A S and Prabhu S B 2018 Wear behaviour of in situ Al/TiB2 composite: influence of the microstructural instability Tribol. Lett. 66 41
[59] Ambigai R and Prabhu S 2017 Optimization of friction and wear behaviour of Al–Si–N4 nano composite and Al–Gr–SiN4 hybrid composite under dry sliding conditions Trans Nonferrous Met Soc China Chinese Ed. 27 986–97
[60] Basavarajappa S and Chandramohan K 2006 Dry sliding wear behavior of metal matrix composites: a statistical approach J. Mater. Eng. Perform. 15 656–60
[61] Kumar A, Patnaik A and Bhat I K 2017 Investigation of nickel metal powder on tribological and mechanical properties of Al-7075 alloy composites for gear materials Powder Metall. 60 371–83
[62] Prashantha Kumar H G and Anthony Xavior M 2017 Effect of graphene addition and tribological performance of Al6061/graphene flake composite Tribol.- Mater Surfaces Interfaces 11 88–97
[63] Ellka K K, Chauhan S R and Varun 2015 Dry sliding wear characteristics of SiC and Al2O3 nanoparticulate aluminium matrix composite using taguchi technique Arab. J. Sci. Eng. 40 571–81
[64] Kaur K and Pandey O P 2010 Dry sliding wear behavior of zircon sand reinforced Al–Si alloy Tribol. Lett. 38 377–87
[65] Yang L J 2003 An integrated transient and steady-state adhesive wear model Tribol. Trans. 46 369–75
[66] Chandra Verma P et al 2015 Braking pad-disc system: wear mechanisms and formation of wear fragments Wear 322–323 251–8
[67] Buytoss S 2006 Effects of FeCrC and FeSiCrC, particles on wear behaviour of aluminium metal matrix composite Mater. Sci. Technol. 22 679–86
[68] Jojith R and Radhika N 2018 Mechanical and tribological properties of LM13/TiO2/MoS2 hybrid metal matrix composite synthesized by stir casting Part. Sci. Technol. 1–13
[69] Hariharasakthisudhan P et al 2020 Steady-state wear behavior of multi-scale hybrid composite—AA6061/Al2O3(μm)/Si3N4(nm)/graphite—EN31 steel tribosystem J. Tribol. 142 1–16
[70] Wang Y et al 2001 Dry wear behaviour and its relation to microstructure of novel 6092 aluminium alloy-Ni3Al powder metallurgy composite Wear 250 1421–32
[71] Kik M 2006 Abrasive wear of Al2O3 particle reinforced 2024 aluminium alloy composites fabricated by vortex method Compos Part A Appl. Sci. Manuf 37 457–64
[72] Thakanchan T and Prakash K S 2017 Microstructural, mechanical and tribological behavior of aluminium nitride reinforced copper surface composites fabricated through friction stir processing route Mater. Sci. Eng. A 688 301–8
[73] Lu J et al 2011 Tribological behavior of aluminium matrix composites containing complex metallic alloys AlCuFeB or AlCuFeCr particles Wear 270 528–34
[74] Li W Q, Fei H Y and He M 2008 Effect of filler on the self-lubrication performance of graphite antimony composites J. China Univ. Min. Technol. 18 441–5