Journal of Bio- and Tribo-Corrosion (2021) 7:122
https://doi.org/10.1007/s40735-021-00558-9

A Review on the Significance of Hybrid Particulate Reinforcements on the Mechanical and Tribological Properties of Stir-Casted Aluminum Metal Matrix Composites

Ramesh Manjunath[1] · Deepak Kumar[1] · Ajay Kumar[1]

Received: 4 February 2021 / Revised: 5 June 2021 / Accepted: 17 June 2021 / Published online: 30 June 2021

Abstract
Since several years, monolithic aluminum alloys were replaced by aluminum metal matrix composites, which could be used in structural, aerospace and automotive sectors because of its superior strength and stiffness, better performance during low cycle fatigue and wear resistant. Now a days, materials got diversified from pure to composite forms as per the global needs; because of its reduced weight, cheaper, stronger, better quality which are more efficient for various applications. Recent developed metal matrix composites exhibit some important mechanical properties like low density, high strength, stiffness, better wear resistance, better toughness and stiffness. explore several applications in automotive sector. The objective of this review article is to give an insight into the latest understandings of effect of adding hybrid particulate reinforcements like aluminum oxide, silicon carbide, graphite, fly ash, zirconium, titanium silicon carbide and graphite into the aluminum metal matrix and to highlight the main concerned areas which need to be overcome if these composites could be scaled up its full commercial potential. Hence authors have concluded that when aluminum metal matrix is incorporated with graphite as a soft lubricant and Silicon carbide as a hard reinforcement can improve desirable properties like wear and strength of the composites as compared to the properties of composites which contains single reinforcement, either silicon carbide or graphite alone. These composites are substantially maintaining green or ecofriendly tribological properties, features like sustainability and energy efficient since oil and grease-based lubricants releases hazardous pollutants into atmosphere.

Keywords Aluminum metal matrix composites · Silicon carbide · Aluminium oxide · Particulate reinforcements · Stir casting · Wear

1 Introduction

Kelly A [1], have reviewed the contribution of several socio technological factors in the era of modern material sciences which exhibit revolutionary advancement during the development of metal matrix composites.

Authors [2, 3] were of opinion that aluminum metal matrix when reinforced with ceramic particulates can lead to a development of new customized engineering components with better properties. The application of hybrid aluminum metal matrix composites reinforced with any of the reinforcements like aluminum oxide, silicon carbide, graphite, fly ash, zirconium, titanium for developing automotive components like pistons, engine blocks, brake rotors, drums, calipers, connecting rods, drive shafts. G. B. Veeresh Kumar, et al. [4], have revealed from their extensive literature that SiC particles are generally considered as reinforcements because of its enriched properties like strength, hardness, density, elastic modulus, excellent thermal shock and chemical resistance and observed an enhancement in the strength of composites when incorporated in combination with reinforcements like graphite, zircon, aluminum oxide and mica. The hybrid composites incorporated with two or more different reinforcement particles like silicon carbide, aluminum oxide, graphite, fly ash, extend the invent of tailor-made composite material to conquer the required property. The most commonly used reinforcements for the fabrication of composites are tabulated in Table 1.

✉ Ramesh Manjunath
rameshslp@gmail.com

[1] Department of Mechanical Engineering, University of Petroleum and Energy Studies, Dehradun 248001, Uttarakhand, India

Table 1 Properties different reinforcements

Reinforcement materials	Nominal size	Density	UTS (Mpa)	Modulus of elasticity (Gpa)
Al_2O_3		3.9	379	370
Nitrides		3.26	2069 (24 ℃)	310 (1090 ℃)
Si_3N_4	40–60	3.18		207
TiC		4.93	55 (1090℃)	269(24 ℃)
SiC	15–340	3.2	–	324 (1090 ℃)
TiB_2		4.5	–	414(1090℃)
B_4C	40–300	2.52	2759 (24 °C)	418 (24 °C)
SiO_2	40–60	2.44	–	73
Graphite	40–250	1.6–2.22	–	–
MgO_2	40–60	2.72–3.6	41 (1090 °C)	3191 (1090 ℃)

Courtesy: P. Venkateshwar Reddy et al. [5]

Suresh Kumar, et al. [6], have emphasized on the effects of incorporating different combination of hard and soft self-lubricated reinforcement particles into aluminum metal matrix on various mechanical and tribological properties and found remarkable effect on the tribological performance of hybrid aluminum matrix composites. V.Sharma et al. [7], have noticed a remarkable improvement in the mechanical and wear properties of aluminum metal matrix composites when incorporated with reinforcements in the form of particulate, whisker, continuous or discontinuous fibers that developed components which are best economically suited for various industrial applications with affordable reduced prices. M. N. Rittner [8] were of opinion that interaction and reaction among the reinforcements develop an interfacial adhesion which plays a vital role on the performance of composite materials and mentioned that the nature, shape, size and volume fraction of the reinforcement particles dominate the behavior of hybrid aluminum metal matrix composites. S. Das, et al [9] were of opinion that, all commercially used metal matrix composites depend on continuous reinforcements like graphite, silicon carbide and aluminum oxide fibers. Authors [10, 11] have summarized in their exhaust literature review that, the mechanical properties of an aluminum alloys can be improved by incorporating reinforcement particles like silicon carbide and aluminum oxide and graphite particles which further enhanced the wear properties of composites. Latest technical studies emphasized on the effect of size, shape and diffusion of reinforcement particles in exploiting the complete potential of metal matrix composites under fatigue load during structural applications. Kouzeli M et al. [12] were of opinion that, the best-enhanced fracture properties of composites can be obtained when the reinforcement particles with fine size are distributed uniformly in the matrix. During their experimental study, Spowart JE, et al. [13] have noticed reduction in density and mechanical properties like hardness, tensile strength, and yield strength of Al 6061 metal matrix composite reinforced with a single ceramic particle; but, same matrix further, when incorporated with dual reinforcement particles like silicon carbide, aluminum oxide and fly ash exhibited excellent mechanical properties. Lewandowski JJ et al. [14],were of opinion that addition of silicon carbide into the aluminum metal matrix enhances various mechanical properties like hardness, impact toughness, tensile strength, ductility and tribological properties under the influence of their particle size, weight or volume fraction. During their review, they mentioned that, when the % of silicon carbide is increased, then properties like density, hardness, tensile strength of the composites increased; but parallel properties like ductility, impact toughness and coefficient of friction have decreased. Bhanu Prasad VV et al. [15] were of opinion that the strength of aluminum composites is proportional to its % volume and size of the reinforced particles. Authors [16, 17] were of opinion that the nature and properties of aluminum matrix composites are controlled by the type, size of the reinforcement and the nature of bonding among themselves. Moreover, the processing method adopted for fabricating aluminum matrix composites depends on the nature of the matrix alloy and type of reinforcements which further have impact on final properties of composites. Authors [18, 19] mentioned in their article that, the viability of adopting simple, cost effective and technically efficient processing method in fabricating metal matrix composites is being explored by several researchers of most developing countries. Numerous processing methods are used in fabricating metal matrix composites are of either liquid processing or solid sintering. Ch. Hima Gireesh et al. [20] have attempted to discuss the various techniques available in fabricating the composite materials and concluded that Stir casting technique is the most suitable technique because of its simplicity, flexibility and commercial viability.as shown in Fig. 1, shows the various fabricating methods used with their percentage usage by manufacturers.

But the main problem with stir casting process is wettability. Hence Rama Krishna Uyyuru et al. [21], have suggested to mix dehydrated Borax in ratio 2:1 under preheat condition to overcome the problem of wettability which is commonly observed during fabrication of Al-SiC composites. The processing technique adopted, the composition of the matrix used and the type of reinforcement are independent to each other and are intimately connected in terms of the different interactions occurring between reinforcements and the matrix alloy under molten state.

2 Properties of Composite Materials

Based on the morphology of the composites, its behavior and properties can be understood by important factors like intrinsic properties, structural arrangement and the interface among the reinforcements. The intrinsic properties of

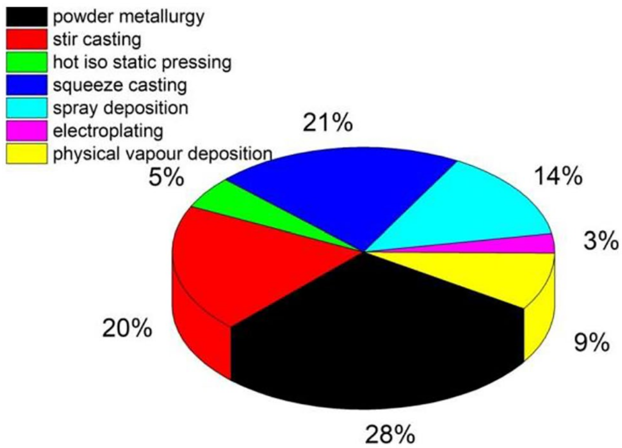

Fig. 1 Percentage usage of various fabrication methods during the past 15 years shown in PIE diagram. Courtesy: P. Venkateshwar Reddy et al. [5]

reinforcements determine the general properties of the composites and its interaction impart some unique properties. The behavior and performance of composites can be emphasized by the shape and size of individual reinforcements and its distribution with the matrix. Other predominant factors that govern the properties of composites include % volume fraction of reinforcements, microstructure, homogeneity and isotropy of the system.

2.1 Physical Properties

The characteristics of composites are truly affected by its density. The matrix and reinforcement of composites is expressed either in terms of weight fraction (wt.%), which is associated with the fabrication or volume fraction (v), which is used to determine its properties. By relating weight and volume fractions via density (ρ), the following expression can be derived:

$$\rho_{\mathrm{c}} = \rho_{\mathrm{r}} v_{\mathrm{r}} + \rho_{\mathrm{m}} v_{\mathrm{m}}$$

where m is matrix and r is particulate reinforcement.

The above expression can be further deduced into its general form, which is commonly known as law of mixture as:

$$X = X_m v_m + X_{\rho v P}$$

2.2 Mechanical Properties

2.2.1 Hardness

The composites whose particulate reinforcements having low aspect ratio should yield more hardness. S. Suresha, et al.[22], have demonstrated from their experimental studies that, the aluminum matrix incorporated with 10% Silicon carbide and 3% mica have shown maximum strength and hardness during which composite incorporated with mica exhibits good wear resistant with higher density as compared to composites reinforced with ceramics. Chawla N et al. [23], in their research, have noticed increased hardness for aluminum matrix reinforced with silicon carbide and Graphite particles up to 2.5 vol% and beyond which starts declining. They believed that, this increase in hardness might be due to the presence of hard ceramic particles and decrease in the hardness might be due to the presence of soft graphite particles and exhibited enhancement in the porosity of the composite. Kouzeli M et al. [24] have revealed in their studies that, hybrid aluminum composite reinforced with 8% rice husk ash and silicon carbide enriched its hardness value by 50% and concluded that this enrichment in hardness might be due to the presence of hard ceramic particles, which in turn shown improvement in the resistance of composites leading to dislocations. Suresha, S et al. [25], have studied the effect of particle size of aluminum oxide which is incorporated into aluminum metal matrix and noticed increased hardness when its particle size was finer rather than coarse particles, since finer size of the particles offer higher barriers per unit volume compared with matrix reinforced with larger sized particles for the same wt.% similarly Casati R et al. [26], have reported better thermal conductivity when aluminum matrix is incorporated with finer sized particles as compared to coarse sized particles.

The experimental results of hardness have been illustrated in Fig. 2 and it can be concluded that the hardness of composites were rational to be higher than that of its base material; as the reinforcement percent increases in the composite, the hardness also increases.

Aleneme KK et al. [28], have studied the friction and wear properties of an Al 6061 hybrid composite reinforced with 8% Silicon carbide and 1%, 3%, and 5% graphite particle and noticed enhancement in hardness and wear resistance property of composite when percentage of graphite particles was decreased. Aleneme KK et al. [29] have conducted experiments on aluminum metal matrix composite reinforced with silicon carbide varying from 5 to 30 wt.% and found increased impact strength and hardness when wt.% of silicon carbide increased.

2.2.2 Fracture Toughness

Fracture toughness of composite material is a property, which defines the ability of a material to resist for a crack to propagate and is one of the most important properties of any material considered during various design applications. Reinforcement particle debonding or interfacial cracking is one of the reasons for fracture in composite material. Since ceramic reinforcement particles are generally hard and brittle

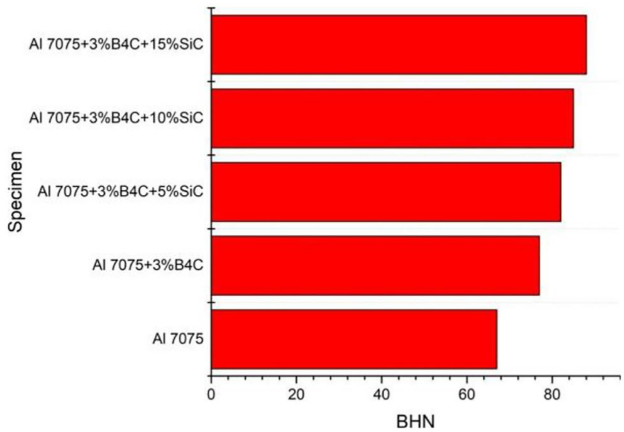

Fig. 2 Effect of reinforcement on hardness of hybrid composite. [27] Courtesy: Alaneme KK et al.

in nature, they have some tendency to resist rapid crack propagation and hence metallic composites reinforced with conventional hard ceramics exhibits poor fracture toughness. Aleneme KK et al. [30], have conducted extensive research on hybrid aluminum composites incorporated with bamboo leaf ash and silicon carbide and observed an increment in the fracture toughness when wt.% of both is increased. Again, Authors [31, 32] have done another research in order to determine the fracture toughness of hybrid aluminum matrix composites which denotes increase in fracture toughness value in load extension plot during fracture test. S. Suresha, et al [33], during their research, have noticed an increment in the fracture toughness of composites, when the wt.% of silicon carbide and fly ash was increased and found maximum toughness value for composite having 10 wt.% silicon carbide and 5 wt.% fly ash. Hence based on the exhaustive literature review and findings from different researchers, it is found that the fracture toughness of most of the engineering materials is inversely proportion to the yield strength, which might be due to the presence of soft particles in the composites.

2.2.3 Tensile Strength

Yalcin Y et al. [34], have reported that the strength of aluminum composites can be enhanced by incorporating hard and stiff reinforcement into the matrix which increases the resistance of composite to deform plastically during external loading, since it transfers the load which is applied on the metal matrix to the reinforcements by forming dislocations. Further, they also noticed increment in the density and strength depending on the particle size of the reinforcement. K.R. Ahmad et al. [35], have reported in their investigation that, aluminum metal matrix when reinforced with 10% silicon carbide and 10% fly ash, increased its tensile strength to 12%.Shyam Rangrej [36] were of opinion that addition of graphite reinforcement improves the tensile strength, elastic modulus and ductility of AMMCs but at the expensive of its hardness. Iacob G et al. [37], have found in their research that, the tensile strength of the aluminum composite when reinforced with 10 wt.% silicon carbide and varying the percentage of mica from 0 to 6 wt.%, found to be increased and beyond which it started to decrease. Velmurugan C. et al. [38], have reported in their studies that, the yield strength and ultimate tensile strength of aluminum matrix reinforced with 0–8 wt.% rice husk ash and 0–8 wt.% silicon carbide being increased when the wt.% fraction of the reinforcements increased gradually and noticed reduction in the % elongation due to the presence of hard ceramic particles in the composite, which further increased the brittleness and decreased the elongation in composites and concluded that the enhancement in the strength of composites is either due to increase in wt.% of reinforcements or due to the difference in the coefficient of thermal expansion.

Alaneme, K. K. et al. [39], have observed an improvement in the hardness and tensile strength of the composites with increased particle size and wt.% of silicon carbide particles and further significant improvement in ultimate tensile strength of composites due to strong bonding between the matrix and reinforcement which is shown in Fig. 3.

Singla M. et al. [40], during their experiments, have noticed an enrichment in hardness and tensile strength of Al 6061 hybrid composites having 7 wt.% Sic, 4 wt.% Gr when compared with plain aluminum matrix alloy and beyond which the strength of composite found to be reduced.

2.2.4 Tribological Properties

The gradual removal of material from the surface of solids in the form of debris is referred as wear and is also a continuous loss of material during sliding action between the two mating surfaces, leading to micro-cracks or localized plastic deformation, which may occur due to different physical, mechanical or chemical phenomenon. Wear resistance is an important property on which rest of the properties of metal matrix composites are depended [41]. Alaneme, K. K. et.al, have discussed the various kinds of wear like abrasive, adhesive, corrosive, oxidation, fretting, fatigue and erosion which removes the material from the surface. The experimental set up used for conducting wear test using pin on disc is as shown in Fig. 4.

Authors [42, 43] were of opinion that though it is very hard to completely nullify the effect of wear, but it can be minimized by proper lubrication, maintaining the surface smooth, reducing friction among the components and by proper aligning the components. Aluminum alloys have two basic wear mechanisms, i.e. mild wear due to oxidation and severe metallic wear. Many researchers have largely

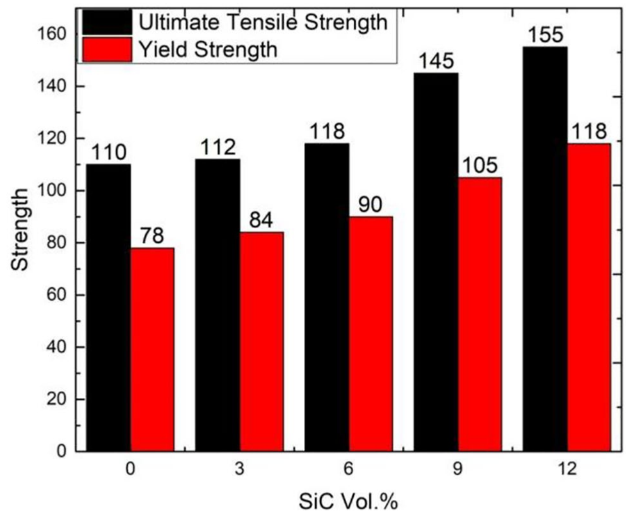

Fig. 3 Volume fraction influence of SiC on UTS and YS of hybrid composites. [39] Courtesy: Alaneme, K. K et al

contributed in exploring the tribological properties of hybrid aluminum matrix composites and few have been summarized here. Boopathi, M. M. et al. [44], have explored the significance of load, sliding velocity and composition of alloy on the wear resistance property in their experiment. The influence of load and sliding velocity on the friction is noticed but has no significance on the mechanism of wear.

Jitendra M Mistry. et al. [45], have noticed that adding hard reinforcements intrinsically improves the wear resistance of the matrix metal and further adding soft reinforcement like graphite can provide intrinsic lubricity. Thella Babu Rao [46], in their article, mentioned that most commonly used commercial reinforcements in various applications are Al_2O_3, B4C, BeO, graphite, Mo, NbC, SiC, TaC, TiB, TiB_2, TiC, W and WC. Among SiC is the most commercially used reinforcement, followed by Al_2O_3 and TiC.

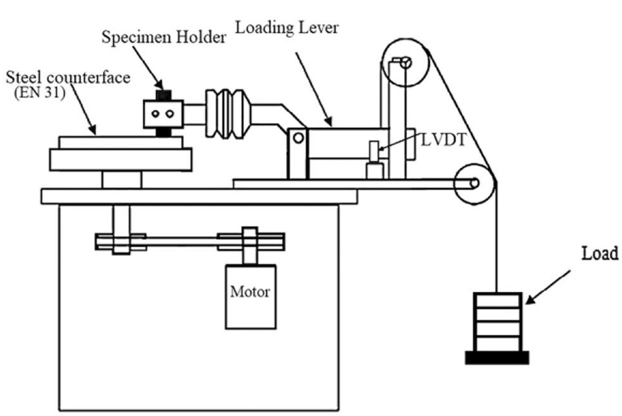

Fig. 4 Schematic diagram of wear test rig. Courtesy: Alenene KK et al. [40]

Michael Oluwatosin Bodunrina et al. [47], have summarized in their extensive review that an enhanced wear resistance of aluminum metal matrix is strongly dependent on the type of reinforcements like Al_2O_3 and SiC in the form of either whiskers or fibers and vol% Authors [19, 48–50] have suggested that factors like shape, size, vol% of reinforcements and the rake angle of particles influence the wear behavior and were of opinion that the wear mechanism of the composites depend not only on the nature of the particles, but also on the rubbing action of the particles against the surface in several situations. Kouzeli M et al. [24], during their demonstration on the effect of SiC/Gr and SiC/Al_2O_3 on Al 6061-T6 alloy, have noticed improvement in the hardness of hybrid aluminum composites reinforced with SiC/Al_2O_3 and less wear resistance as compared to composite containing only graphite which serves as a solid lubricant.

Authors Elango G et al. [51] conducted wear test on three specimens for different proportions and revealed that wear rate is decreased from 0.013 to 0.004 with the addition of reinforcement particles for 10 N of loading, and with 20 N loading and on increasing the wt.% of SiC fraction, wear rate is decreased from 0.014 to 0.0055 which illustrated in bar charts in Fig. 5.

T. Miyajima et al. [52], have emphasized on the significance of incorporating SiC as a hard ceramic particle into the aluminum matrix in protecting its surface against friction during the abrasive wear process, which is used in an environment where wear resistance is of main concern during application apart from weight reduction. They also found increased wear resistance with lesser coefficient of friction for aluminum composite than matrix alloy. S.K. Khatkar et al. [53], have highlighted that self-lubricated lightweight components possessing high-strength and wear-resistant property, used for specific applications and improvement in fuel efficiency can be developed by incorporating graphite

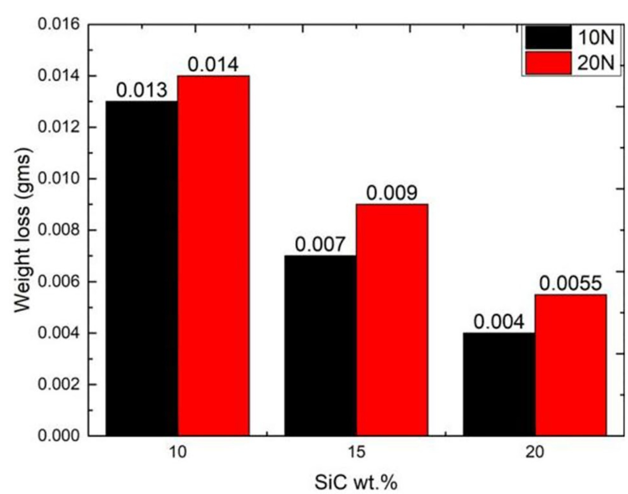

Fig. 5 Results of wear test. [51] Courtesy: Elango G. et al.

particles into aluminum matrix. Since Graphite can develop a tribo layer on the surface under friction possess stable frictional coefficient and further upon rupture of that layer, new particles of graphite become active to reduce the frictional coefficient in making its application where improved tribological properties is essential. A M Rajesh et al. [54], have carried out an exhaust literature review on the effect of incorporation of both single reinforcement and multiple reinforcements with aluminum metal matrix in developing products for various tribological applications. They revealed that the incorporation of multiple reinforcements into aluminum matrix enriches the tribological properties and among them, Silicon carbide is most commonly used reinforcement owing to its good mechanical properties, durability, availability, and low cost. The authors further perceived that the effect of Graphite when added with silicon carbide as secondary particle has improved the tribological properties and increased the co efficient of friction and wear resistance. Y. Wang et al. [55], have framed out the recent advancements in the area of self-lubricated hybrid metal matrix composites using graphite as a secondary reinforcement. They emphasized on the mechanical and tribological behavior of Aluminum and magnesium based self-lubricated hybrid metal matrix composites and discussed on the effects of different hybrid reinforcements especially graphite on the strengthening mechanism of aluminum composites. With further extended developments, few attempts have been made by authors [56–58] to develop hybrid aluminum matrix composites reinforced with combinations of silicon carbide, aluminum oxide and graphite. P.K. Rohatgi et al. [59], have studied the dry sliding wear behavior of Aluminum composites reinforced with Graphite and silicon carbide particulates up to 10 wt.% at room temperature which exhibited better wear resistance for aluminum composites. During their investigation made on Al 7075 composites, Mares M [60], have observed a decrement in the wear rate of composites when single reinforcement particle is incorporated even with higher wt.% fraction and hence, they recommended for combining two different reinforcements rather than single reinforcement to enhance the tribological properties of the aluminum composites. They further noticed the highest wear resistance when 10 wt.% silicon carbide and 10 wt.% aluminum oxide is added after ageing, beyond which decrement in wear rate. In majority of the works, the hybrid composites have been developed by single step stir casting routes; but two-step stir casting method shown an advantage over single step stir casting route, in terms of promoting wettability, reducing porosity and homogeneous distribution of reinforced particles, which offer better tribological properties as disclosed by authors [61, 62]. In their studies, Radhika N et al. [63], have noticed a wear loss of 2 microns in aluminum matrix which can be reduced to 0.5 microns when reinforced with 30% of Al_2O_3 particles and have further noticed a wear loss of 7 microns when reinforced with 10 wt.% SiC. Adalet Zeren [64], have noticed a wear loss of 18 mm^3/m for A356 matrix alloy and 12 mm^3/m when reinforced with 5 wt.% SiC particles. Pranav Dev Srinivas et al. [65], have investigated the tribological behavior of aluminum composites and noticed an increment in the wear rate and decrement in the coefficient of friction when the normal load increased. They further studied the tribological behavior of aluminum composite brake pad tribo-couple under dry sliding conditions to understand the effect % volume fraction of reinforcement and its particle size distribution on the wear characteristics. Authors [66–68] have noticed an improvement in the wear properties of metal matrix composites when graphite particles alone were added up to 1 wt.% and beyond which shown reduction in mechanical properties. Hence, to compensate this reduction in mechanical properties, authors Kumar et al. [69], have recommended incorporating aluminium oxide as a secondary reinforcement particle which is being hard and brittle in nature and easily gets mix up in soft ductile aluminum metal matrix and to further enhance the stiffness and strength of the metal matrix composites. Similarly Authors Mahdavi S et al. [70], have noticed a reduction in the mechanical properties when only graphite alone was incorporated into the aluminum metal matrix composite and hence have suggested to add aluminium oxide as a secondary reinforcement of particulate size 15–20 microns to improve the properties and further inferred that incorporating graphite as a primary reinforcement increases the wear resistance of composites by forming a protective layer between pin and counter face of the disc during wear. Further authors Ravindran P et al [71], again studied the dry sliding wear behavior of aluminum metal matrix reinforced with 3, 6 and 9 wt. % of aluminium oxide along with 3 wt.% of graphite and noticed a remarkable improvement in both mechanical properties and wear resistance of composites since graphite in turn formed a protective layer between the sliding parts to minimize wear. Devaraju A et al. [72], have conducted experiments to study the wear behavior of aluminum metal matrix composites and noticed an improvement in the wear resistance and reduction in coefficient of friction of matrix alloy when incorporated with graphite particles. S. Das [73] have studied the effect of graphite particles on the properties of Al SiC/Gr composites and concluded that the addition of graphite up to 6% and 5% silicon carbide into aluminum metal matrix has improved the wear resistance and lubrication properties of the composites. Hutchings IM [74], have tried to explore the mechanical and tribological properties of aluminum metal matrix composites with different reinforcements and made an exhaust review to analyze the effect of each reinforcement—its percentage, type and size on the properties of composites. They concluded that the wear property of composites is affected by various parameters like applied load, sliding velocity, sliding distance, dry/wet conditions. Kulik T et.al. [75], have investigated the behavior of aluminum metal matrix composites reinforced with silicon carbide and graphite (2.5–10 wt. %) particulates under friction and noticed an improvement in the hardness of hybrid aluminum metal matrix composite, beyond which shown reduction in hardness due to the presence of hard ceramic particles and soft graphite particles, respectively. Jain-main T et.al. [76], have observed a wear loss of 18 mm^3/m for A356 Aluminum alloy which was further reduced to 12 mm^3/m when reinforced with 5% silicon carbide particles during wear tests under dry sliding conditions at 5 N load, 0.4 m/s speed and for 1000 mm sliding distance. N. Axen et al. [77], have explored the wear behavior of Al6061 by incorporating silicon carbide particles and noticed a wear loss of 3 mg for aluminum matrix alloy, further which is reduced to 1.2 mg when matrix was reinforced with 30% silicon carbide particles during wear test under 150 N load and at 2000 rpm. A. G. Wang et al. [78],have conducted an experiment to study the wear behavior of Al-Cu/SiC composite by adding 13 wt.% silicon carbide during wear test under dry conditions at a speed of 1 m/s, sliding distance of 1000 mm, at varied load and noticed an increased wear loss from 3 to 5 mg when load is varied from 30 to 70 N. Aleksandar Venc Filip Vučetić et al. [79], have observed a better wear resistance for composites when compared to matrix alloys during their studies made on Al6061/SiC and Al7075/Al_2O_3 composites and further noticed better wear resistance when aluminum alloy is added with aluminium oxide particles than that of addition ofsilicon carbide particles. Guo MLT et al. [80], have studied the effect of hybrid particles like silicon carbide (0–40 vol%, 19 µm) and graphite (9 vol%) into Al6061 alloy fabricated using both powder metallurgy and stir casting routes and concluded that the hybrid aluminum matrix composites have exhibited improvement both in wear resistance and hardness in comparison with non-reinforced matrix alloy and further noticed an increment in both volumetric loss and wear rate by 76% on increasing silicon carbide from 20–40 vol% and reduction in the coefficient of friction by adding silicon carbide particles up to 30 vol%. Korkut MH [81] have studied the microstructure and mechanical properties of hybrid aluminum nano composite reinforced with 5% SiC and 5–10% graphite and noticed an enhancement in mechanical properties like hardness, strength, wear resistance and reduced coefficient of friction of composite. Biswas SK et al. [82], have reported that the wear resistance of composites being reduced due to addition of 20 vol% fraction of aluminium oxide having coarse size of 20 microns in its fragmented form. On the other hand, they briefed that the composites have shown improvement in the wear resistance when particle size decreases, during which noticed a transition in the wear behavior. Gibson PR et al. [83], were of opinion that the wear rate of aluminum composites reduced up to 48% when incorporated with 10 wt.% silicon carbide as compared to the A356 thixo alloy and also noticed 77% wear rate for hybrid composite containing 10 wt.% silicon carbide and 3 wt.% graphite particles when compared with composite reinforced only with silicon carbide particles and hence concluded that incorporation of hard ceramic particle as a primary reinforcement improves the wear resistance of composite. Yang JB et al. [84], during their work, have emphasized on the hardness of aluminum metal matrix composites and concluded that hardness depends on the type of matrix material and the nature of reinforcement as well as its amount, size, shape and its distribution inside the metal matrix. Again in the same year, Vencl A et.al [85], have noticed a substantial reduction in the wear rate of aluminum matrix composite incorporated with graphite particles in comparison with only aluminum matrix alloys and also noticed that, when the vol% of graphite exceeds above 20%, then coefficient of friction approaches equal to that of pure graphite beyond which becomes independent of the matrix alloy which is clearly indication of an effective intervention of thin graphite film between the matrix and the counter face. Basavarajappa S et al. [86], have comprehended on the beneficial effects of addition of graphite as a single hard reinforcement on the coefficient of friction of aluminum metal matrix composites and hybrid composites containing some hard reinforcement particles along with the graphite particles and have noticed only slight change in the coefficient of friction with increased wear rate of the composite containing graphite up to 5 wt.%, beyond which showed a downfall to lower value. Leng J et al. [87], were of opinion that, wear rate of aluminum composite is significantly affected by the strength of the matrix, wt.% of reinforcement particles and its distribution and they concluded that if the particles have sustained good bonding with the aluminum matrix during friction, the matrix gets worn out under the influence of the particles and the wear rate can be controlled because of the decoherence of reinforcement particles. During their experimental studies, M. Suwa et al. [88], have reported that dry sliding wear rate of Al-Si alloy LM13 composite containing 2.7 and 5.7 wt.% graphite particles of size 50–200 µm is more than that of the aluminium matrix alloy. Similar findings were reported by Madeva Nagaral et al. [89], for Al-Si alloy-based composites having 8 wt.% graphite particles of size 150 microns and observed reduction in tensile strength and ductility. Hazim Faleh et al. [90], have discovered during their studies that, dry sliding wear of Al-Si alloy A356 composites containing graphite particles(2–8 wt.%, 15 microns) was much more than that of the aluminium matrix alloy and noticed lower wear rate for composites containing 4 and 6 wt.% graphite particles than that of the base matrix alloy. Similar outcome was noticed in the previously published research article by A.K. Jha et al. [91], on the same hybrid composite containing silicon carbide particles(10 wt.%, 39 μm)and graphite particles (1 wt.%, 35 μm),with different contact geometry. F. M. Hosking et al. [92], have tested Al–Cu alloy composite containing silicon carbide (10 wt.%, 25 μm) and graphite (3 wt.%,45 μm) under dry sliding conditions at normal loads of 0.1–0.8 MPa, sliding speed of 1.5–6.1 m/s and found increased wear resistance by wiping off graphite particles. S. Bajwa et al. [93], have demonstrated that graphite particles (3 wt. %, 1, 6 and 20 μm) along with silicon carbide particles when added into the aluminum alloy, shown an increased wear rate when the size of graphite particles was increased gradually. Similar beneficial effect was noticed by Y.Q. Wang et al. [94], in bronze composites incorporated with larger graphite particles when tested under dry sliding under normal load of 4.9 MPa at sliding speed of 0.2 m/s. During their studies, they noticed decreased wear rate when the size of graphite particles varied from 100 to 2000 μm which made plastic flow of metal matrix during sliding, by covering smaller embedded graphite particles before they get squeezed out and adhere to the sliding surface. Author Rohatgi et al. [95] have investigated the wear property of Al 2219 alloy incorporated with silicon carbide and graphite particles (2–4 wt.%) and found better wear resistance for composite than that of non-reinforced matrix alloy and decreased wear rate for the corresponding increment in wt.% of silicon carbide and graphite particles. Same authors were of opinion that, to develop efficient aluminum metal matrix composites, need to incorporate with graphite particles which reduces the metal-to-metal contact during sliding wear, first the graphite particles are made to shear into layers and then making those layers to adhere to the metal surface with its major axis parallel to the sliding direction and have noticed increment in the wear rate up to 14% when vol% of graphite increased linearly. Again same authors [95] have comprehended that composites having aluminum oxide (2–30 wt.%) and silicon carbide (size varied from 1 to 142 microns) have exhibited excellent wear resistance of 20% whereas those with small to moderate quantity of non-metallic particles shown reduction in tensile properties when compared to aluminium matrix alloy. Authors [95] Rohatgi, P. K et al. have concluded that the aluminum composites incorporated with zircon and silicon carbide particles in the ratio of 1:3 exhibited better wear resistance compared to other combinations and noticed improvement in wear resistance when incorporated with appropriate proportion of dual reinforcement particles as compared to incorporating single reinforcement particle and further noticed an enrichment in the wear resistance of the composites under the service temperature and high load. Authors have studied the sliding wear behavior of aluminum metal matrix hybrid composites reinforced with aluminum oxide and silicon carbide under both dry and lubricated conditions and noticed an enhancement in tribological properties of hybrid composites.

3 Conclusions and Future Scope

This review article outlines the contributions made by various researchers on the mechanical and tribological properties of hybrid aluminum metal matrix composites incorporated with both hard metallic/ceramic particulates like silicon carbide, aluminum oxide, titanium carbide, boron carbide as primary reinforcement and a secondary reinforcement like graphite, which is found its wide applications as self-lubricating particles. In the present comprehensive review, substantial investigational outcomes from the various published articles on mechanical and tribological properties of aluminum based self-lubricating hybrid metal matrix composites have been considered. The conclusions inferred experimentally from the previous researchers are summarized as follows:

(i) The graphite used as a dry solid lubricant exhibited its significance as secondary reinforcement in improving mechanical and tribological properties of self-lubricating aluminium hybrid metal matrix composites.
(ii) The incorporation of graphite particles within the specified proportional quantity enhances the wear resistance of hybrid composites at the expenditure of strength of its matrix material, but, which can be overcome by mixing hard ceramics like silicon carbide, aluminum oxide, boron carbide into aluminum matrix material.
(iii) The hybrid metal matrix composites reinforced with graphite can reduce wear loss and frictional coefficient of composites at higher speed.
(iv) The literature review revealed that stir casting method has been reported as the most commercial and economical fabricating technique followed by powder metallurgy for self-lubricated aluminum hybrid composites.
(v) Hence it is revealed from the detailed extensive literature that, the combination of silicon carbide and graphite is the most commercial used hybrid reinforcement in fabricating aluminium based self-lubricated hybrid metal matrix composites.
(vi) The comprehensive literature in this review discovered that most of the research is done in the area of self-lubricating hybrid composites by incorporating graphite as a solid lubricant into aluminum matrix alloys; however in future, researchers may focus on the use of different other metallic and ceramic particulates like titanium, zirconium, magnesium, nickel, silver, copper, zinc, bronze, alumina, silicon nitride. It is also suggested to explore in the area of bio reinforcements.

(vii) The extensive literature discussed in this review has discovered that majority of researchers attentive on very few mechanical properties like hardness and tensile strength of self-lubricating hybrid composites; whereas other properties like toughness, impact strength, fatigue strength, compressive strength and creep have investigated less.

Acknowledgements Thanks to the co-authors for the cooperation during the review of articles. Thanks to all publishers who permit me to take some relevant diagrams, graphs, tables, etc. from the published articles. Special thanks to editor in chief and reviewers for the support given during the process of publication.

Funding It is declared that there is no funding is received from anywhere to publish the article.

Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

References

1. Kelly A (1985) Composites in context. Compos Sci Technol 23(3):171–219
2. Ahlatci H, Kocer T, Candan E, Cimenoglu H (2006) Wear behavior of Al/(Al_2O_3/SiCp) hybrid composites". Tribol Int 39:213–220
3. Ozdemir N, Yakuphanoglu F (2006) The effects of particle size and volume fraction of Al_2O_3 on electronic thermal conductivity of α-Al_2O_3 particulate reinforced aluminum composites (Al/Al2O3-MMC). Int J Adv Manuf Technol 29:226–229
4. Veeresh Kumar GB, Rao CSP, Selvaraj N (2011) Mechanical and tribological behavior of particulate reinforced aluminum metal matrix composites—a review. J Miner Mater Charact Eng 10(1):59–91
5. Venkateshwar Reddy P, Suresh Kumar G, Mohana Krishnudu D, Raghavendra Rao H (2020) Mechanical and wear performances of aluminium-based metal matrix composites: a review. Journal of Bio- and Tribo-Corros 6:83. https://doi.org/10.1007/s40735-020-00379-
6. Kumar S, Panwar RS, Pandey OP (2013) Effect of dual reinforced ceramic particles on high temperature tribological properties of aluminum composites. Ceram Int 39:6333–6342
7. Sharma V, Kumar S, Panwar RS, Pandey OP (2012) Microstructural and wear behavior of dual reinforced particle (DRP) aluminum alloy composite. J Mater Sci 47:6633–6646
8. Rittner MN (2000) Metal matrix composites in 21st century: markets and opportunities, report GR-108R. Business opportunity (BCC), Inc, Norwalk, CT
9. Das S, Das K, Das S (2009) Abrasive wear behavior of Al–4.5 wt.% Cu/(zircon s and þ silicon carbide) hybrid composite. J Compos Mater 43:2665–2672
10. Kaur K, Pandey OP (2010) Dry sliding wear behavior of zircon sand reinforced Al–Si alloy. Tribol Lett 38:377–387
11. Song SG, Shi N, Gray GT III, Roberts JA (1996) Reinforcement shape effects on the fracture behavior and ductility of particle-reinforced 6061-Al matrix composites. Metall Mater Trans A 27:3739–3746
12. Kouzeli M, Weber L, San Marchi C, Mortensen A (2001) Influence of damage on the tensile behaviour of pure aluminum reinforced with ≥ 40% vol. alumina particles. Acta Mater 49:3699–3709
13. Spowart JE, Miracle DB (2003) The influence of reinforcement morphology on the tensile response of 6061/SiC/25p discontinuously-reinforced aluminum. Mater Sci Eng A 357:111–123
14. Lewandowski JJ, Liu C (1989) Effects of matrix microstructure and particle distribution on fracture of an aluminum metal matrix composite. Mater Sci Eng A 107:241–255
15. Bhanu Prasad VV, Bhat BVR, Mahajan YR, Ramakrishnan P (2002) Structure-property correlation in discontinuously-reinforced aluminum matrix composites as a function of relative particle size ratio. Mater Sci Eng A 337:179–186
16. Kouzeli M, Dunand DC (2003) Effect of reinforcement connectivity on the elasto-plastic behavior of aluminum composites containing sub-micron alumina particles. Acta Mater 51:6105–6121
17. Tewari A, Spowart JE, Arun G, Rajiv M (2006) The effects of friction stir processing (FSP) on the spatial heterogeneity of discontinuously reinforced aluminum (DRA) microstructures. Frictions stir welding and processing II. Mater Sci Eng A. https://doi.org/10.1016/j.msea.2006.04.106
18. Soboyejo W (2002) Mechanical properties of engineered materials, 1st edn. CRC press. https://doi.org/10.1201/9780203910399
19. Miracle DB (2005) Metal matrix composites-from science to technological significance. Compos Sci Technol 65(15–16):2526–2540
20. Hima Gireesh Ch, Durga Prasad KG, Ramji K (2018) Experimental Investigation on mechanical properties of an Al6061 hybrid metal matrix composite. J Compos Sci 2:49. https://doi.org/10.3390/jcs2030049
21. Uyyuru RK, MirleBrusethaug SS (2005) Effect of reinforcement volume fraction and size distribution on the tribological behavior of Al-composite/brake pad tribo-couple. Wear 260(11–12):1248–1255. https://doi.org/10.1016/j.wear.08.01
22. Suresha S, Sridhara BK (2010) Effect of addition of graphite particulates on the wear behavior in aluminum–silicon carbide–graphite composites. Mater Des 31:1804–1812
23. Chawla N, Andres C, Jones JW, Allison JE (1998) "Effect of SiC volume fraction and particle size on the fatigue resistance of a 2080 Al/SiCp composite. Metall Mater Trans 29:2843–2854
24. Kouzeli M, Mortensen A (2002) Size dependent strengthening in particle reinforced aluminum. Acta Mater 50:39–51
25. Suresha S, Sridhara BK (2012) Friction characteristics of aluminum silicon carbide graphite hybrid composites. Mater Des 34:576–583. https://doi.org/10.1016/j.matdes.2011.05.010
26. Casati R, Vedani M (2014) Metal matrix composites reinforced by nano-particles—a review. Metals 4(1):65–83
27. Uvaraja VC, Natarajan N (2012) Optimization of friction and wear behaviour in hybrid metal matrix composites using Taguchi technique. J Miner Mater Charact Eng 11(08):757
28. Alaneme KK, Bodunrin MO (2013) Mechanical behaviour of alumina reinforced AA 6063 metal matrix composites developed by two step—stir casting process. Acta Tech Corvininesis—Bull Eng 6(3):3–18
29. Alaneme KK, Aluko AO (2012) Production and age-hardening behavior of borax premixed SiC reinforced Al–Mg–Si alloy composites developed by double stir-casting technique. West Indian J Eng 34(1–2):80–85
30. Alaneme KK (2011) Corrosion behavior of heat-treated Al-6063/SiCp composites immersed in 5 wt. % NaCl solution. Leonardo J Sci 18(18):55–64
31. Behera MP et al (2019) Conventional and additive manufacturing with metal matrix composites: a perspective. Procedia Manuf 30:159–166. https://doi.org/10.1016/j.promfg.02.023

32. Rajmohan T, Palani Kumar K, Ranganathan S (2013) Evaluation of mechanical and wear properties of hybrid aluminum matrix composites. Trans Nonferrous Metals Soc China 23(9):2509–2517
33. Suresha S, Sridhara BK (2010) Effect of addition of graphite particulates on the wear behaviour in aluminum–silicon carbide–graphite composites. Mater Des 31:1804–1812
34. Yalcin Y, Akbulut H (2006) Dry wear properties of A356-SiC particle reinforced MMCs produced by two melting routes. Mater Des 27(10):872–881
35. Ahmad KR, Jamaludin SB, Hussain LB, Ahmad ZA (2005) The influence of alumina particle size on sintered density and hardness of discontinuous reinforced aluminum metal matrix composite". J Teknologi 42:49–57
36. Rangrej S, Pandya S, Menghani J (2020) Effects of reinforcement additions on properties of aluminium matrix composites—a review. Mater Today. https://doi.org/10.1016/j.matpr.2020.10.604
37. Iacob G, Ghica VG, Buzatu M et al (2015) Studies on wear rate and hardness of the Al/Al2O3/Gr hybrid composites produced via powder metallurgy. Compos Part B Eng 69:603–611
38. Velmurugan C, Subramanian R, ThirugnanamAnandavel SAB (2012) Investigation of friction and wear behavior of hybrid aluminum composites. Ind Lubr Tribol 64:152–163
39. Alaneme KK, Aluko AO (2012) Fracture toughness (K1C) and tensile properties of as-cast and age-hardened aluminum (6063)–silicon carbide particulate composites. Sci Iran 19(4):992–996
40. Singla M, Dwivedi DD, Singh L, Chawla V (2009) Development of aluminum-based silicon carbide particulate metal matrix composite. J Min Mater Charact Eng 8(6):455–467
41. Alaneme KK, Bodunrin MO, Awe AA (2016) Microstructure, mechanical and fracture properties of groundnut shell ash and silicon carbide dispersion strengthened aluminum matrix composites. J King Saud Univ-Eng Scie 30(1):96–103
42. Alaneme KK (2012) Influence of thermo-mechanical treatment on the tensile behavior and CNT evaluated fracture toughness of borax premixed SiCp reinforced aluminum (6063) composites. Int J Mech Mater Eng 7(1):96–100
43. Ravesh SK, Garg TK (2012) Preparation & analysis for some mechanical property of aluminum-based metal matrix composite reinforced with SiC & fly ash. Int J Eng Res Appl 2(6):727–731
44. Boopathi MM, Arulshri KP, Iyandurai N (2013) (2013) Evaluation of mechanical properties of aluminium alloy 2024 reinforced with silicon carbide and fly ash hybrid metal matrix composites. Am J Appl Sci 10(3):219–229
45. Mistry JM, Gohil PP (2016) An overview of diversified reinforcement on aluminum metal matrix composites: tribological aspects. Proc Inst Mech Eng J. https://doi.org/10.1177/1350650116658572
46. Rao TB (2017) An experimental investigation on mechanical and wear properties of Al7075/SiCp composites: effect of SiC content and particle size". J Tribol. https://doi.org/10.1115/14037845
47. Bodunrina MO, Alaneme K, Chown LH (2015) Aluminum matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics". J Mater Res Technol 4(4):434–445
48. Hosking FM, Portillo FF, Wunderlin R, Mehrabian R (1982) Composites of aluminum alloys: fabrication and wear behavior. J Mater Sci 17(2):477–498
49. Wilson S, Alpas AT (1997) Wear mechanism maps for metal matrix composites. Wear 212(1):41–49
50. Deuis RL, Subramanian C, Yellup JM (1997) Dry sliding wear of aluminum composites—a review. Compos Sci Technol 57(4):415–435
51. Elango G, Raghunath BK (2013) Tribological behavior of hybrid (LM25Al+ SiC+ TiO2) metal matrix composites. Procedia Eng 64:671–680
52. Miyajima T, Iwai Y (2003) Effects of reinforcements on sliding wear behavior of aluminum matrix composites. Wear 255:606–616
53. Khatkar SK, Suri NM, Kant S, Pankaj (2018) A Review on mechanical and tribological properties of graphite reinforced self-lubricating hybrid metal matrix composites. Rev Adv Mater Sci 56(1):1–20
54. Rajesh AM, Kaleemulla M, Doddamani S (2019) Effect of addition of Sic and Al_2O_3 on wear behavior of hybrid aluminum metal matrix composites. Acta Technica Corviniensis – Bulletin of Engineering. 12(1): 43–52
55. Wang Y, Wang HY, Xiu K, Hong-Ying Wang QC, Jiang, (2006) Fabrication of TiB2 particulate reinforced magnesium matrix composites by two step processing method. Mater Lett 60:1533–1537
56. Zhou W, Xu ZM (1997) Casting of SiC reinforced metal matrix composites. J Mater Process Technol 63:358–363
57. Moustafa SF, Soliman FA (1997) Wear resistance of δ-type alumina fiber reinforced Al-4 percentage Cu matrix composite. Tribol Lett 3(4):311–315
58. Rohatgi PK, Liu Y, Ray S (1992) Friction and wear of metal-matrix composites. In: Blau PJ (ed) ASM handbook. Friction, lubrication, and wear technology, vol 18. ASM International, Metals Park, pp 801–811
59. Rohatgi PK, Ray S, Liu Y (1992) Tribological properties of metal matrix-graphite particle composites. Int Mater Rev 37(1):129–152. https://doi.org/10.1179/imr.1992.37.1.129
60. Mares M (2001) Some issues on tailoring possibilities for mechanical properties of particulate reinforced metal matrix composites. J Optoelectron Adv Mater 3(1):119–124
61. Hassan AM, Hayajneh TM (2002) The effect of the increase in graphitic volumetric percentage on the strength and hardness of Al-4 weight percentage Mg-graphite composites. Mater Eng Perform 11:250–255
62. Radhika N, Subramanian R, Venkat Prasat S (2011) Tribological behavior of aluminum/alumina/graphite hybrid metal matrix composite using Taguchi's techniques. J Min Mater Charact Eng 10(5):427-443 69
63. Radhika N, Subramanian R, Venkat Prasat S, Anandavel B (2012) Dry sliding wear behavior of aluminium/alumina/graphite hybrid metal matrix composites. J Ind Lubr Tribol 64(6):359–366
64. Zeren A (2015) Effect of the graphite content on the tribological properties of hybrid Al/SiC/Gr composites processed by powder metallurgy. Ind Lubr Tribol 67(3):262–268
65. Srinivas PD, Charoo MS (2018) Aluminum metal matrix composites a review of reinforcement; mechanical and tribological behavior. Int J Eng Technol 7(24):117–122. https://doi.org/10.1419/ijet.v7i2.4.13020
66. Gurler R (1999) Sliding wear behavior of a silicon carbide particle-reinforced aluminum–magnesium alloy. J Mater Sci Lett 18(7):553–554
67. Reihani SS (2006) Processing of squeeze cast Al6061–30% vol percentage SiC composites and their characterization. Mater Des 27(3):216–222
68. Lim SC, Gupta M, Ren L, Kwok JKM (1999) The tribological properties of Al–Cu/Sic metal–matrix composites fabricated using the rheocasting technique. J Mater Process Technol 89:591–596
69. Kumar GV, Rao CSP, Selvaraj N, Bhagya Shekar MS (2010) Studies on Al6061-SiC and Al7075-Al_2O_3 metal matrix composites. J Min Mater Charact Eng 9(1):43–55
70. Mahdavi S, Akhlaghi F (2011) Effect of the SiC particle size on the dry sliding wear behavior of SiC and SiC–Gr-reinforced Al6061 composites. J Mater Sci 46(24):7883. https://doi.org/10.1007/s10853-011-5776-1

71. Ravindran P, Manisekar K, Narayanasamy P, Selvakumar N, Narayanasamy R (2012) Application of factorial techniques to study the wear of Al hybrid composites with graphite addition. Mater Des 39:42–54
72. Devaraju A, Kumar A, Kotiveerachari B (2013) Influence of addition of Grp/Al_2O_3p with Sic on wear properties of aluminum alloy 6061–T6 hybrid composites via friction stir processing. Trans Nonferrous Metals Soc China 23(5):1275–1280
73. Das S (2004) Development of aluminium alloy composites for engineering applications. Trans Indian Inst Metals 57(4):325–334
74. Hutchings IM (1987) Wear by particulates. Chem Eng Sci 42:869–878
75. Kulik T, Kosel TH (1989) Effects of second-phase particle size and edge micro fracture on abrasion of model alloy. In: Ludema KC (ed) Wear of Materials. ASME, Colorado, pp 71–78
76. Xian G, Zhang Z (1986) Sliding wear of polyetheramide matrix composites influence of short fiber composites. Tribo Int 19(3): 145–156
77. Zum Gahr KH (1987) Microstructure and wear of materials. Elsevier, Newyork
78. Wang AG, Hutchings IM (1989) Wear of alumina fibre–aluminium metal matrix composites by two-body abrasion. Mater Sci Technol 5:71–76. https://doi.org/10.1179/mst.1989.5.1.71
79. Vučetić AVF, Bobić B, Pitel J, Bobić I (2019) Tribological characterization in dry sliding conditions of compo casted hybrid A356/Sic/Grp composites with graphite macro particles. Int J Adv Manuf Technol 100:2135–2146
80. Guo MLT, Tsao C-YA (2000) Tribological behavior of self-lubricating aluminum/Sic/graphite hybrid composites synthesized by the semi-solid powder-densification method. Compos Sci Technol 60(1):65–74
81. Korkut MH (2004) Effect of particulate reinforcement on wear behavior of aluminum matrix composites. Mater Sci Technol 20(1):73–81
82. Biswas SK, Bai BNP (1981) Dry wear of Al-graphite particle composites. Wear 68(3):347–358
83. Gibson PR, Clegg AJ, Das AA (1984) Wear of cast Al-Si alloys containing graphite. Wear 95(2):193–198
84. Yang JB, Lin CB, Wang TC, Chu HY (2004) The tribological characteristics of A356.2Al alloy/Gr (p) composites. Wear 257(9–10):941–952
85. Vencl A, Bobic I, Stojanovic B (2014) Tribological properties of A356 Al-Si alloy composites under dry sliding conditions. Ind Lubr Tribol 66(1):66–74
86. Basavarajappa S, Chandramohan G (2005) Dry sliding wear behavior of hybrid metal matrix composites. Mater Sci 11(3):253–257
87. Leng J, Longtao J, Wu G, Tian S, Chen G (2009) Effect of graphite particle reinforcement on dry sliding wear of Sic/Gr/Al composites. Rare Metal Mater Eng 38(11):1894–1898
88. Asthana R (1998) Processing effects on the engineering properties of cast metal matrix composites. Adv Perform Mater 5:213–255. https://doi.org/10.1023/A:1008634531980
89. Madeva Nagaral BK, Shivananda J, Auradi V, Kori SA (2016) Effect of SiC and graphite particulates addition on wear behavior of Al 2219 alloy hybrid composites. Mater Sci Eng 149:012108. https://doi.org/10.1088/1757-899X/149/1/012108
90. Faleh H, Noori M, Florin Ș (2015) Properties and applications of aluminum-graphite composites. Adv Mater Res 1128:134–143
91. Jha AK, Prasad SV, Upadhyaya GS (1989) Sintered 6061 aluminum alloy-solid lubricant particle composites : sliding wear and mechanisms of lubrication. Wear 133:163–172
92. Hosking FM, Folgar PortilloWunderlin FR, Mehrabian TR (1982) Composites of aluminum alloys: fabrication and wear behavior. J Mater Sci 17:477–498
93. Bajwa S, Rainforth WM, Lee WE (2005) Sliding wear behavior of SiC/Al_2O_3 nano composites. Wear 259:553–561
94. Wang YQ, Afsar AM, Jang JH, Han KS, Song JI (2010) Room temperature dry and lubricant wear behaviors of Al_2O_3/SiCp/Al hybrid metal matrix composites. Wear 268:863–870
95. Rohatgi PK, Ray S, Liu Y (1992) Tribological properties of metal matrix-graphite particle composites. International materials. Reviews 37(1):129–152. https://doi.org/10.1179/imr.1992.37.1.129