Wear and Friction Behavior of Gr/Sn Solid Lubricated Dual Reinforced AMCs

Varun Singhal \(^1\) · O. P. Pandey \(^1\)

Received: 16 June 2021 / Accepted: 19 August 2021 / Published online: 31 August 2021
© Springer Nature B.V. 2021

Abstract
The current work has been undertaken to see the effect of Gr/Sn as a solid lubricant for the development of hybrid aluminum metal matrix composite (HAMCs). HAMCs were fabricated by reinforcing 10 wt% (sillimanite + ilmenite) minerals with or without 1 wt% Sn/Gr/both via stir casting technique. Optical microscopy revealed a homogenous distribution of reinforced particles with the refinement of silicon. Vicker hardness of the HAMCs showed a good interfacial bonding of particles with the matrix. The formation of porosity during fabrication of composite is ~ 1.74 %. The maximum reduction in wear rate and coefficient of friction of the HAMCs are for composite containing tin and graphite as lubrication agents. This composite exhibited a ~ 6 % less wear resistance than commercial grey cast iron specimen used in the brake rotor in the automobile industries. It seems that wear rate of composite containing tin and graphite as solid lubricants are in tune with the cast-iron. Abrasive wear was dominant at low loads and adhesive wear at high loads, as confirmed from SEM analysis.

Keywords Solid lubricants · Wear and friction · Density · Hardness · LM30 alloy · Sillimanite · Ilmenite

1 Introduction
In the past few decades, many scientists are searching a substitute for ferrous metals to increase fuel efficiency for different automobile parts. Aluminum alloy can be considered as the perfect substitute for ferrous material if its strength and hardness are improved. Al-alloys having relatively lower density made revolutionary changes in many sectors of automobile, aeronautical and marine industries for developing lightweight spare parts [1]. Also, Al has specific characteristics like ductility, recyclability, strength to weight ratio [2]. Apart from these properties, its applicability is being compromised in terms of its low hardness, which has been modified by incorporating different ingredients and forming a composite. This exhibits the enhanced properties based on the degree of interfacial bonding of the ingredients mixed homogenously throughout the composites.

Al-Si alloy containing nearly 13 wt% Si is the most practiced alloy due to its good castability, low density, and high corrosion resistance [2, 3]. Aluminum matrix composites (AMCs) exhibit a wide range of applications [4–6]. Most of the research groups have investigated the properties of AMCs by incorporating (i) synthetic and (ii) natural reinforcement. Synthetic ceramic compounds such as SiO\(_2\) [7], ZrO\(_2\) [8], SiC [9], B\(_4\)C [10], Al\(_2\)O\(_3\) [11], etc., as reinforcement have shown an excellent wear resistance of Al-alloy matrix composites [12–14]. At the same time, natural minerals like rutile [15], garnet [16, 17], zircon [18] etc. can reduce the human efforts by lowering the cost of manufacturing to achieve similar or even better tribological properties along with high corrosion resistance [19–23]. Therefore, most research groups use natural minerals to enhance the hardness, wear, and corrosion resistance of Al or its alloys [24]. Sillimanite reinforced in an aluminum matrix such as LM6 [25], LM30 [21] enhances tribological properties. However, these authors have studied the effect of particle size on wear rate on LM6 and LM30 alloys. Moreover, sillimanite has high mechanical (hardness, modulus) and thermal properties. Also, sillimanite is an ore of aluminum. It will improve the wettability between the aluminum matrix and sillimanite. At the same time, ilmenite also has high mechanical properties. Considering these aspects, reinforcement of more than one mineral in the AMCs will be a more
effective and cheapest route to enhance AMC properties. Such hybrid composites (HAMCs) have not been studied extensively.

Gupta et al. [26] concluded that the addition of dual reinforcement (sillimanite + rutile) provided enhancement in wear resistance compared to the composites reinforced with only sillimanite or rutile. Kaushik and Rao [27] observed the formation of intermetallic phase during heat treatment (T6) which helped to reduce wear rate by 27% of dual reinforced (Al-SiC-Gr) composite sample and 23% of single reinforced (Al-SiC) composite sample as compared to Al-6082 alloy.

Moreover, to reduce the seizure wear and friction in pistons and cylinder, solid lubricants like graphite (Gr), tin (Sn), lead (Pb) and MoS2, etc. are added during the manufacturing of composite, which can also provide inherent reduced wear loss [18–20]. Tyagi [28] and Das et al. [29] suggested the enhancement in interfacial interaction between matrix and individual reinforcements (TiC and graphite, respectively), resulting the enhanced adhesive and seizure wear resistance, respectively. Moreover, tin (Sn) can also be used as a lubricating agent due to its low melting point, which helps to fill the surface pores during sliding over the counter surface [2].

The present work is based on the development of HAMCs with both sillimanite (Al2SiO5) and ilmenite (FeTiO3) minerals incorporated in LM30 alloy through the stir-casting route which have not been studied so far. Further, a small amount (1 wt%) of solid lubricants (Gr and Sn) were also incorporated in the prepared composite to study their impact on the wear behavior of hybrid composites. Moreover, from an application point of view, the wear properties of the best HAMCs is also compared with the brake drum material (cast iron) used in the automobile sector. The chemical composition of cast iron is listed in Table 1.

2 Materials and Methods

2.1 Materials

In order to prepare HAMCs, Al-alloy LM30 was obtained from Emmes Metal Pvt. Ltd., Mumbai (India). Natural minerals sillimanite (Al2SiO5) and ilmenite (FeTiO3) were procured from Indian Rare Earths Limited, Mumbai (India). Sillimanite and ilmenite have different properties. Sillimanite has high hardness and good wettability whereas ilmenite has high thermal conductivity which is helpful to improve the wear resistance of composite. Based on the reported work, 10 wt. reinforcement shows the higher improvement in wear resistance of samples. Further, authors have selected 0.5 wt% reinforcement of each one so that both reinforcement can participate for the improvement equally for the improvement of the wear resistance [30, 31]. The chemical composition of Al-Si alloy and respective reinforcement are enlisted in Table 1. Sn and Gr were procured from Loba Chemie and was added to melt as a solid lubricant to reduce friction and wear between two relative sliding surfaces.

Gr has poor wettability and does not form bonds either with Al or with ceramic particles. Being a lighter substance, it gets agglomerated. Because of this, the optimum amount of Gr (1 wt%) is chosen. Further, 1 wt% Sn was added in to the melt. The solubility of the Sn in Al is maximum at 627 °C (0.1 wt%) and minimum (0.05 wt%) at eutectic temperature (228 °C). This further drops down at room temperature. Small amount (1 wt%) of Sn is added to have solid lubrication in the system [32]. Al-Sn is immiscible alloy. At room temperature Sn gets distributed along the grain boundary and helps to provide lubricating properties [33, 34]. During sliding of pin, more amount of Sn is leached out at the contact surface, which is further smeared off with increased load due to frictional heating during continuous sliding. Therefore, an optimum amount of Sn is required to keep the lubricating film continuous.

2.2 Method

HAMCs samples were produced by stir casting techniques using a graphite stirrer, as shown in Fig. 1(a) [35]. An electric resistance furnace was used to melt the Al-Si alloy (LM30) in a graphite crucible at 750 °C. In the first step, the molten alloy was stirred at 620 rpm for 4 min. Before charging the reinforcement, it was heated at 350 °C to remove the moisture and other volatile substance to have better wettability of reinforcement particles. After that, preheated micro-size minerals (~37 μm average size (Fig. 1(b, c))) (5 wt% sillimanite + 5 wt% ilmenite) were added to the molten alloy after reducing the stirring speed at 265 rpm. These particles were added slowly while stirring. The stirring was continued for 11 min at 620 rpm speed to get uniform distribution of particles in the Al-matrix. Finally, the molten mass was transformed in a 12 × 12 × 4 cm2 rectangular permanent cast-iron mold and left to solidify at room temperature. Another set of composites was also developed with the exact content of minerals but with solid lubricating agents Gr/Sn/both in the molten mass. Table 2 presents the designation of different HAMCs fabricated in the present study.

2.3 Optical microscopy examination

Further, samples were polished for optical microscopy examination by following the ASTM standard E3-11 (2011). Optical microscope (Eclipse-MA100, Nikon instrument, Tokoyo (Japan) was used to examine the distribution of particles.
2.4 Density and Hardness

The Archimedes principle is used to calculate the experimental density ($\rho_{ex}$) of all prepared samples. Also, theoretical density ($\rho_{th}$) was calculated through the rule of mixture (Eq. 1).

$$\rho_{th} = \rho_1 v_1 + \rho_2 v_2 + \rho_3 v_3 + \rho_4 v_4 + \rho_5 v_5$$  (1)

The Vickers-hardness was measured on the Vicker scale with 100 Kgf load with diamond indenter using the Mitutoyo Vickers hardness instrument model MVKHO. The microhardness was taken at three different places (particle, interface, and matrix) as per the ASTM E-92. In addition, the Rockwell hardness of prepared samples was also measured using the Rockwell hardness tester (model no. TRSND, fine manufacturing Industries (India)) at 100 kg load on B-scale for 5 s dwell time and 1/16” ball indenter. Both hardness results presented are an average of 5 readings at a given composition.

2.5 Wear and Coefficient of Friction Measurement

For the wear test, a pin-on-disc setup was used in which a cylindrical pin was mounted on a rotating steel disc. The test was conducted as per ASTM G99 05 (2010) norms. All the tests were performed at 8 mm cylindrical diameter specimens (Fig. 1a). The test was carried out up to 3000 m sliding distance by varying load at 9.81, 29.43, 49.05, and 68.67 N at a constant velocity of 1.6 m/sec on wear and friction monitor (TR-2 L). Dismuc Instruments, Bangalore (India). A steel disk of EN32 steel (832 HV hardness) was used as a counter body [36, 37]. The testing condition has been selected based upon the research reported literature. The velocity and loads representation of braking environments for brake rotor and asbestos shoe used in automobile applications. Asbestos is a softer material. Hence to observe adverse wear conditions, wear tests were performed against a hard EN32 steel disc [26, 38–42].

In this instrument, the LVDT sensor was used to measure the decrement in height (in µm) of the sample, and wear rate was calculated by using Eq. 2. Before the wear test, samples were ground on 1000 µm grit size paper and cleaned with acetone. This test was performed three times to determine the average wear rate. The friction force was continuously measured during the experiment, and the coefficient of friction (COF) was calculated using Eq. 3.

$$W_R = \frac{H_L \times A_C}{D_S}$$  (2)

Coefficient of friction (COF) = Friction force ($F_f$) / Applied load ($A_L$)  (3)

Notification:

- $H_L$ - Height loss (LVDT sensor display on screen).
- $A_C$ - Contact area ($= \frac{\pi d^2}{4}$), d specimen diameter (mm)
- $W_R$ - Wear rate (mm$^3$/m).
- $D_S$ - Sliding distance ($= 1.6 \times $ time) (m).

2.6 SEM Analysis

Scanning electron microscope JOEL, JSM-6510LV, Tokoyo (Japan) was used to establish the wear mechanism and to compare the structural-tribological relationship at different
load conditions. The EDS analysis of cast iron sample was performed on JOEL, JSM-ITLV, Tokoyo (Japan) scanning electron microscopy.

3 Results and Discussion

3.1 Microscopic Examination

3.1.1 Base Material

The optical microstructure of the B1 sample is given in Fig. 2 at low and higher magnification. It is observed that the B1 sample contains the coarse primary-Si phase along with the eutectic Al-Si mixture. During the solidification, heterogeneous nucleation occurs inside the molten Al-Si mixture. Thus, primary Si was nucleated as a faceted structure in the $\alpha$-Al phase. This faceted morphology is like a cube, star, and polygon. At a later stage, solidification of the eutectic mixture occurs where the fine size of Si is shown in Fig. 2a.

3.1.2 Fabricated composites

It has been observed that the addition of natural minerals (sillimanite + ilmenite) exhibited the outstanding homogeneity

| Table 2 | Details of the formulated sample |
|---------|---------------------------------|
| Sample ID | Matrix (wt%) | Amount of different reinforcements (wt%) |
|          |       | sillimanite | Ilmenite | Sn | Gr |
| B1      | 100   | -           | -        | -  | -  |
| H1      | 100   | 5           | 5        | -  | -  |
| HT      | 100   | 5           | 5        | 1.0| -  |
| HG      | 100   | 5           | 5        | -  | 1.0|
| HTG     | 100   | 5           | 5        | 0.5| 0.5|
of reinforced particles (Fig. 3a and b). This was due to the effect of mechanical mixing. During rotation, it executed a dynamic shear force between molten alloy and reinforcement particles [3]. The exerted shear force hindered the settling of dense ceramics particles inside the molten alloy, as shown in Fig. 3a. Also, there are considerable differences in the thermal conductivity between the matrix and reinforced particles [43]. Thus, the reinforced ceramic particles provided the surface for the nucleation of the Si phase. Because of many particles inside the molten mass, needle-shaped finer silicon nucleates, as shown in Fig. 3a. Moreover, the primary silicon size also got reduced.

Some research groups have observed the enhancement in mechanical properties of Al-Si alloy as an effect of silicon refinement due to its high hardness [44, 45]. Further, it is a well-known fact that the heat treatment cycle of any alloy/
composite manifests the morphological features of prepared samples. Therefore, all the samples were prepared under similar conditions. The EDS line profile of the SEM image indicates the presence of Al, Si, Fe, Ti, and O, showing the presence of sillimanite and ilmenite particles (Fig. 3c and d).

Figure 4(a, b) represents the optical micrographs of the prepared sample (HT) with 1 wt% Sn as a solid lubricant and 10 wt% natural minerals as reinforcements. Abis et al. [46] have discussed the refinement of Si due to Sn addition because of the lower solubility of Sn in Al and the considerable difference in respective melting points so that it can get quickly filled inside the surface pores during sliding over the counter surface. Also, Sn atoms have more binding energy with vacancy due to their sizeable atomic size. These vacancies enhance the diffusion of eutectic-Si all over the matrix [47]. This helps in refining the Si, which can be seen in Fig. 4a. An optical micrograph supports the above statement with smaller primary silicon (Fig. 4b). Since reinforced particles and Sn can not be distinguished in the optical micrograph, a respective EDS line profile of the SEM image has also been taken, as shown in Fig. 4c and d. The bright phase represents the presence of Sn. The lower melting point of Sn compared to Al covers the reinforcement in a liquid state, as shown in Fig. 4c. Further, Sn has refined the silicon (Fig. 4a) to an appreciable extent compared to unlubricated samples (Fig. 3a).

Figure 5(a, b) exhibits the microstructure of sample HG, which shows 1 wt% self-lubricating Gr particles, which helps to refine the primary silicon morphology. Graphite particles act as the nucleus to provide a solidification site for the remaining mass. Graphite particles were poured into the vortex formed in liquid during the mechanical stirring. By the string action, graphite particles overcome the surface energy barriers due to poor wettability of graphite with LM30 (Al-Si) alloy and the local shear force exerted on the bulk Gr agglomerates breaks the bulk cohesive graphite powder leading to a uniform

Fig. 4 Represent the micrograph of 1 wt% (sillimanite & ilmenite) reinforced composite with 1 wt% Sn at (a) 100 X, (b) 500X magnification, and (c & d) EDS line profile of SEM image of HT sample
distribution in the matrix [48, 49]. Graphite particles form the glaze film on the pin surface during the sliding motion and reduce the apparent contact area [50]. Figure 5c and d shows the EDS line profile of the SEM image of the HG sample to investigate the presence of Gr particles.

Figure 6(a, b) represents the microstructure of the HTG sample, which is the mixture of (0.5 wt% Gr + 0.5 wt% Sn) with 10 wt% (sillimanite + ilmenite). The microstructure reveals the presence of primary faceted Si and needle type eutectic Si having refined structure as compared to other composites. Since the reinforcement particles (sillimanite + ilmenite) and graphite particles have a high melting point so it provides more number of nucleation sites. Higher nucleation sites lead to the hindrance for the growth of primary silicon. Sillimanite, ilmenite, and graphite all restricted the growth of silicon primary phase and help to generate refined structure, which further helps in improved mechanical properties of composites [51]. The EDS line profile of the SEM image of HTG sample is shown in Fig. 6c and d. The presence of both tin and graphite as a solid lubricant can be seen.

3.2 Density and porosity

Figure 7a represents the comparative study of theoretical densities ($\rho_{th}$) and experimental density ($\rho_{ex}$), respectively. The graph shows the marginal difference between the $\rho_{th}$ and $\rho_{ex}$ of the synthesized composite. Moreover, $\rho_{th}$ and $\rho_{ex}$ densities of the composite are more than the B1 sample. It was due to incorporating the minerals having higher density particles than the base alloy. The study of Fig. 7b reveals that the overall $\rho_{th}$ of the formulated composites is less than commercial cast iron (C) material. It is observed that the $\rho_{th}$ of formulated composite HTG was ~ 60 % less than automobile grade cast iron density.

The porosity of the composites was calculated using the formula \(\text{porosity} \% = \left(1 - \frac{\rho_{op}}{\rho_{th}}\right) \times 100\), where $\rho_{th}$; theoretical densities, $\rho_{ex}$; experimental density. Calculated values are
It is observed that the overall porosity was ~ 1.74 %, which is negligible [52].

3.3 Hardness

3.3.1 Micro-hardness

Figure 8a shows the variation in the Vickers hardness of the prepared composites at matrix (M), reinforcement particles (P), and interface (I) between the matrix and reinforcement. It is revealed from Fig. 8a that the micro-hardness of the B1 sample increased with the incorporation of reinforcement (sillimanite & ilmenite) particles. There are three distinct hardness zones for the composite, where low hardness was observed in the matrix zone. Next, the zone with the maximum hardness was the reinforced particles, and the zone where the hardness value lies between the particle and the matrix was named the interfacial zone. The high hardness values at the particle-matrix interface represent the excellent bonding of particles with the matrix.
The Vickers hardness of the HT and HTG composite was ~4 % and ~15 %, more than the H1 sample, respectively. The hardness of fabricated composite increased due to the (i) incorporation of harder reinforcement particles to the soft Al alloy which causes strain around the reinforced particles. (ii) refinement of microstructure with strong interfacial bonding between particles and matrix [51, 53]. Thus, the processing route followed for the fabrication of the composites was adequate to achieve sound composites. However, the microhardness of HG sample showed a minimal increment ~3 % than the other prepared composite, which was due to the addition of soft Gr particles. Gr particles have eased the movement of grains besides the slip planes and could lead to large deformation of material [54].

### 3.3.2 Bulk Hardness

Figure 9b represents the bulk hardness of B1 composite and commercial cast iron samples at the scale of B. It can be observed from the graphical data that the Rockwell hardness of prepared composites has increased by the addition of reinforcement (sillimanite & ilmenite) particles. It is also observed that the hardness of HG sample decreases due to the incorporation of Gr soft particles. The HTG sample exhibited a ~44 % increment in the Rockwell hardness than the B1 sample. Moreover, the Rockwell hardness of the HTG sample is ~7 % less as comparisons to cast iron (CI). The addition of the sillimanite and ilmenite minerals refines the microstructure of the composites. This causes are increased in hardness of the composites.

### 3.4 Wear Analysis

#### 3.4.1 Effect of sliding distance and applied load on the wear losses

Figure 9(a-e) exhibits the variation in wear rate of different samples with sliding distance. For the base alloy and the composites, a similar trend in the wear results was observed. Figure 9 exhibits the two distinct zones viz. run-in wear (up to 1500 m) and steady-state wear (1500-3000 m). Initially, the wear rate of fabricated samples is higher up to the 250 m sliding distance. The initial increase in the wear rate of the samples is attributed to the asperity-to-asperity contact. Applying shear forces during sliding the cutting and plowing action of the sharp asperities of matrix in contact with the counter surface generates debris causing heavy material losses till 250 m sliding distance [34, 35]. This shows abrasive wear nature during the relative motion (Fig. 9).

Beyond the sliding distance of 250 m wear rate decreases, the continuous sliding increases the contact temperature and leads to the formation of oxides on the pin surface. The oxides decrease the relative area of contact between the pin and disc. Hence, a decrease in the wear rate is observed [55].

Next, in steady-state wear zone, the smaller debris was embedded between the counter surface and pin surface valleys. Now, the wear mechanism is converted from a two-body wear mechanism into a three-body wear mechanism. During continuous sliding, the contact temperature increases in the initial stage and after that wear is little increased. In this period, the pin’s surface gets oxidized and forms a thermal barrier between pin and counter surface, preventing the contact pin subsurface from leading to reduced wear loss [36, 38].

Figure 10(a, b) represents the comparative study of maximum run in wear rate and average steady wear rate of all samples, respectively, at different applied loads (9.81-
Fig. 9 Representative wear behavior of (a) Base alloy and (b-e) Formulated composite showing run in and steady-state wear at different load (9.81–68.67 N).

Fig. 10 Represents the study of dry sliding wear behavior of B1 and various formulated samples (a) Maximum wear rate and (b) Average steady-state wear at 9.81–68.67 N applied loads.
The wear rate of LM30 (Al-Si) alloy and synthesized composites increases with the applied load. Higher applied load increases the frictional heating between the pin and the counter surface. This increases the contact temperature and causes softening of the pin surface and removing the oxidized area of the pin. This exposes new areas to wear. In addition, the counter surfaces get welded to the disc surface, tearing the pin surface and increasing wear rate. Also, higher load exhibited higher content of plastic deformation, resulting in higher wear loss. The material removal induced the delamination (severe fracture of the interface), forming micro-cracks and micro-plowing due to the application of shear force on the sub-surface during sliding motion [32, 35–38].

3.4.2 Effect of the Reinforcement and Lubricating Material

Figure 10(a, b) represents the effect of reinforcement particles (sillimanite + ilmenite) on the maximum run in and average steady-state wear of fabricated composites. As a result of the incorporation of the natural mineral(s) inside the metallic LM30 matrix, the wear loss has been reduced by ~ 37% and ~ 29% (run in wear) and 26 and 23% (steady state wear) at lower load (9.81 N) and higher load (68.67 N), respectively. Generally, the observed wear behavior is associated with the presence of ceramics phase in the matrix [56]. Moreover, some of the research groups have also suggested the influence of the re-distribution of Si inside the Al matrix that causes less wear losses as Si is hard phase [57].

The wear rate of the samples decreased with the incorporation of sillimanite and ilmenite particles. This was attributed to the fact that at a given applied load, sillimanite and ilmenite particles bear a major portion of the applied load. The strong interfacial bonding keeps the particles stable and bonded to the matrix and hence, carries a major portion of applied load. Sillimanite and ilmenite particles protrude from the matrix and hold a significant portion of the applied load. The ceramics particles shield the matrix from deformation. Due to the continuous deformation, when one particle is fractured, the load is transferred to the other particles. Thus, further enhancement in the wear resistance is observed. Therefore the outcome is the reduced wear rate [45, 46, 58].

To investigate the effect of solid lubricant (Sn and Gr) on wear performance of natural mineral reinforced Al-alloy composite, tin (Sn), graphite (Gr), and both were reinforced in the LM30 matrix with reinforcement minerals during the casting process. As a result, both components (Sn or Gr) exhibited their presence in the metallic (LM30) matrix, as shown in Fig. 9c and d, respectively. Here, Fig. 10b depicts the effect of solid lubricant (Sn/Gr/both) on the average steady-state wear rate on cast composites. As a result of the addition of solid lubricant(s), overall steady-state wear resistance has been increased up to ~ 3% (at 9.81 N) and ~ 24% (at 68.67 N) as compared to composites without solid lubricant(s).

In Gr-reinforced (1.0 wt%) composite samples (HG), a decrement of ~ 12% has been observed at 9.81 N, while ~ 14% has occurred at 68.67 N. The observed variation might be associated with the layered hexagonal structure of graphite and resulted in graphitized tribo-film along with Al-oxide film during the relative motion between pin and counter material [44, 45]. Due to the formation of a lubricating film which may behave like a barrier between asperities of pin and counter surface, it reduces the coefficient of friction and hence, reduces the shear stress between contact surfaces and enhances the wear resistance [59–62].

Similarly, Sn-reinforced (1.0 wt%) composite samples (HT10) reduced the wear rate ~ 11% at 9.81 N and ~ 41% at 68.67 N, respectively. The observed decreased wear loss can be asserted to two significant factors that are (i) formation of Sn-oxide layer on the surface of the pin and (ii) melting of Sn due to frictional motion between pin and counter disc. Latter resulted in filling the asperities with molten Sn, which may further support the formation of the Sn-oxide layer and reduce seizure wear [63]. Moreover, Fig. 10(b) also revealed the enhanced wear resistance of dual lubricant reinforced composite samples (HTG) with ~ 52% at 9.81 N and ~ 39% at 68.67 N compared to individual lubricant (Gr or Sn) composite samples. During the relative motion between the pin and counter surface, the combination of Sn and Gr resulted in the formation of lubricating film and oxide film, which enhanced the wear resistance [64].

Further, Fig. 11 shows the comparative wear behavior study of cast iron (C) and HTG sample. Sample HTG exhibited ~ 6% less wear resistance as compared to cast iron. But, a lower density of aluminum enables its applicability as brake rotors [65]. Thus, the observed results suggested that the
HAMCs is an alternate material to substitute the cast iron for industrial application.

### 3.5 Coefficient of Friction

The study of coefficient of friction (COF) of the B1 sample and synthesized composite at various loads (9.81–68.67 N) is shown in Fig. 12. The graph trend is similar for all the samples, where it initially increases up to the applied load of 29.43 N, and after that, a decrease in COF is observed. For low load, less frictional heating is generated between the contact surfaces; thus, the COF at low applied load is less. For the low load (9.81 N), the COF of the B1, H1, HT, HG, and HTG samples was observed to be 0.55, 0.42, 0.29, 0.32, and 0.20, respectively. After that, the frictional heating increases with increasing the load. Therefore, an increment in the COF is also observed (Fig. 12). For the applied load of 29.43 N, the COF of the B1, H1, HT, HG, and HTG samples was observed to be 0.76, 0.62, 0.55, 0.59, and 0.52, respectively. The COF is increased till the applied load of 29.43 N, beyond which the decrease in the COF is observed. For the applied load of 49.05 N, the COF of the B1, H1, HT, HG, and HTG samples was observed to be 0.73, 0.60, 0.52, 0.54, and 0.50, respectively. During wear the welded surface gets plastically deformed and due to ploughing action debris are formed. These debris are the mixture of solid lubricants and reinforcement which form the stable lubricating film on the pin surface under continues sliding motion. This lubricating film has provided antifriction properties and reduce the wear losses. Hence reduce the coefficient of friction at higher load [66, 67]. Also, increased frictional heating leads to the formation of an oxide layer on the pin surface and protects the surface from sliding contact. At higher applied loads, i.e., up to 49 N, formation of MML occurs, which inhibits metal to metal contact and lowers the COF of the composites. For the high applied load of 68.67 N, the COF of the B1, H1, HT, HG, and HTG sample was observed to be 0.64, 0.52, 0.45, 0.47, and 0.42, respectively. The incorporation of solid lubricating ingredients has a significant effect on the COF of the samples. The COF of the HT sample was lesser than the HG sample. The lowest COF was observed for the HG composite, the value of COF was 0.42. It shows that the COF of HTG sample is ~ 16 % higher than the grey cast iron.

### 3.6 Track and debris analysis

Figure 13(a) shows the images of wear track of all samples at 68.67 N load. Figure 13(b, c) shows the SEM image of worn tracks of the HTG sample at 9.81 and 68.67 N load, respectively. The SEM images exhibit the grooves mark parallel in the direction of relative motion on the sample surface with some delamination mark. At low load of 9.81 N, these narrow grooves on the sample lead to the abrasion wear between the contact surfaces. A few debris was also observed on the pin surface. Due to continuous sliding, some debris gets embedded into the soft matrix material. Moreover, wider grooves were observed under the action of the high applied load. The asperities become wider and deformed in the direction of sliding, while the size of the asperities increases with the increase of the applied load up to 68.67 N (Fig. 13c). Also, during the sliding the material undergoes higher plastic deformation under the action of shear stress. This leads to the formation of microcracks. When these cracks meet each other material loss occurs in the form of debris as delamination of the sample surface (Fig. 13c) [59, 60, 68–71]. This represents that for 68.67 N load, the material removal is the adhesive wear nature. In this order, small debris is also seen on the wear track due to the continuous motion. Due to the combined action of applied load and constant sliding speed, the debris gets embedded in the wear tracks of the pin surface (Fig. 13c). The HAMC surface had undergone mild wear, which can be attributed to the oxidative wear mechanism. Oxide layers were formed on the surface of the composite as the pin scratches away some of the surface material. This oxide layer restricts further removal of material by limiting the formation of the transfer layer.

Figure 13d and e present the SEM images of wear debris of the HTG sample at an applied load of 9.81 and 68.67 N, respectively. Majorly flake-like debris was observed. Flake-like debris is formed as a result of delamination. The continuous sliding leads to the plastic deformation of the pin surface and leads to microcracks. When microcracks meet with each other, they lead to the removal of material in the form of flakes, leading to the formation of flake-like debris [41]. Grooves
on debris are also visible. The debris’s grooves indicate micro plowing action during the initial run-in wear zone [43]. The presence of grooves on debris reveals that initially, abrasive wear was dominant [44].

Further, a few small-sized wear debris are attached to the wear surface, which signifies the continuous removal of debris from their surface [21]. These wear debris reduced the wear rate of the composite by avoiding the exposure of soft matrix material to the steel counter surface. As sliding distance increases, crack formation followed by material removal in the form of flakes has occurred by leaving a crater behind it. The presence of microcracks on the wear debris represents the plastic deformation of the working surface due to the application of shear force on the subsurface during sliding motion.

Figure 13f represents the SEM micrograph of wear track of cast iron sample at 68.67 N load. The micrograph contains small amount of the grooves. Under the action of high applied load (68.67 N) the micro-cracks propagated on the pin surface and enhance the delaminated area.

Figure 14(a) represents the EDS analysis of the HTG wear track at a 68.67 N applied load. Spectrum peaks are observed for various elements like Al, Cu, Fe, Ti and O. The presence of oxygen proves that the formation of aluminum oxide, iron oxide, and silicon oxide during wear. The source of iron is the counter surface. Due to the continuous sliding at higher applied load leads to debris formation from the pin surface. This debris gets trapped between the pin and the counter surface and prevents direct metal-to-metal contact of pin and disc. The debris of the pin surface and the counter surface gets compacted between the pin and the disc and begin to flow/roll in the direction of sliding. The possibility of accumulation of wear debris at the valleys between protruded corundum...
particles is higher for the composites than the base alloy. As a result, higher counter surface material gets transferred and finally accommodated as MML on the composite surface and increases the wear resistance of the prepared composites. Figure 14b present the EDS analysis of HTG sample wear debris at a load of 68.67 N. The spectrum of the debris shows peaks of different elements like Al, Cu, Fe, and O. Further, the presences of carbon in the wear debris indicate their role as solid lubricants. These lubricating agents compliment the wear resistance and provide superior wear resistance to the composites. Moreover, Fig. 14(c) shows the EDS analysis of wear track of grey cast iron (CI) sample. In the EDS spectrum of CI sample the major elements are Fe and O. As observed from EDS analysis of composite and CI sample that the higher concentration of oxygen is in HTG composite. This leads to formation of wide and stable oxide layer compared to CI sample.

4 Conclusions

The influence of solid lubricant on the wear properties of synthesized composites has been studied. Some significant studies are given below:

- Optical micrographs show the presence of uniformly distributed sillimanite and ilmenite particles throughout the
matrix. Other solid lubricants viz. Sn and Gr were homogeneously distributed throughout the matrix. Also, the addition of ceramic particles refined the primary and eutectic silicon morphology.

- Vickers hardness study revealed that ~ 15 % high hardness at the particle-matrix interface, indicating strong interfacial bonding of particles with the matrix. Thus, the processing method adopted for the fabrication of the composites was successful. Further, Rockwell hardness showed HTG sample exhibited a ~ 44 % increment than the base material. Moreover, the Rockwell hardness of the HTG sample is ~ 7 % less as comparisons to cast iron (CI).

- The addition of solid lubricants decreased the wear rate and coefficient of friction of the composites. Best wear results were observed for the composites with both Sn and Gr. The COF of HTG sample is ~ 16 % higher than the grey cast iron, which will increases the braking capacity.

- SEM analysis shows that at a low load of 9.81 N, the abrasive wear mechanism was dominant. The high load of 68.67 N adhesive wear mechanism was dominant for material removal. Further, EDS analysis indicates the formation of higher content oxygen on the pin surface and wear debris, indicating an stable oxide layer and mechanically mixed layer on the composite pin surface rather than cast iron pin surface.

- The wear rate of the composites was comparable to the cast iron. Moreover, the composites have a lower density than the cast iron. Thus, for industrial applications like brake rotors, composites provide a significant weight reduction over the conventional cast-iron material.

Acknowledgements Author (VS) thanks Dr. Aayush Gupta for valuable suggestions in drafting the manuscript.

Author Contribution Varun Singhal: Conceptualization, design of study, data optimization, analysis, manuscript writing. O. P. Pandey: Results analysis, manuscript writing.

Data Availability All the data and material incorporated in the present manuscript will be made available whenever required.

Declarations Formal consent is not compulsory for the above type of work.

Consent to Participate Authors does not performed any studies involving human or animal participation.

Consent for Publication Consent was got from all individual authors included in the study to publish data.

Conflict of Interest Authors do not have any conflict of interest.

References

1. Rohatgi P (1991) Cast aluminum-matrix composites for automotive applications. Jom 43(4):10–15. https://doi.org/10.1007/BF03220538
2. Garg T, Mathur P, Singhval V, Jain C, Gupta P (2014) Underwater friction stir welding: an overview. Int Rev Appl Eng Res 4(2):2248–9967
3. Kumar S, Sharma V, Panwar RS, Pandey OP (2012) Wear behavior of dual particle size (DPS) zircon sand reinforced aluminum alloy. Tribol Lett 47(2):231–251. https://doi.org/10.1007/s11249-012-9983-y
4. Maurya M, Kumar S, Bajpai V (2019) Assessment of the mechanical properties of aluminium metal matrix composite: A review. J Reinf Plast Compos 38(6):267–298. https://doi.org/10.1177/0731684418816379
5. Tjong SC (2013) Processing and deformation characteristics of metals reinforced with ceramic nanoparticles. Noncrysalline Materials: Their Synthesis-Structure-Property Relationships and Applications: 269–304
6. Rino JJ, Chandramohan D, Jebin VD (2012) Research review on corrosion behaviour of metal matrix composites. [Online]. Available: http://www.journalakra.com
7. Radhika N, Raghu R (2019) Abrasive wear behavior of monolithic alloy, homogeneous and functionally graded aluminum (LM25/AlN and LM25/SiO2) composites. Part Sci Technol 37(1):10–20. https://doi.org/10.1080/02726351.2016.1199074
8. Kumar GBV, Pramod R, Sekhar CG, Kumar GP, Bhanumurthy T (2019) Investigation of physical, mechanical and tribological properties of Al6061–ZrO2 nano-composites. Heliyon. 5:11. https://doi.org/10.1016/j.heliyon.2019.e02858
9. Singla M, Dwivedi DD, Singh L, Chawla V (2015) Development of aluminium based silicon carbide particulate metal matrix composite. J Miner Mater Charact Eng 08(06):455–467. https://doi.org/10.4236/jmmce.2015.63531
10. Canakci A, Arslan F (2012) Abrasive wear behaviour of B4C particle reinforced Al2024 MMCs. Int J Adv Manuf Technol 63:5–8. https://doi.org/10.1007/s00170-012-3931-8
11. Yilmaz O, Buytoz S (2001) Abrasive wear of Al2O3-reinforced aluminium-based MMCs. Compos Sci Technol 61(16):2381–2392. https://doi.org/10.1016/S0266-3538(01)00131-2
12. Bodunrin MO, Alaneme KK, Chown LH (2015) Aluminium matrix hybrid composites: A review of reinforcement philosophies; Mechanical, corrosion and tribological characteristics. J Mater Res Technol 4(4):434–445. https://doi.org/10.1016/j.jmrt.2015.05.003
13. Abdizadeh H, Baghchesara MA (2013) Investigation into the mechanical properties and fracture behavior of A356 aluminum alloy-based ZrO2-particle-reinforced metal-matrix composites. Mech Compos Mater 49(5):571–576. https://doi.org/10.1007/s11029-013-9373-z
14. Zuhailawati H, Samayamuthirian P, Mohd Haizu CH (2007) Fabrication of low cost of aluminium, matrix composite reinforced with silica sand. J Phys Sci 18(1):47–55. http://www.usm.my/jps/18-1-07/Article18-1-5.pdf
15. Arora R, Kumar S, Singh G, Pandey OP (2015) Effect of applied pressure on the tribological behaviour of dual particle size rutile reinforced LM13 alloy composite. In: Characterization of Minerals, Metals, and Materials, pp 755–762
16. Sharma SC (2001) The sliding wear behavior of A16061-garnet particulate composites. Wear 249(12):1036–1045. https://doi.org/10.1016/S0043-1648(01)00810-9
17. Ranganath G, Sharma SC, Krishna M (2001) Dry sliding wear of garnet reinforced zinc / aluminium metal matrix composites 251: 1408–1413
18. Kumar S, Panwar RS, Pandey OP (2012) Tribological characteristics of Aluminium tri-reinforced particles (Al- TRP) composites developed by liquid metallurgy route. Adv Mater Res 585:574–578. https://doi.org/10.4028/www.scientific.net/AMR.585.574
19. Vinod B, Ramanathan S, Ananthi V, Selvakumar N (2019) Fabrication and characterization of organic and inorganic reinforced A356 aluminium matrix hybrid composite by improved double-stir casting. Silicon 11(2):817–829. https://doi.org/10.1007/s12633-018-9881-5
20. Prasad SV, Asthana R (2004) Aluminium metal – matrix composites for automotive applications: tribological considerations. Tribol Lett 17(3):445–453
21. Sharma S, Nanda T, Pandey OP (2018) Effect of particle size on dry sliding wear behaviour of sillimanite reinforced aluminium matrix composites. Ceram Int 44(1):104–114. https://doi.org/10.1016/j.ceramint.2017.09.132
22. Singh M, Mondal DP, Jha AK, Das S, Yegneswaran AH (2001) Preparation and properties of cast aluminium alloy–sillimanite particle composite. Compos Part A Appl Sci Manuf 32(6):787–795
23. Kasirjar J, Krishna AR, Rao CS (2013) Fabrication and investigation on properties of Ilmenite (FeTiO3) based al-nanocomposite by stir casting process. Int J Bio-Sci Bio-Technol 5(4):193–199
24. Gupta A, Singhal V, Pandey OP (2018) Facile in-situ synthesis of NbB2 nanoparticles at low temperature. J Alloys Compd 736:306–313. https://doi.org/10.1016/j.jallcom.2017.10.257
25. Singh M, Mondal DP, Jha AK, Das S, Yegneswaran AH (2001) Preparation and properties of cast aluminium alloy ± sillimanite particle composite. Compos Part A Appl Sci Manuf 32:787–795
26. Gupta R, Sharma S, Nanda T, Pandey OP (2020) Wear studies of hybrid AMCs reinforced with naturally occurring sillimanite and rutile ceramic particles for brake-rotor applications. Ceram Int 46(10):16849–16859. https://doi.org/10.1016/j.ceramint.2020.03.262
27. Kaushik NC, Rao RN (2016) Tribology International Effect of applied load and grit size on wear coefficients of Al 6082 – SiC –Gr hybrid composites under two body abrasion. Tribology Int 103: 298–308. https://doi.org/10.1016/j.triboint.2016.07.018
28. Tiagi R (2005) Synthesis and tribological characterization of in situ cast Al-TiC composites. Wear 259(1):63–634. https://doi.org/10.1016/j.triboint.2005.01.051
29. Das S, Prasad SV, Ramachandran TR (1989) Microstructure and wear of (Al-Si alloy)-graphite composites. Wear 133:173–187
30. Sarada BN, Murthy PLS, Ugrasen G, Zhang H, Teng J (2018) Wear characteristics of hybrid aluminium metal matrix composites produced by stir casting technique. Mater Today Proc 2(4–5):2878–2885. https://doi.org/10.1016/j.matpr.2017.05.075
31. Zeng X, Yu J, Fu D, Zhang H, Teng J (2018) Wear characteristics of hybrid aluminium-matrix composites reinforced with well-dispersed reduced graphene oxide nanosheets and silicon carbide particulates. Vacuum 155(June):364–375. https://doi.org/10.1016/j.vacuum.2018.06.033
32. Baker H (1992) Alloy Phase Diagrams, ASM International, vol 3
33. Guđić S, Smoljko I, Klikić M (2010) The effect of small addition of tin and indium on the corrosion behavior of aluminum in chloride solution. J Alloys Compd 505(1):54–63. https://doi.org/10.1016/j.jallcom.2010.06.055
34. Kaur K, Pandey OP (2013) High temperature sliding wear of spray-formed solid-lubricated aluminium matrix composites. J Mater Eng Perform 22(10):3101–3110. https://doi.org/10.1007/s11665-013-0594-z
35. Sharma S, Nanda T, Pandey OP (2018) Effect of dual particle size (DPS) on dry sliding wear behaviour of LM30/sillimanite composites. Tribol Int 123:142–154. https://doi.org/10.1016/j.triboint.2017.12.031
36. Rajesh GL, Auradi V, Kori SA (2016) Mechanical behaviour and dry sliding wear properties of ceramic boron carbide particulate reinforced Al6061 matrix composites. Trans Indian Ceram Soc 75(2):112–119. https://doi.org/10.1007/s007150X.2016.1168318
37. Karun AS, Hari S, Ebbota WS, Rajan TPD, Pillai UTS, Bai BC (2017) Design and processing of bimetallic aluminum alloys by sequential casting technique. Metall Mater Trans A Phys Metall Mater Sci 48(1):279–293. https://doi.org/10.1007/s11661-016-3824-9
38. Sharma S et al (2018) Effect of dual particle size (DPS) on dry sliding wear behaviour of LM30/sillimanite composites. Tribol Ind 123:142–154. https://doi.org/10.1016/j.triboind.2018.10.004
39. Daoud A, El-khair MTA, Abou El-khair MT (2010) Wear and friction behavior of sand cast brake rotor made of A359-20 vol% SiC particle composites sliding against automobile friction material. Tribol Int 43(3):544–553. https://doi.org/10.1016/j.triboind.2009.09.003
40. Shorowordi KM, Haseeb ASMA, Celis JP (2006) Tribo-surface characteristics of Al-B4C and Al-SiC composites worn under different contact pressures. Wear 261(5-6):634–641. https://doi.org/10.1016/j.wear.2006.01.023
41. Sharma S, Nanda T, Pandey OP (2019) Investigation of T4 and T6 heat treatment on the wear properties of sillimanite reinforced LM30 aluminium alloy composites. Wear 426:27–36
42. Blau PJ, Jolly BC, Qu J, Peter WH, Blue CA (2007) Tribological investigation of titanium-based materials for brakes. Wear 263(7–12 SPEC. ISS):1202–1211. https://doi.org/10.1016/j.wear.2006.12.015
43. Sharma V, Kumar S, Panwar RS, Pandey OP (2012) Microstructural and wear behavior of dual reinforced particle (DRP) aluminium alloy composite. J Mater Sci 47(18):6633–6646. https://doi.org/10.1007/s10853-012-6599-4
44. Vijeesh V, Prabhu KN (2014) Review of microstructure evolution in hypereutectic Al-Si alloys and its effect on wear properties. Trans Indian Inst Met 67(1):1–18. https://doi.org/10.1007/s12666-013-0327-x
45. Jorstad J, Apelian D (2009) Hypereutectic al-si alloys: Practical casting considerations. Int J Met 3(3):13–36. https://doi.org/10.1007/BF03355450
46. Abis S, Barucca G, Mengucci P (1994) Electron microscopy characterization of AlSn metal-metal matrix composites. J Alloys Compd 215:1–2. https://doi.org/10.1016/0925-8388(94)90859-1
47. Sofyan BT et al. (2005) Effects of Sn content on the characteristics of 319 aluminium alloy. Proc Australas Conf Exhib - Alum Cast House Technol 2005:161–168
48. Saheb DA (2011) Aluminium silicon carbide and aluminium graphite particulate composites. J Eng Appl Sci 6(10):41–46
49. Sharma P, Sharma S, Khanduja D, (2015) Journal of Asian Ceramic Societies A study on microstructure of aluminium matrix composites. Integr Med Res 3(3):240–244. https://doi.org/10.1016/j.jascer.2015.04.001
50. Omrani E, Moghadam AD, Menezes PL, Rohatgi PK (2016) Influence of graphite reinforcement on the tribological properties of self-lubricating aluminum matrix composites for green tribology, sustainability, and energy efficiency.— A review. Int J Adv Manuf Technol 83:1–4. https://doi.org/10.1007/s00170-015-7528-x
51. Kumar S, Panwar RS, Pandey OP (2013) Effect of dual reinforced ceramic particles on high temperature tribological properties of aluminium composites. Ceram Int 39(6):6333–6342. https://doi.org/10.1016/j.ceramint.2013.01.059
52. Priyadarsini D, Sharma RK (2016) Porosity in aluminium matrix composites: cause, effect and defence. Mater Sci Ind J 14:119–129
53. Venkatesh VSS, Deoghare AB (2021) Microstructural characterization and mechanical behaviour of SiC and Kaoline reinforced
aluminium metal matrix composites fabricated through powder metallurgy technique. Silicon. https://doi.org/10.1007/s12633-021-01154-9

54. Seah KHW, Sharma Sc, Girish Bm (1995) Mechanical particulate properties composites of cast ZA -27 / graphite particulate Composites. Mater Des 16(5):1–5

55. Lim SC (2002) The relevance of wear-mechanism maps to mild-oxidational wear. Tribol Int 35(11):717–723. https://doi.org/10.1016/S0301-679X(02)00033-6

56. Singh J, Chauhan AC (2015) Overview of wear performance of aluminium matrix composites reinforced with ceramic materials under the influence of controllable variables. Ceram Int 42(1):56–81. https://doi.org/10.1016/j.ceramint.2015.06.008

57. Panwar RS, Kumar S, Pandey R, Pandey OP, Singh R, Suresh P (2014) Study of non-lubricated wear of the Al-Si alloy composite reinforced with different ratios of coarse and fine size zircon sand particles at different ambient temperatures. Tribol Lett 55(1):83–92. https://doi.org/10.1007/s11249-014-0335-y

58. Rajmohan T, Palanikumar K, Ranganathan S (2013) Evaluation of mechanical and wear properties of hybrid aluminium matrix composites. Trans Nonferrous Met Soc China (English Ed 23(9):2509–2517. https://doi.org/10.1016/S1003-6326(13)62762-4

59. Sivaramakrishnan CS, Mahanti RK, Kumar R (1984) The dispersion of lead and graphite in aluminium alloys for bearing applications. Wear 96(2):121–134. https://doi.org/10.1016/0043-1648(84)90089-9

60. Torabian H, Pathak JP, Tiwari SN (1994) On wear characteristics of leaded aluminium-silicon alloys. Wear 177(1):47–54. https://doi.org/10.1016/0043-1648(94)90116-3

61. Mahdavi S, Akhlaghi F (2011) Effect of the graphite content on the tribological behavior of Al/Gr and Al/30SiC/Gr composites processed by in situ powder metallurgy (IPM) method. Tribol Lett 44(1):1–12. https://doi.org/10.1007/s11249-011-9818-2

62. Baradeswaran A, Elaya Perumal A (2014) Study on mechanical and wear properties of Al 7075/Al2O3/graphite hybrid composites. Compos Part B Eng 56:464–471. https://doi.org/10.1016/j.compositesb.2013.08.013

63. Surappa MK (2003) Aluminium matrix composites: Challenges and opportunities. Sadhana - Acad Proc Eng Sci 28(1–2):319–334. https://doi.org/10.1007/BF02717141

64. Srivastava S, Mohan S, Srivastava Y, Shukla AJ (2012) Study of the wear and friction behavior of immiscible as cast-Al- Sn / Graphite composite. Int J Mod Eng Res 2(2):25–42

65. Kaur K, Pandey OP (2010) Microstructural characteristics of spray formed zircon sand reinforced LM13 composite. J Alloys Compd 503(2):410–415. https://doi.org/10.1016/j.jalcom.2010.04.249

66. Natarajan N, Vijayarangan S, Rajendran I (2006) Wear behaviour of A356/25SiCp aluminium matrix composites sliding against automobile friction material. Wear 261:7–8. https://doi.org/10.1016/j.wear.2006.01.011

67. Pradhan S, Ghosh S, Barman TK, Sahoo P (2017) Tribological behavior of Al-SiC metal matrix composite under dry, aqueous and alkaline medium. Silicon 9(6):923–931. https://doi.org/10.1007/s12633-016-9504-y

68. Basavarajappa S, Chandramohan G, Mukund K, Ashwin M, Prabu M (2006) Dry sliding wear behavior of Al 2219/SiCp-Gr hybrid metal matrix composites. J Mater Eng Perform15(6):668–674. https://doi.org/10.1361/105994906X150803

69. Mahmoud TS (2008) Tribological behaviour of A390/Grp metal-matrix composites fabricated using a combination of rheocasting and squeeze casting techniques. Proc Inst Mech Eng Part C J Mech Eng Sci 222(2):257–265. https://doi.org/10.1243/09544062JMES468

70. Doddamani S, Kaleemulla M, Begum Y, KJ A, Anand KJ (2017) An investigation on wear behavior of graphite reinforced aluminium metal matrix composites. J Res. Sci. Technol. Eng. Manag: 1–6

71. Manikanand R, Arjunan TV, Akhil AR (2020) Studies on micro structural characteristics, mechanical and tribological behaviours of boron carbide and cow dung ash reinforced aluminium (Al 7075) hybrid metal matrix composite. Compos Part B Eng183(October 2019). https://doi.org/10.1016/j.compositesb.2019.107668

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.