Generation of mechanically mixed layer during wear in hybrid aluminum MMC under as-cast and age hardened conditions

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Abstract

In the present investigations, dry sliding wear test is conducted using a pin on disc tribometer at room temperature for both the as-cast and age hardening conditions. Al7075 has chosen as the matrix material. The reinforcement used are particles of silicon carbide and alumina with 5 wt%, 10 wt%, and 15 wt%. Hybrid aluminum metal matrix composites are produced utilizing stir casting route for enhancing the wear behavior. In the aluminum matrix, micro-structural characterization reveals the homogeneous mixing of reinforcements. From the investigation, it is observed that composites containing 10% by weight of silicon carbide and aluminum oxide reinforcements with ageing exhibited superior tribological properties. From the micro-structural study, it has been observed that the generation of the mechanically mixed layer in the hybrid aluminum metal matrix composites will lead to a reduction in wear rate.

Keywords Al7075/SiC–Al₂O₃ · HAMMC · Wear rate · MML · Dry sliding wear

1 Introduction

Composite materials are the combination of a matrix and a reinforcement material. To gain the advantages of mixing of the two different reinforcements in a single matrix, hybrid composites have been developed. In recent times hybrid composites have been established as highly efficient, high performance structural materials and their use is increasing rapidly. This is due to their improved properties which are gained from the combining of two reinforcements. Hybrid composites provide combination of properties such as tensile modulus, compressive strength and impact strength which cannot be recognized in composite materials.

Metal matrix composites (MMC) comprise of an alloy or a metal as the matrix and reinforcement such as the particles, short fiber or whisker and/or long fiber. Particulate reinforced metal matrix composites are not expensive to

manufacture than reinforced composites and exhibit the isotropic properties [1], whereas the properties of composites with fibre aligned reinforcements are highly anisotropic. Typically, SiC, Al₂O₃, B₄C, and graphite [2] materials are used as reinforcements in particulate reinforced metal matrix composites.

A surface phenomenon referred to as wear will occur by relocation and separation of material. It generally suggests a progressive loss of material and change of measurements over some undefined time frame. The main components that influences wear and friction behavior of aluminum alloys are sliding distance and speed, normal load, frictional temperature, surface finish and contaminants, hardness, microstructure etc. Aluminum matrix composites (AMCs) are majorly impacted by the characters of the matrix and reinforcement material. The layer, mechanically mixed layer (MML) is produced during wear of aluminum alloys,

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sliding against ferrous alloy. Due to the shift and combination of materials, under definite load and velocity range, the mechanically mixed layer is formed. The generated mechanically mixed layer consists of materials from both contact surfaces. It was also reported that the hardness of the generated mechanically mixed layer is greater than the bulk hardness of the composite. The generated mechanically mixed layer is majorly responsible for the decrement of wear rate and holding-up of transition to severe wear. The thickness of the mechanically mixed layer is varied with the load forms the subsurface zones of the materials as shown in Fig. 1.

Zone 1: Base material—Characterize to the base material which is not disturbed or unique sample material in the un-deformed state. Zone 1 material, when loaded in tribo-contact, encounters thermal cycling and elastic deformation. Zone 1 material's properties and structure are indistinguishable to those preceding wear tests.

Zone 2: Plastic deformation zone—Due to cyclic tribo-contact, zone 2 material comprises of the part of the base sample that has acquired altered properties. Fundamentally, zone 2 material suffered a distorted transitional area of fundamental material. In zone 2, in ductile materials, particularly plastic deformation happens, molecules are contorted & micro voids may propagate.

Zone 3: Mechanically mixed layer—is referred to as tribo-layer which generates in situ, and generally, have synthetic

substance categories from counter-face and test condition and in addition the bulk material.

Doddamani et al. [3] conducted experimentation on wear behaviour of Aluminum-graphite metal matrix composites. From the results, it is found that the adding of particles of graphite has increased the resistance to wear of the metal matrix composites. Also, it is reported that the addition of particles of graphite in aluminum reduces the friction than that of the base alloy.

Rajesh et al. [4–7] conducted experimentations like hardness, wear behavior at as-cast and age hardened conditions etc. on aluminum hybrid metal matrix composites. The matrix material considered is Al7075, and reinforcement material is SiC and alumina. From the results, it is clear that the hybrid aluminum metal matrix composites (HAMMCs) have better properties as compared to unreinforced aluminum alloy. Mouritz et al. [8] reported changes of resistance to abrasive wear of aluminum matrix composite when subjected to the various ageing environment. In aged conditions, composite materials exhibit relatively high wear resistance.

Radhika [9] studied abrasive wear behavior of cast aluminum-SiC composite with nickel coating. For the study of wear behavior they utilized Taguchi design of experiments and Analysis of Variance (ANOVA).

The enhancement of resistance to wear in the composite is the inclusion of steel from the surface of counter face. The inclusion of steel on the worn surfaces of the

Fig. 1 MML formation [25]

composites leads to increment the resistance of wear [10]. It demonstrates the inclusion of the steel acts as the addition of reinforcements on the wear surfaces of composites and helps to enhance the load bearing capacity [11–13]. The inclusion of the counterface material on the surface of composites leads to the generation of a thick layer called the mechanically mixed layer. The generated mechanically mixed layer serves as a lubricant and also act as a defensive layer on the worn surfaces of the composite [14, 15]. Venkataraman and Sundarajan [16–18] reported that the transfer layer thickness increased under increasing load conditions. Due to the inclusion of steel which forms the mechanically mixed layer, reduces the rate of wear of disc and pin at high speed. High temperature is formed due to the increased speed which produces an increased amount of formation of the layer. The amount of wear endow with the transfer layer can be found by speed, applied load, and surrounding conditions. The thickness of the layer is increased as load increases because of the increment in the heat generation and gives the superior compaction [19].

In the aluminum matrix composites, the development of tribolayer setbacks the changeovers from mild to severe wear. The exclusion of tribolayer from contact surfaces, the bulk materials becomes direct contact with the counterface and accordingly, it becomes intricate to generate another tribolayer on the heated and soft matrix [20]. Because of additional sliding, a drop in the frictional force is seen on the grounds that the mechanically mixed layer gets isolated from the pin surface, caused by delamination which exposes the fresh pin surface [21]. The outcome demonstrates that dissimilar types of reinforcement can create mechanically mixed layers. It can be accomplished that the mechanically mixed layer is created from the sources namely: counterface, matrix and the particles [22].

It is noticed from the literature that more research conducted on the wear characteristics of Al–SiCp, Al–Li/SiC metal matrix composites. Although, an important scope exists for research on the aluminum matrix particulate hybrid composite reinforced with alumina, silicon-carbide mainly in the area of wear behavior and mechanically mixed layer. In this background, this research work is proposed to investigate the behaviour of aluminum matrix hard particulate reinforced composite material at different weight fraction, under different wear condition that generates the mechanically mixed layer.

The main objective of the proposed work is to develop the hybrid composite in-order to improve the strength and wear resistance characteristics of the material that generate mechanically mixed layer.

2 Materials and processing

2.1 Materials

It is identified from the literature that more research work has been done on the wear behavior of Al–SiC_p, Al–graphite, Al–Fly Ash metal matrix composites. In the background, hybrid aluminum metal matrix composites have a wide range of scope for the research in wear characterization. The material selected for the research work is Al7075 as matrix and silicon carbide and alumina particles as reinforcement. The Al7075/SiC/Al₂O₃ particulate metal matrix composites are discontinuously reinforced composites which are nearly isotropic [5] and also have exceptional combinations of tribological and weight reduction properties. The motivation to utilize Al7075 is the tensile strength of the material which is higher than any other grades of the aluminum. The main constituents in the Al7075 are Si = 0.4%, Zn = 6.1%, Mg = 2.9%. The SiC material is a blend of silicon and carbon, outstanding abrasive material. Now a day, the SiC material is formed into a technical grade better quality ceramic with excellent mechanical/physical properties. Some of the key properties of silicon carbide utilized here are Density—3.1 g/cc, melting point—2730 °C, molecular mass—40.10 g/mol, particle size = 100 µm, Appearance—Black in colour. The alumina (Al₂O₃) is corundum. The alumina as a reinforcement is steadier with aluminum and withstand higher temperatures. Some of the key properties of aluminum oxide utilized here are density = 3.69 g/cc, melting point—2072 °C, particle size = 60 µm, appearance—white in colour.

2.2 Processing

Al7075–SiC/Al₂O₃ samples are formed at varied weight fractions of SiC/Al₂O₃ (5%, 10%, and 15%) utilizing stir casting technique. The aluminum slabs were melted in the furnace. In the wake of liquefying, liquid aluminum was superheated to 750 °C temperature.

The required measures of SiC/Al₂O₃ particles were added to the liquid aluminum while mixing with a stirrer at 600 rpm speed [20]. The liquid Al7075–SiC/Al₂O₃ was filled a permanent mold and it was permitted to set. The Al7075–SiC/Al₂O₃ composite bars were taken out from the mold. The samples were set up from as-cast combinations for investigation of required properties.

To determine the chemical composition of the said hybrid composites, Energy-dispersive X-ray (EDX) spectroscopy measurements are carried out in the SEM on individual specimens. The corresponding EDX profile analysis shown in Fig. 2 provides the atomic percentages of the elements found on the specimen surface.

Fig. 2 EDX profile analysis for the surfaces: Al7075–10 wt% of SiC/Al₂O₃ reinforcement

Table in the Fig. 2 describes the atom percentage of Si, magnesium, carbon, and aluminum. The content of silicon, zinc and magnesium indicates that the presence of Si and Mg in the Al7075 alloy. The existence of MgAl₂O₄ at interfaces was confirmed in a detailed study on the interfaces in discontinuously reinforced metal-matrix composites. In all the compositions of Al7075–SiC, alumina, oxygen (O) content has been obtained. The content of O is due to the formation of Al₂O₃ on the top of the pits as the main compound on the surface [7].

The as-cast composite specimens were heat treated at a temperature of 465 °C for 02 h taken after by quickly quenched in cool water. After quenching the specimens, these are subjected to an age (precipitation hardening) by heat-treatment the specimens to 120 °C, maintaining this temperature for 05 h and after that taken after cooling in air to room temperature.

3 Experimentation

Dry sliding wear experimentation for various samples is carried out by utilizing a pin-on-disc [14] wear testing machine. The machine model available in the laboratory is Wear and Friction Monitor TR-20 which was DUCOM made. The pin is held in opposition to the counterface of a rotating disk with 90 mm wear track diameter. The pin is subjected to a load in opposition to the disc all the way through dead weight loading systems. The wear experimentation for all samples is carried out for the load 2 kg, 4 kg, 6 kg and a fixed velocity of sliding of 0.942 m/s, 1.8849 m/s, 2.82 m/s for 200, 400, 600 rpm respectively for about 5 min. The pin specimens are of length 35 mm and diameter 10 mm. Before the wear tests, the pins were polished by using emery paper (1000 size grit) in-ordered to

make sure that efficient contact between the flat surfaces and the steel disc. Acetone is used to clean the specimens & wear track. The wear rate is determined by the weight loss method.

A steel disc as conterbody was used, to promote a mechanically mixed layer. It was found from the literature that, the presence of major alloying elements in the Al-alloy that have high solubility in steel promoted a thick mechanically mixed layer. The solubility of Al-alloy elements in Fe is in the order of Si, Mn, Cu, Mg, which roughly approximates the thickness of the mechanically mixed layer formed, while the Fe content of the mechanically mixed layer also scaled in this order. As for the ceramic material, which also can be used as a conterbody during the wear test, the mechanically mixed layer was derived from fracture of the slider, and also from transfer and re-transfer of the aluminium alloy. To analyze the true effect of the work hardening induced by wear, a ceramic slider was used, to minimize the formation of a mechanically mixed layer [21].

4 Results and discussions

The wear tracks obviously specify the high magnitude of crater lines intimately packed at a high weight percentage of reinforcement as shown in Fig. 3a.

Figure 3b shows the scanning electron microscope (SEM) images hybrid aluminum metal matrix composites (age hardening). The allocation of the Silicon carbide and alumina particle in the aluminum matrix composites [23] is noticed a by the homogeneous uniform circulation of the reinforcements in the matrix is necessary to form a composite with standardized mechanical properties. The agglomeration of particles is small. The worn surface

Fig. 3 Worn surface of HAMMCs **a** as-cast, **b** age hardened

Fig. 4 Influence of load on wear-rate at 848.23 m

of the metal matrix composites leads to the formation of iron-rich layers. The worn surface Fig. 3a, b show the white patches of iron oxide and exposed particles on the contact surface of Al7075 + 10%SiC + 10%Al₂O₃ hybrid aluminum metal matrix composites. Development of the FeO₂ was less significant at medium load than that of lesser loads. The occurrence of aluminum-oxide and silicon carbide was seen at the morphological surface. Figure 3a, b illustrate the features of the worn surface of

Al7075–10%SiC–10%Al₂O₃ hybrid aluminum metal matrix composites.

Figure 4 shows the comparison of as-cast and age hardened hybrid aluminum metal matrix composites for different load and at a sliding distance of 848.23 m. In the metal matrix composites (MMCs) increase wt% of SiC + Al₂O₃ reinforcement improves the hardness. Addition of hard particulate reinforcement in the composites restricts the composites from getting soft. It results in reductions in the

Fig. 5 EDX profile analysis Al7075–10 wt% of SiC/Al₂O₃ composite surface after wear test

wear rate. It was observed that the volumetric wear rate decreased in heat treated hybrid aluminum metal matrix composites with increased SiC + Al₂O₃ reinforcement and aging when compared with the base alloy the weight loss was decreased [23, 24] in metal matrix composites. In hybrid aluminum metal matrix composites the weight loss was further reduced when compared with aged conditions. Remarkably the lowest weight loss was observed in Al7075–10 wt%SiC–10 wt%Al₂O₃ with aged hybrid aluminum metal matrix composites.

At 15 wt% of reinforcement, it is observed that decrease of wear rate on increment of sliding distance. With increase of sliding distances tribo-oxidation intensify. More tribo-oxides results in the decrease of coefficient of friction and wear rate.

Figure 5 shows the element analysis of the said hybrid composite material after wear test. The solubility of Al-alloy elements in Fe is in the order of Si, Mn, Cu, Mg, which roughly approximates the thickness of the mechanically mixed layer formed, while the Fe content of the mechanically mixed layer also scaled in this order.

Table in the Fig. 5 describes the atom percentage of iron, silicon, magnesium, carbon, and aluminum. The content of silicon, zinc and magnesium indicates that the presence of Si, Zn and Mg in the Al7075 alloy. The presence of the Fe is the effect of steel counterbody. Due to the rubbing of the pin on the disc material there is a formation of iron content on the surface of the composite body. This form a layer on the surface of the composite is referred as mechanically mixed layer.

Al7075+10%SiC+10%Al₂O₃ at 6Kg, 600RPM

Al7075+10%SiC+10%Al₂O₃ at 6Kg, 600RPM

Fig. 6 Worn surface of HAMMCs **a** as-cast, **b** age hardening

5 Mechanically mixed layer

5.1 Description of the mechanically mixed layer (MML)

Figure 6a, b demonstrates scanning electron microscope pictures of the hybrid aluminum metal matrix composites wear surface. The scanning electron microscope illustrates various lengthy groove, craters on the worn surface with the increment in load to 58.86 N at sliding speeds of 2.827 m/s. due to increase in load, the composite wear behaviour change starting abrasion to delamination from the scanning electron microscope picture. It is plainly seen that the mechanically mixed layer are somewhere in the range of three and five times harder than the AA7075 alloy.

The particles present beneath the layer were hard, brittle than the matrix alloy. Mechanically Mixed Layer shows hardness around 6 times better while comparing to bulk composite [16, 17]. Mechanically Mixed Layer was absent on the worn surface of the aluminum. Presence of these layers probably restricts the rate of wear [18]. It is revealed to facilitate aluminum experienced a change from conversion from mild to severe wear at 58.86 N. It is

comprehensible that the mechanically mixed layer available on specimens experienced at load in the mild wear zone while the mechanically mixed layer was deficient on specimens which experienced severe wear. Due to the superior rate of wear temperature raises at the specimen sliding surface, the pin is softened and results in plastic, it reacts with O and results in oxides. The attention of the interface layer affects the rate of wear. As the raise in the reinforcements the thickness of the mechanically mixed layer increases.

5.2 Effect of thickness of mechanically mixed layer

For as-cast and age hardened hybrid aluminum metal matrix composites, thickness analysis using a scanning electron microscope is carried out for this purpose. For this rate of wear was generally not sensitive to the thickness of mechanically mixed layer for the Al7075, in spite of the fact that rate of wear decremented in a linear mode with incrementing thickness of the mechanically mixed layer. Figures 7 and 8 shows the thickness of as-cast and age hardened hybrid aluminum metal matrix composites determined using scanning electron microscope analysis.

Fig. 7 SEM images showing thickness of mechanically mixed layer at as-cast condition **a** Al7075, **b** Al7075 + 5%SiC + 5%Al₂O₃, **c** Al7075 + 10%SiC + 10%Al₂O₃, **d** Al7075 + 15%SiC + 15%Al₂O₃

Fig. 8 SEM images showing thickness of MML at age hardening condition **a** Al7075, **b** Al7075 + 5%SiC + 5%Al₂O₃, **c** Al7075 + 10%SiC + 10%Al₂O₃, **d** Al7075 + 15%SiC + 15%Al₂O₃

Fig. 9 Comparison of the thickness of MML for as-cast and age hardened conditions

Mechanically mixed layer generated is of wave-like formation [23] as shown in the Figs. 7 and 8.

Figure 9 shows the comparison of as-cast and age hardened hybrid aluminum metal matrix composites for the

thickness of the mechanically mixed layer. From the scanning electron microscope analysis, it is clear that the rate of wear was a strong function.

Further, on a study of this analysis, it is seen that production of the mechanically mixed layer on the composite worn surface, increases with increasing reinforcement content. These results also show that higher reinforcement content leads to greater material transfer from the counter surface with consequent faster development of a protective mechanically mixed layer on the worn surface.

It shows that raise in vol% of silicon carbide and Al₂O₃ increments the thickness of mechanically mixed layer lying on the pin surface. The mechanically mixed layer thickness at 58.56 N for various range of compositions and as composition increases thickness of the mechanically mixed layer increases up to 10% for both the reinforcements and it is decreased at 15% reinforcements due to agglomeration. It is to be noted that while the thickness of the mechanically mixed layer increases with incrementing load in the mild wear region. The mechanically mixed layer was seen in all the test materials, particularly in the mild wear regime. The mechanically mixed layer was seen only in the mild wear zone.

6 Conclusions

From the investigation, the following conclusions were drawn on the mechanical and wear performance of as-cast and T6 ageing of hybrid aluminium metal matrix composites—Al7075–SiC–Al₂O₃. Wear resistance of Al7075/Al₂O₃ + SiC composites incremented with weight percentage. The reduction in the rate of wear with sliding distances, composition. It enhances with loads for age hardening and without age hardening. The age hardened Al-7075/SiC + Al₂O₃ Composite shows excellent resistance to wear while comparing to Al7075/Al₂O₃ + SiC it has the distinctive property as the addition of Silicon-carbide and Aluminum-oxide. The microstructural characterization discovered that the homogeneous circulation of the particle in the matrix system with a minimal amount of porosity. The micro-structural studies of the scanning electron microscope and EDX techniques shows the homogeneous distribution of the particulates in the hybrid composites.

In T6 heat treated (age hardening) Al7075 – 10 wt% SiC + 10 wt% Al₂O₃ hybrid aluminum metal matrix composites improved the wear resistance was observed when compared with base alloy. Highest resistance to wear was observed in Al7075 – 10 wt%SiC + 10 wt% Al₂O₃ due to the presence of reinforcements. Further, it is observed the decrement in wear rate with increment in weight per cent of reinforcement for the desired sliding distances. From the investigation, it was concluded that composites containing 10% weight of silicon carbide and 10% weight of aluminum oxide reinforcements with ageing exhibited superior mechanical and tribological properties.

It is noticed that mechanically mixed layer presence in the mild wear regime, it is absence in the severe wear regime. Therefore, it is noticed non-formation of the mechanically mixed layer is dependable for the onset of severe wear. It is noticed that reducing the rate of wear with increment in mechanically mixed layer thickness. The mechanically mixed layer thickness increases by rising reinforcement composition up to 10% the development of hard mechanically mixed layer (stable, thin) layer will give the finest resistance to wear.

Acknowledgements I wish to thank University B.D.T. College of Engineering (Davangere), DST-PURSE Laboratory of Mangalore University, VGST-K FIST facility for melting and Material Testing (SJMIT, Chitradurga) for their support in providing facilities for various characterizations of materials and helped me to complete this research work.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. ASM Handbook (2001) Composites, ASM International, p 21
2. Miller DM (1987) Glass fibers, composites, engineered materials handbook. ASM Int 1:45–48
3. Doddamani S, Kaleemulla M, Begum Y, Anand KJ (2017) An investigation on wear behavior of graphite reinforced aluminum metal matrix composites. *JoRSTEM* 2017:1–6
4. Rajesh AM, Kaleemulla M (2016) Experimental investigations on mechanical behavior of aluminum metal matrix composites. *Mater Sci Eng*. <https://doi.org/10.1088/1757-99x/149/1/012121>
5. Rajesh AM, Kaleemulla M (2016) Experimental investigations on mechanical and wear behavior of hybrid aluminum alloy. *IJERT* 05(13):128–131
6. Rajesh AM, Kaleemulla M (2017) Effect of heat treatment on hybrid aluminum metal matrix composites. *Int J Emerg Res Manag Technol* 6(5):548–551
7. Rajesh AM, Kaleemulla M, Doddamani S (2019) Effect of addition of SiC and Al₂O₃ on wear behavior of hybrid aluminum metal matrix composites. *ACTA Tech Corviniensis Bull Eng* 12(1):43–52
8. Song WQ, Kraulis P, Mourrtz AP (1995) The effect of thermal ageing on the abrasive wear behaviour of age-hardening 2014 Al/SiC and 6061 Al/SiC composites. *Wear* 85:125–130
9. Radhika N (2018) Analysis of three body abrasive wear behaviour of centrifugally cast aluminum composite reinforced with Ni coated SiC using taguchi technique. *Tribol Ind* 40(1):81–91. <https://doi.org/10.24874/ti.2018.40.01.07>
10. Paulo Davim J, Conceicao Antonio CA (2001) Optimal drilling of particulate metal matrix composites based on experimental and numerical procedures. *Int Mach Tools Manuf* 41:21–31
11. Alpas T, Zhang J (1994) Effect of microstructure (particulate size and volume fraction) and counter face material on the sliding wear resistance of particulate reinforced aluminum matrix composites. *Metall Mater Trans A* 25:969–983
12. Zhang J, Alpas AT (1997) Transition between mild and severe wear in aluminum alloys. *Acta Mater* 45:513
13. Wilson S, Alpas AT (1996) Effect of temperature on the sliding wear performance of A1 alloys and A1 matrix composites. *Wear* 196:270–278
14. Uyyuru RK, Surappa MK, Brusethaug S (2007) Tribological behavior of Al–Si–SiCp composites/automobile brake pad system under dry sliding conditions. *Tribol Int* 40:365–373
15. Hassan AM, Alrashdan A, Hayajneh MT, Mayyas AT (2009) Wear behavior of Al–Mg–Cu–based composites containing SiC particles. *Tribol Int* 42:1230–1238
16. Venkataraman B, Sundararajan G (1996) The sliding wear behaviour of Al–SiC particulate composites. II. The characterization of subsurface deformation and correlation with wear behaviour. *Acta Metall Mater* 44:461–473
17. Venkataraman B, Sundararajan G (2000) Correlation between the characteristics of the mechanically mixed layer and wear behaviour of aluminum, Al-7075 alloy and Al-MMCs. *Wear* 245:22–38
18. Tyagi R (2005) Synthesis and tribological characterization of in situ cast Al–TiC composites. *Wear* 259:569–575
19. Riahi AR, Alpas AT (2001) The role of tribo-layers on the sliding wear behaviour of graphitic aluminum matrix composites. *Wear* 251:1396–1407
20. Prasad PR, Ray S, Gaindhar JL, Kappor ML (1985) Mechanical properties of Al-10% Cu alloy particulate composites. *Scr Mater* 19:1019–1022
21. Rosenberger MR, Forlererc E, Schvezova CE (2009) Wear behavior of AA1060 reinforced with alumina under different loads. *Wear* 266:356–359

22. Las L, Rodriguez Ibabe JM (2003) Wear behaviour of eutectic and hypereutectic Al–Si–Cu–Mg casting alloys tested against a composite brake pad. *Mater Sci Eng, A* 363:193–200
23. Rajesh AM, Kaleemulla M, Doddamani S (2019) Material characterization of SiC and Al₂O₃ reinforced hybrid aluminum metal matrix composites on wear behavior. *Adv Compos Lett SAGE* 28:1–10. <https://doi.org/10.1177/0963693519856356>
24. Rajesh AM, Kaleemulla M, Doddamani S (2019) Effect of heat treatment on wear behavior of hybrid aluminum metal matrix composites. *Tribol Ind* 41:1–11. <https://doi.org/10.24874/ti.2019.41.03.04>
25. Ghazali MJ, Rainforth WM, Jones H (2005) Dry sliding wear behaviour of some wrought, rapidly solidified powder metallurgy aluminum alloys. *Wear* 259:490–500

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