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REVIEW ARTICLE

# Fabrication characteristics and tribological behavior of Al/SiC/Gr hybrid aluminum matrix composites: A review

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**Abstract:** Improvement in surface properties and retainment of bulk properties are essential requirements for the design of components for wear resistance applications. This paper summarizes various features of Al/SiC/Gr hybrid composites that can be employed in different tribological applications. The study has revealed that the processing route plays a significant role in obtaining a homogeneous structure of these composites. In powder metallurgy, the selection of sizes of the matrix and reinforcement powders is crucial, whereas the wettability between the reinforcement particles and molten alloy is a major challenge in liquid metallurgy. The incorporation of SiC particles increases the mechanical strength and wear performance of Al composites. However, ejection of these particles can reduce the wear performance of Al composites under severe conditions. The addition of Gr particles helps in the formation of a thick and extensive tribolayer on the wear surface. This layer reduces direct contact between the rubbing surfaces, thereby decreasing the wear rate under certain conditions. Morphological analysis of worn surfaces has confirmed that the hybrid composites exhibit superior wear properties than the pure Al alloy and the ceramic-reinforced composite. However, increase in the Gr content beyond a limiting value can deteriorate the tribological properties of these composites. Therefore, true optimization of a tribosystem (of the hybrid composite and counterface) can be achieved by selecting appropriate reinforcement contents.

**Keywords:** metal matrix composites (MMCs); sliding wear; solid lubricant particles; scanning electron microscopy (SEM); casting/sintering

## 1 Introduction

Aluminium (Al) and its alloys have potential applications in various automotive components because of the excellent combination of properties, such as high strength to weight ratio, good thermal conductivity, and high corrosion resistance [1, 2]. However, one of the major drawbacks of these materials is their low wear resistance. This limitation is due to the fact that Al alloys undergo extensive plastic deformation and material removal under sliding wear conditions [3–7]. Furthermore, protective layers are not formed on the wear surface of these alloys under severe conditions, and direct metal-to-metal contact occurs between the sliding surfaces. Thus, the wear rate of Al alloys increases, leading to increased plastic deformation of the wear surface. Previous investigations have reported that the tribological performance of Al alloys can be improved by adding ceramic reinforcements [8–10]. Moreover, the wear resistance of the composites increases with increasing reinforcement contents of ceramics. Therefore, metal matrix composites, especially Al composites, have been considered as exceptional materials for the design of components with enhanced wear resistance.

The wear resistance of a material depends on the interaction of asperities of the sliding surfaces. In Al alloys, wear resistance is partly due to the plastic deformation of soft asperities at high temperatures [11]. However, Al composites consist of hard and

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brittle reinforcements protruding over the surface (acting as asperities). These asperities interact with the counterface and provide more strength to the composites during the initial run-in-period [12–15]. Increased strength results in low deformation of asperities, which leads to the abrasion of the wear surface [16]. As the hard reinforcements (asperities) are removed under severe sliding conditions, the wear resistance of these composites is also reduced. Under low load conditions, the removal of the wear particles/debris from the surface occurs because of abrasive wear [17]. Abrasive wear is initiated at some critical value of operating load, and the reinforced composites exhibit superior wear performance than the unreinforced component under these conditions.

However, adhesive wear is related to material transfer from one surface to another because of localized bonding of the surfaces, which occurs comparatively at high load. The frictional contact increases the operating temperature and results in softening of the wear surface. Furthermore, the particles removed from one surface are attached to the other surface (either permanently or temporarily). The wear of Al composites occurs because of a combination of abrasion and adhesion under these sliding conditions, and the reinforced part exhibits wear performance similar to the unreinforced part. Therefore, Al composites are not recommended for use in wear resistance applications under these conditions [8, 18, 19].

The addition of hard ceramic reinforcements such as SiC, $Al_2O_3$, $B_4C$, $TiB_2$, and $MoS_2$ to the Al matrix may adversely influence the wear properties of the resultant composites [20–24]. The major limitation of ceramic reinforcements is that they increase the hardness of the composites. Moreover, the wear resistance of the tribosystem is reduced because of an increase in the counterface wear [25–27]. However, the presence of ceramic reinforcements in the Al matrix is essential for maintaining the strength and stiffness of the composites. Therefore, the positive influence of ceramic reinforcements must be maintained without compromising the strength and wear properties of Al composites.

The Al/SiC composites reinforced with graphite (Gr) particles have shown significant potential in wear resistance applications [28–33]. Previous studies have found that Gr particles smear at the interface and reduce the friction coefficient during sliding wear of Al/SiC/Gr hybrid composites. Additionally, frictional heat produced during the sliding contact is also reduced. Therefore, a solid lubrication film is formed on the surface due to the addition of carbon improving the wear resistance of carbon-based hybrid composites. This film reduces the frictional force between the composite and counterface material. Moreover, the application of self-lubricating Al composites to different applications will reduce the use of toxic and external lubricants, thereby achieving environmental sustainability and energy efficiency under normal conditions [34]. At high values of normal load and sliding speed, the localized melt and slip and the large plastic deformations (caused by the high frictional heat) are the dominant factors contributing to the removal of surface film from the wear surface. The removal of this surface film will increase the wear rate of hybrid Al composites under these conditions [35–37]. Therefore, the conditions that will result in superior wear properties of these hybrid composites should be identified.

Although the presence of solid lubrication can lead to low wear rates, but the selection of Gr contents is a key influencing parameter as it can adversely affect the strength of composites [30, 31, 34]. Therefore, the influence of Gr contents on the tribological properties of Al/SiC/Gr composites must be analyzed. The production method is also a significant factor that influences the porosity levels, distribution of particles, and matrix/reinforcement interfacial properties [38]. The present article presents various aspects regarding fabrication and characteristics of Al/SiC/Gr hybrid composites. The influence of Gr contents on the wear properties (e.g., wear rate, friction coefficient, and morphology of wear surface) of Al/SiC/Gr hybrid composites has been investigated. The performance of the tribosystem (consisting of Al composite and the counterface material) is also reviewed and discussed.

The general techniques used for the fabrication of Al composites and their related characteristics are presented in section 2. Section 3 presents the fabrication characteristics of Al/SiC/Gr composites, such as microstructural features, density, and hardness. The wear characteristics, such as wear loss, friction coefficient, and surface and subsurface behavior, are reviewed in section 4. Section 5 elaborates the characteristics of the worn surfaces of these composites. Finally, section 6 concludes the study and provides related comments regarding the review of various aspects of these composites.

## 2 Fabrication techniques

The major challenge associated with Al composites is the uniform distribution of reinforcement particles within the matrix alloy. This issue requires the careful identification of processing techniques and operating parameters. Two generic techniques can be used for composite production, i.e., powder metallurgy and molten metal method [38–40]. Both of these techniques have their own merits and limitations depending on the operating parameters.

### 2.1 Powder metallurgy

In powder metallurgy, the Al alloy powder is blended with reinforcement particles to obtain a homogeneous mixture. The sizes of the alloy and reinforcement powders must be selected carefully to avoid agglomeration after the blending process [38, 39]. The appropriate size ratio of alloy and reinforcement particles will help to obtain uniform distribution in the final product [40, 41]. The appropriate size ratio for the Al/SiC composite has been noted to be of the order of 7:10. Moreover, the hard reinforcement particles are prone to fracture. Particle fracture during blending depends on the aspect ratio and flaw density. The size of Al alloy and reinforcement powder should be in the range of 20–40 and 3–20 μm, respectively, with aspect ratios less than 5:1 [39].

The first step of this method involves blending of powder mixtures, which ensures the initial homogeneity of the mixtures [40]. The mixture is then compressed in an isostatic process at room temperature. Thereafter, the water molecules must be removed from the mixture to avoid porosity during consolidation. During the final consolidation phase, vacuum hot pressing method can be used to obtain densified composites (up to 95%). This process can be carried either below solidus point of the alloy or in liquid-solid state [38]. In liquid phase sintering, the chances of reaction between the reinforcement and molten alloy are high. Liquid phase sintering can also degrade the microstructure of the rapidly solidified powder particles to form coarse intermetallic phases in the melted regions. Solid-state compaction can overcome these limitations to a certain extent. The final product of powder metallurgy can be obtained by extrusion with a minimum ratio of 20:1 [39]. To obtain good interfacial bonding between the particles, a high extrusion ratio is required. Such a ratio will also help in achieving a uniform distribution of reinforcement particles within the matrix alloy. The plastic flow of the material will avoid particle clustering because of the dispersion of particles. The values of the extrusion ratio and temperature should be selected carefully to avoid degradation of material properties. The details of the fabrication process used in powder metallurgy are presented in Fig. 1, and various steps have been shown in a sequential pattern [38, 39].

Powder metallurgy has a number of benefits [38–42]. First, any type of alloy and reinforcement can be used for the fabrication of composites. This process is performed at a low temperature, thereby minimizing the reaction between two components of Al composites. Second, these composites have higher strength at high temperatures than conventional alloys. Third, composites with high reinforcement contents can be fabricated by this method, which will increase the elastic modulus while reducing the coefficient of thermal expansion. However, powder metallurgy is quite complex and expensive [39]. Moreover, it involves handling of a large quantity of reactive (alloy and

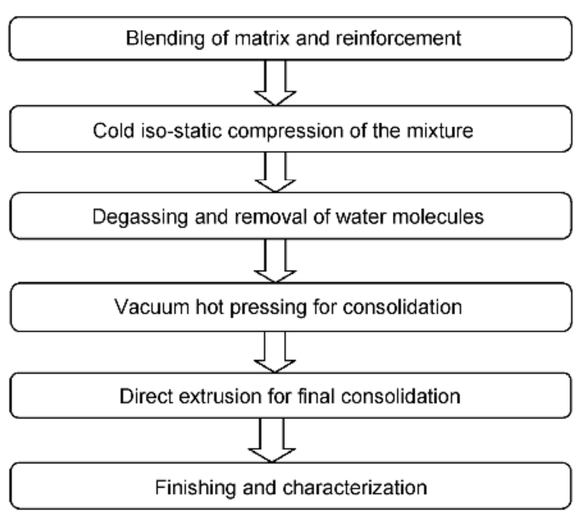


**Fig. 1** Powder metallurgy route for developing Al composites.

reinforcement) powders, which requires a long mixing time for uniform distribution of particles [43, 44].

### 2.2 Liquid metallurgy

In these methods of composite fabrication, the thermodynamics of incorporating reinforcement particles into the molten alloy should be considered [38, 39, 45, 46]. The contact angle between the reinforcing particles and the melt must be less than 90°. However, the contact angle is influenced by a number of parameters such as interfacial bonding and temperature. Thus, the wettability of reinforcing particles in the melt is a major challenge in most casting methods. The vortex method developed by Surappa and Rohatgi [47] is quite helpful to achieve this objective. In this process, a vortex is created within the molten alloy by a mechanical impeller. Thereafter, the ceramic particles are introduced in the rotating melt. The addition of a small amount of surface-active elements such as magnesium helps in achieving the required wettability of reinforcing ceramic particles. Initially, the application of the process was limited to coarse particles (>50 μm) and low volume fractions (<10%) [39]. However, the method can be used for developing composites up to a volume fraction of 25% [48].

The molten metal vortex method is a highly attractive processing route because it is very cheap and highly productive [38, 39]. The major problems with this method are the reactivity between the alloy and reinforcement and the segregation of reinforcing particles. Therefore, the volume fraction for reinforcement particles should be selected carefully to achieve uniform distribution of particles within the matrix. The detailed process followed in the vortex method is shown in Fig. 2. The alloy matrix is melted initially in a crucible under a cover by nitrogen or argon gas. The alloy is heated by an electrical resistance furnace above superheating temperature. During this process, the molten alloy is rotated by a mechanical stirrer to create a vortex. The depth of the impeller immersed in the melt is adjusted to two-thirds of the total depth of the melt in the crucible. The speed of the stirrer can also be adjusted up to a limiting value.

During stirring, the addition of a suitable quantity of magnesium can be helpful to increase the wettability

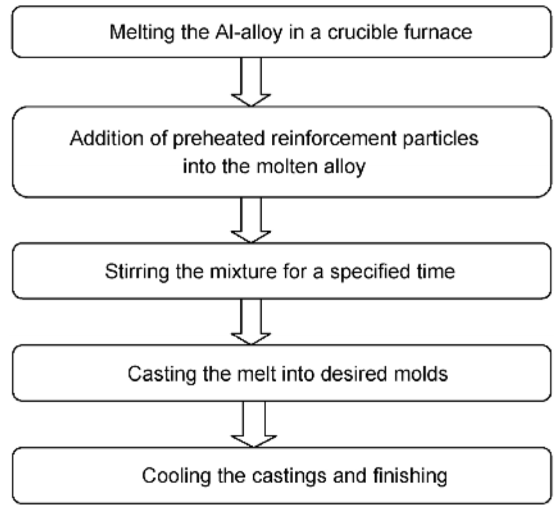


**Fig. 2** Vortex matrix method used for developing Al composites.

of reinforcement particles and reduce surface tension. Magnesium reacts with oxygen present on the surface of dispersoid and reduce the agglomeration of particles in the melt. Finally, the molten alloy is poured into molds of the desired shape. After the casting process, the composite can be subjected to various heat treatment processes to improve surface properties. Notably, the poor wettability of reinforcing particles in the matrix alloy and the difference in densities of the matrix and alloy can result in non-uniform distribution of reinforcing particles [38–40]. The segregation of particles caused by the pushing effect during solidification and porosity at the matrix/reinforcement phase can deteriorate material properties.

### 2.3 *In-situ* powder metallurgy (IPM)

To overcome the problems related to conventional processing techniques (power metallurgy and vortex method), a new technique known as IPM is applied [40, 41]. This method is an integrated process that involves the combination of vortex and powder metallurgy processes. First, the matrix alloy is melted in a crucible furnace at a suitable temperature. Subsequently, reinforcement particles are added to the molten alloy and the mixture is stirred for a specified time. The temperature during the stirring operation is also maintained constant. This process results in a mixture of Al droplets and the reinforcement particles caused by the non-wetting nature of reinforcement particles. The mixture obtained in this way is cooled in air for final consolidation, and the resultant product is free from any pores. Moreover, the process is free of any limitation of both powder metallurgy and vortex techniques.

## 3 Fabrication characteristics

### 3.1 Microstructural features

The overall purpose of the fabrication of Al composites is to obtain a uniform distribution of reinforcing particles within the matrix alloy [38, 39]. This type of distribution will help to obtain an isotropic set of properties for the developed composites. Scanning electron microscopy (SEM) can be used for the high magnification analysis of all the materials, whereas X-ray diffraction (XRD) is useful for analyzing the lattice structure of the composite. Mahdavi and Akhlaghi [49] developed Al6061/SiC/Gr composites using IPM. The composite specimens were subjected to heat treatment processes, and the microstructural properties were investigated. Figure 3 shows the micrographs of Al6061/9%Gr/20%SiC composites. The reinforcement (SiC and Gr) particles were uniformly distributed within the matrix alloy, thereby showing that IPM could be used for the production of Al composites with improved properties and reduced particle clusters. The dark regions shown in Fig. 3 represent Gr particles or the pores formed upon polishing the surface. The Gr particles are solid lubricant particles that are abraded easily during polishing of the hybrid composites and reduce the friction coefficient [50–52].

In another study conducted by Ravinderan et al. [52], the influence of increased Gr contents on the microstructural characteristics of Al2024/SiC/Gr hybrid composites was studied. Metallographic specimens were fabricated by using powder metallurgy. The Gr contents were added in the hybrid composites to keep the SiC contents constant. The optical micrographs indicated a flake-like structure for the Gr particles in the composites, whereas the SiC particles appeared like cubes (Fig. 4). The SiC and Gr particles were uniformly dispersed within the Al2024 matrix. The

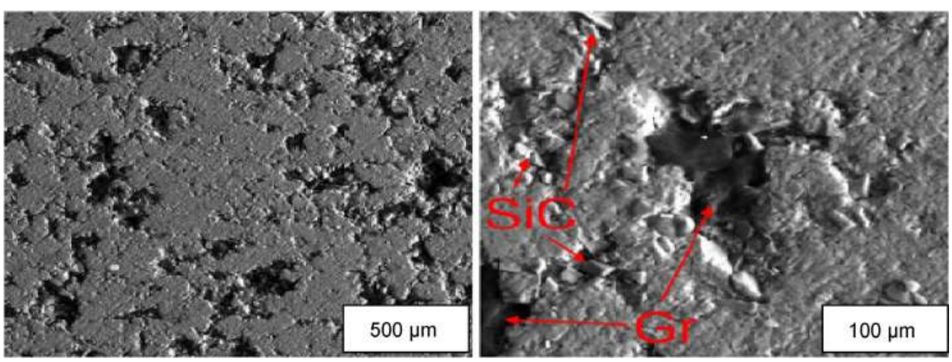


**Fig. 3** Typical SEM micrographs of polished surfaces of Al6061/9%Gr/20%SiC composites. Reproduced with permission from Ref. [49]. Copyright Springer, 2010.

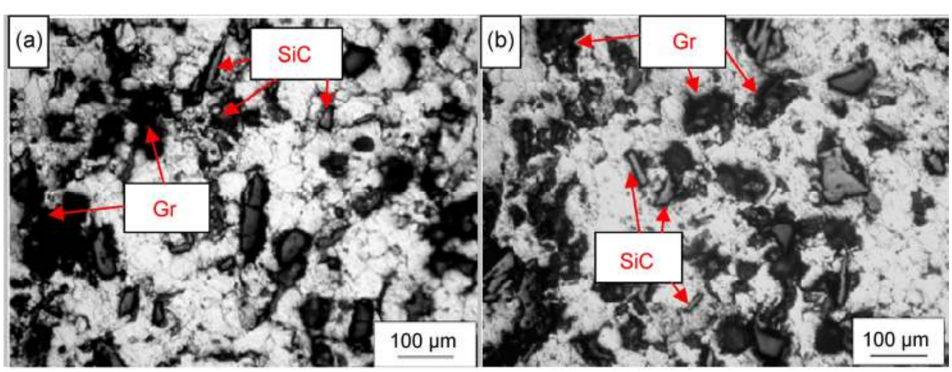


**Fig. 4** Optical micrographs of fabricated composites (a) Al2024/5%SiC/5%Gr and (b) Al2024/5%SiC/10%Gr composites. Reproduced with permission from Ref. [52]. Copyright Elsevier, 2012.

micrographs also indicated perfect bonding between different components of Al composites and absence of cracks.

Ravindran et al. [50] studied different patterns of peaks of Al-based hybrid composites fabricated by powder metallurgy (Fig. 5). The different samples were fabricated containing different volume fractions of SiC and Gr particles. In the hybrid composite, some additional peaks were present in the XRD pattern (carbon peaks). These results indicated the presence of aluminum in the large peaks, and silicon carbide and graphite particles in the minor peaks (in hybrid composites). A number of studies have been carried out for developing Al composites reinforced with SiC and Gr particles, and a homogeneous structure of Al/SiC/Gr composites was obtained [49–53]. A gradual (marginal) shift of Al peaks to high angles with an increase in the wt.% of the Gr particles was also evident. Figure 5 confirms the absence of an oxygen reaction in the samples during the sintering process.

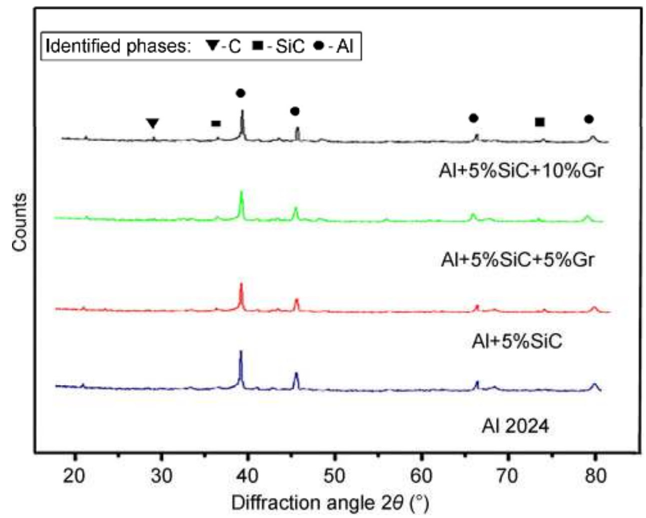


**Fig. 5** XRD patterns for the developed Al/SiC/Gr composites with different compositions. Reproduced with permission from Ref. [50]. Copyright Elsevier, 2013.

### 3.2 Density and hardness

According to Mahdavi and Akhlaghi [51], the porosity of Al-based hybrid composites containing SiC and Gr decreases with an increase in Gr contents. The authors fabricated these composites by powder processing. In general, the hybrid composites are more porous compared with the Al/Gr composites because of the presence of hard SiC particle, which leads to inter-particle spacing in these composites during pressing and increased porosity. Graphite is a solid lubricant that facilitates the movement and rearrangement of reinforcement particles in the matrix alloy. Therefore, increasing Gr contents in the hybrid contents is considered favorable for achieving minimum porosity [52].

The hardness of the hybrid composites has also been found to decrease with increasing Gr contents [53, 54]. Notably, the increase in Gr contents results in decreased porosity levels in the hybrid composites; therefore, the strength and hardness of these composites should increase. However, the decrease in hardness may be attributed to the presence of softer reinforcement (Gr) particles. The presence of a hard ceramic phase (SiC) has a significant contribution in the actual hardness value of the composite [55, 56]. Both of the reinforcing components (SiC and Gr) exert opposing influences on the hardness of the composite. The variation in the density and hardness of Al composites is shown in Fig. 6. The decrease in the density of hybrid composites can be attributed to the density of Gr particles, which is lower than that of the Al matrix [49]. The reduction in hardness of hybrid composites can be attributed to various factors, such as low hardness of Gr particles, uniform distribution of Gr particles in the composites, and decreased density of Al composites (which contributes to decreased hardness).

## 4 Wear behavior

The wear tests for Al composites can be carried under sliding conditions using a pin-on-disc type testing machine according to the ASTM standard. In general, the tests are carried at room temperature without any lubrication. Initially, the samples (pin) are machined and polished to ensure flat contact with the rotating disc (counterface material). During the tests, the sample pins are pressed against the rotating disc by applying adequate loads (Fig. 7). The counterface material is made of steel with suitable hardness (with HRC of the order of 60–70). The wear tests are performed under the specified values of operating parameters such as applied load, sliding velocity, sliding distance, and reinforcement contents. The friction coefficient and wear rate are considered the main response

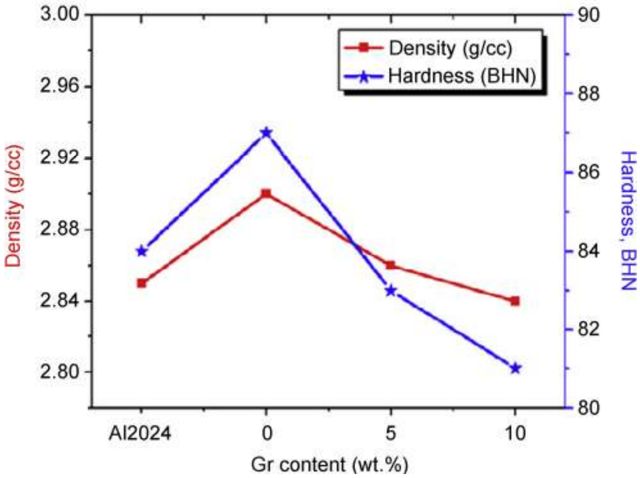


**Fig. 6** Variation in density and hardness of Al/SiC/Gr composites with Gr contents. Reproduced with permission from Ref. [50]. Copyright Elsevier, 2013.

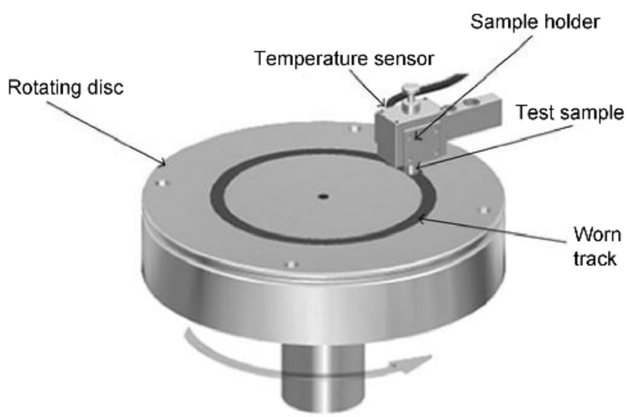


**Fig. 7** Schematic of pin-on-disc test configuration used for wear tests of materials.

functions for evaluating the wear performance of the composites. The relative motion between the sliding surfaces results in deterioration of surface characteristics (of one or both of the sliding surfaces), but deterioration can be reduced to a certain extent using a solid lubricant. Therefore, the surface characteristics (friction and wear) of worn surfaces of the specimen of Al/SiC/Gr hybrid composites (containing ceramics and solid lubricants) are discussed in the succeeding sections. A number of studies have been conducted to determine the relative performance of Al alloys and hybrid composites. These studies are reviewed in the succeeding sections.

### 4.1 Wear rate

Wear is the progressive loss of the material from the sliding surfaces caused by mechanical and chemical processes. Wear can be measured in the form of volume or mass loss during the sliding process. The mass loss of material samples can be determined by weighing the samples before and after the wear tests using an electronic balance with adequate accuracy. In Al/SiC/Gr hybrid composites, the SiC particles act as load carrying elements and increase the strength and hardness of the composite [55, 56]. These enhanced characteristics increase the resistance of the composite to plastic deformation at the subsurface and increase its wear resistance. Therefore, minimal wear debris are formed on the wear surface of the Al/SiC/Gr composite. Moreover, the SiC particles are protruded over the wear surface and aid in the formation of a stable tribolayer on the composite surface. The wear rate of hybrid composites decreases with increasing Gr contents up to a limit after which it starts increasing (Fig. 8). The decrease in wear rate of hybrid composites (up to a limited reinforcement addition) is due to the presence of both of the reinforcing components, which assist in the formation of a stable surface film on the wear surface [57, 58]. The ceramic phase improves the hardness and mechanical properties of the resultant composite, whereas Gr particles help in the formation of a stable tribolayer.

The thickness and area of the wear surface covered by the surface film increase by the addition of Gr particles; thus, wear loss of the surface is reduced. Figure 8 clearly indicates that the wear resistance of Al/SiC/Gr composites is superior to that of the pure alloy, Al/SiC, and the Al/Gr composite. The wear loss

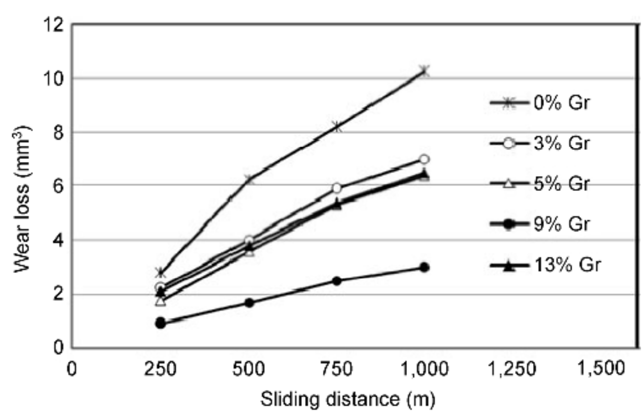


**Fig. 8** Wear loss of Al/30SiC/Gr composites with sliding distance. Reproduced with permission from Ref. [51]. Copyright Springer, 2011.

of hybrid composites is about 15 and 30 times lower than that of the Al alloy and Al/SiC composite. However, the reinforcement contents (of SiC and Gr particles) may be optimized in the Al/SiC/Gr hybrid composites to obtain a significant improvement in wear properties [59–61]. Figure 8 shows that the wear rate of the Al/30SiC/Gr composites is minimum for 9 wt.% Gr particles. Two types of factors are responsible for this type of behavior in Al composites. First, the addition of Gr particles leads to decreased hardness, fracture toughness, and ductility of the hybrid composites [53, 54]. Moreover, it may lead to an increase in void formation and crack propagation under sliding load because of particle agglomeration and weak Al/Gr and SiC/Gr bonding [62, 63]. These effects decrease the wear resistance of the resultant Al composites. Gr addition may lead to decreased porosity level, which leads to increased lubrication of the wear surface. Therefore, the wear resistance should improve with Gr addition. Both factors must be optimized for improving the wear performance of Al-based hybrid composites. An optimum value for graphite reinforcement in Al/SiC/Gr composites can lead to superior wear behavior of these composites [49–51, 62, 63].

### 4.2 Friction coefficient

Friction represents the resistance of Al composites to relative motion of the sliding surfaces against each other. During the sliding motion of solid surfaces, heat is produced and results in increased temperature. The friction coefficient is a quantitative parameter that can be used to measure the frictional behavior of materials. It is the ratio of the frictional force between two surfaces and the normal force pressing them together. Friction in the rubbing surfaces results from the adhesion and plowing of the wear surfaces [50, 52]. The friction coefficient generally decreases with increasing Gr contents in the Al/SiC/Gr composites. This trend may be attributed to the increase in the thickness of the surface film with the increase in the reinforcement contents of lubricating particles [64]. Notably, the addition of a small amount of Gr contents in hybrid composites results in a major decrease in the friction coefficient between the rubbing surfaces. This reduction may be due to the change in the wear mechanism from adhesive wear to delaminating wear. Moreover, the surface area of these films also increases over the composite surface with increasing Gr contents. As such, metal-to-metal contact between the rubbing surfaces and adhesion between the surfaces decrease. The addition of hard SiC particles results in decreased real contact area between the rubbing surfaces caused by the protrusion of SiC particles over the wear surface [50, 52, 64]. This phenomenon favors the formation of a stable and protective surface layer on the wear surface and reduces the wear rate. Given all these reasons, the friction coefficient of hybrid composites is much lower than that of ceramic-reinforced composites.

Ravindran et al. [64] have found that the friction coefficient of Al/SiC/Gr composites increases with increasing sliding distance. This condition can be attributed to the increase in surface temperature caused by increasing contact between the rubbing surfaces [65, 66]. Figure 9 shows that the friction coefficient of Al/SiC/Gr composites is lower than those of Al/SiC composites. The hybrid composite reinforced with 5% Gr content possesses the highest friction coefficient than all other specimens (Al/5%SiC and Al/5%SiC/10%Gr) under all operating conditions. Gr is a solid lubricant that smears the contact surfaces. This ability reduces metal-to-metal contact between the rubbing surfaces and helps in the formation of a surface layer at the interface [67–69]. Therefore, Al/SiC/Gr composites exhibit lower friction coefficient and lower wear rate

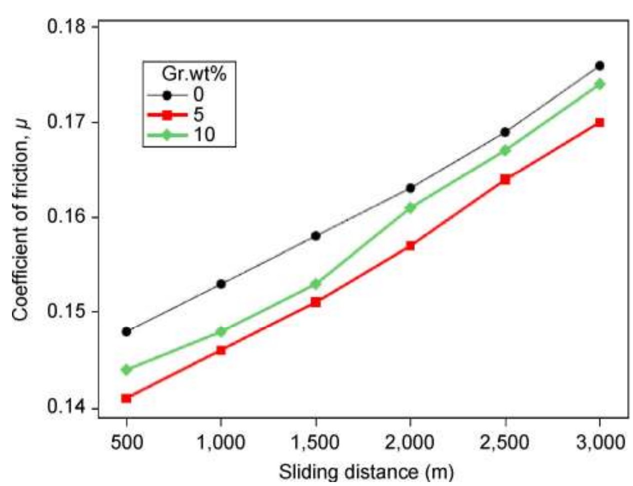


**Fig. 9** Variation in coefficient of Al composites at different Gr reinforcement contents at applied load of 10 kN. Reproduced with permission from Ref. [64]. Copyright Elsevier, 2013.

compared with Al/SiC composites. Figure 9 also presents the variation in friction coefficient of Al composites under different operating conditions. The Al/5%SiC/5%Gr composite possesses the lowest friction coefficient because of better conditions for tribolayer formation. The Al/SiC composite possesses the highest friction coefficient under all tested conditions, whereas the hybrid Al/SiC/Gr composites exhibits the lowest friction coefficient. In this study, the 5% Gr content represents the optimum percentage for obtaining the minimum friction coefficient. An optimum Gr content has been suggested by various authors for developing composites with low friction coefficients [50–52].

### 4.3 Surface and subsurface behavior

Basavarajappa et al. [70] studied the changes in microhardness with the variation in distance from the wear surface of Al composites. The hybrid Al/SiC/Gr composites were fabricated by liquid metallurgy, and their wear behavior was studied under the influence of sliding velocity. The surface and subsurface deformation of Al composites results in a significant variation in the microstructural behavior, thereby influencing the wear behavior of the composites. To measure subsurface behavior, the variation in microhardness was investigated along the depth normal to the wear surface. The authors divided subsurface deformation into three zones, namely, Zones 1, 2, and 3, depending upon the distance from the wear surface (Fig. 10). Results revealed that the microhardness pattern changed with variations in the sliding distance.

In Al/SiC composites, the hardness of the subsurface increases with increasing sliding velocity (3–4.6 m/s) up to a depth of 80 μm. Thereafter, the variation in the microhardness of the subsurface zone disappears in Zone 3. The increased hardness of Zone 1 may be attributed to the higher oxidation of the transferred material at the interface and the presence of surface film on the wear surface [13, 71, 72]. The variation in hardness of the wear surface of the Al/SiC composite at a sliding speed of 4.6 m/s is presented in Fig. 10. The hardness of Zone 1 is higher than that of the two other zones and it decreases with the subsurface depth.

Plastic deformation of the wear surface of the Al/SiC composite continues in Zone 2 up to a depth of about 140 μm because of shear deformation of the subsurface

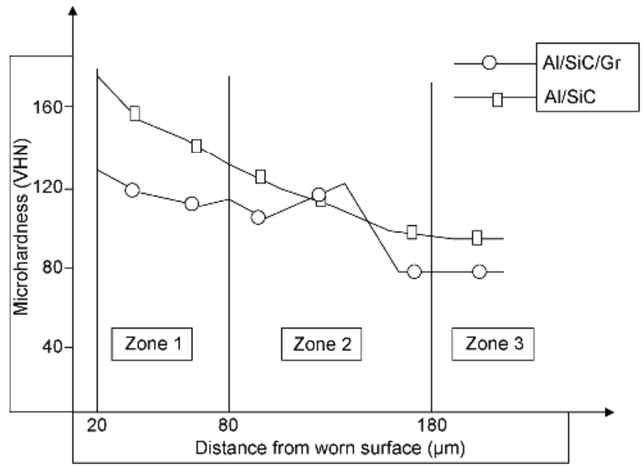


**Fig. 10** Variation in microhardness with the distance from the worn surface along the plane normal to the worn surface for Al2219/15SiC$_p$ and Al2219/15SiC$_p$/3 graphite composite. Reproduced with permission from Ref. [70]. Copyright Elsevier, 2007.

regions [70]. Shear deformation of the subsurface region stabilizes at a depth of 180 μm, and hardness is almost constant after this depth. At higher sliding speeds, wear is related to the removal of surface layers and initiation of cracks in the subsurface, thereby leading to delaminated or severe wear of the wear surface and removal of the material.

In graphitic hybrid composites, surface damage is observed up to a depth of 140 μm and speed of 4.6 m/s (Fig. 10) [70]. Surface damage is attributed to the presence of graphite films, which are formed beneath the surface because of shearing of graphite particles [50]. The microhardness increases above 130 VHN at a depth of 140 μm. In this case, the depth of subsurface deformation is the same, irrespective of the sliding distance, unlike graphite-free composites. The microhardness and depth of subsurface deformation in the Al/SiC/Gr composite are lower than those in Al/SiC composites under all tested conditions, because the graphite layers decrease the magnitude of shear stress transferred to the matrix underneath the surface film [71, 72].

## 5 Morphological analysis of worn surfaces

### 5.1 SEM analysis

Gr particles are relatively soft, and their presence reduces the mechanical properties of the composites

[73]. Therefore, Gr particles cannot resist the formation of wear debris and plastic deformation at the wear surface under heavy load conditions [52, 53]. By contrast, SiC particles are relatively hard and improve the resistance of composites to abrasion and plastic deformation [68, 69, 74]. Moreover, the temperature rise of the wear surface is low in Al/SiC composites because of the low friction coefficient. This phenomenon reduces the material flow/wear loss of the wear surface of these composites. Hard ceramic particles are more prone to escape from the wear surface and form wear debris. The formation of wear debris results in third-body abrasion of the wear surface and great plastic deformation under severe conditions [75]. This phenomenon can be controlled by the addition of Gr particles in the Al/SiC composites, which smears the counterface and reduces the wear rate of the hybrid composites. This phenomenon was confirmed in the micrographs of the worn surfaces of Al/SiC/Gr composites, which revealed the presence of mild wear [76–78].

Ravindran et al. [52] studied the influence of the addition of Gr contents on the morphology of Al/SiC/Gr composites and reported that it reduces metal-to-metal contact because of the presence of a thick layer between the rubbing surfaces. This layer reduces the ejection of hard and brittle particles of ceramic reinforcements and reduces the size of wear grooves and plastic deformation of the wear surface. Figures 11(a) and 11(b) show the micrographs of Al/5%SiC/10%Gr composites; indistinct grooves and fine scratches exist on the worn surface of the composite. The wear mechanisms are characterized by the formation of grooves via plowing of hard asperities of the counterface and hardened wear debris, and temperature rise is one of the most significant factors [79].

The worn surfaces of the hybrid composites (Al/5%SiC/5%Gr) exhibit fine grooves and slight plastic deformation at the edges of the grooves (Figs. 12(a) and 12(b)) [30, 80]. These features may be attributed to the lower temperature rise in this case as compared

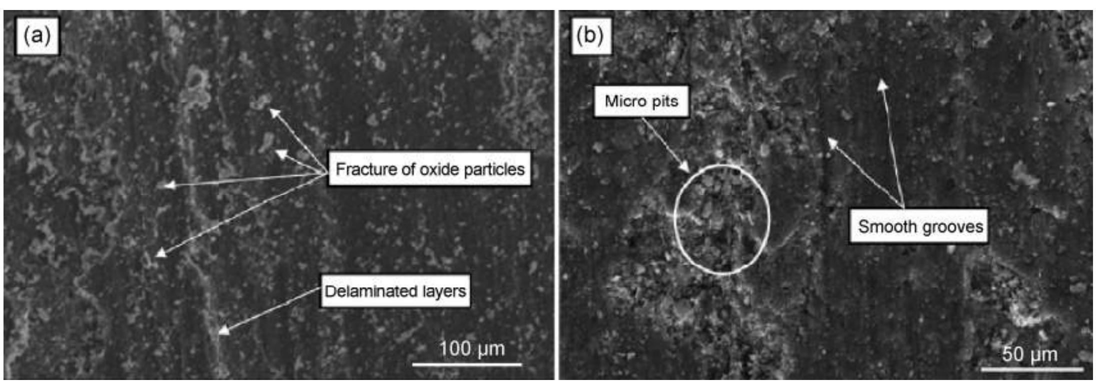


**Fig. 11** SEM morphologies of the worn surface of Al/5%SiC/10%Gr composite at applied load of 20 N at (a) low magnification and (b) high magnification. Reproduced with permission from Ref. [52]. Copyright Elsevier, 2012.

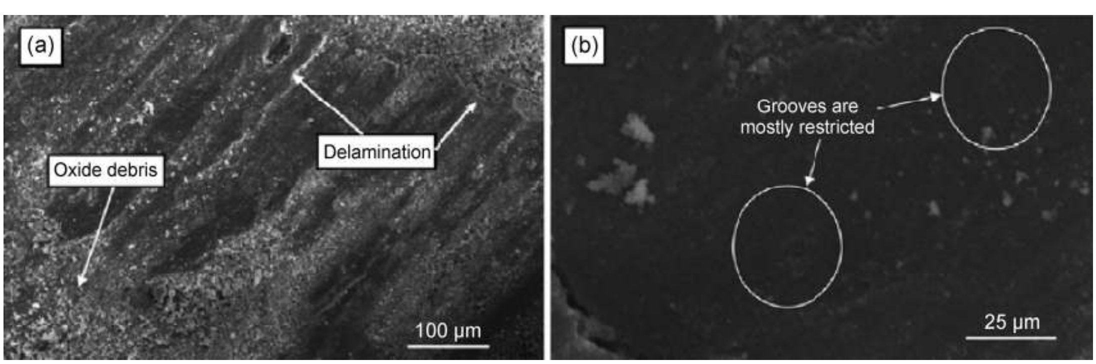


**Fig. 12** SEM morphologies of the worn surface of Al/5%SiC/5%Gr composite at applied load of 20 N at low magnification (a) and high magnification (b). Reproduced with permission from Ref. [52]. Copyright Elsevier, 2012.

with the Al/5%SiC/10%Gr composite. The surfaces also appear smooth because of the presence of the Gr reinforcement. The grooves are restricted to a specific part of the wear surface, thereby indicating the improvement in the wear performance of this composite. These wear mechanisms are characterized by the formation of grooves, which are produced by the plowing action of hard asperities on the counter disc and hardened worn debris.

The different wear mechanisms can also be observed from the SEM images shown in Figs. 11(a), 11(b), 12(a) and 12(b). The friction coefficients of Al/5%SiC/5%Gr composites are lower than that of the Al/5%SiC/10%Gr composite, which may be due to the reduced adhesion at the interface in the former. However, the wear feature size in the worn surface is smaller because of the increased amount of lubrication of Gr particles. Therefore, the probability of adhesive wear in the Al/5%SiC/5%Gr composites is low, and abrasion and delamination are the dominant wear mechanisms [50–52]. A Gr content of 5% is optimum as far as the wear behavior of Al/SiC/Gr composites is concerned. Beyond this percentage, the wear resistance of the hybrid composite is reduced.

In another study, an extensive and thick surface layer was clearly observed on the worn surface of Al2219/15%SiC/3%Gr composite. The composites were fabricated by liquid metallurgy, and tests were carried on a pin-on-disc apparatus. Figures 13(a) and 13(b) show the wear surfaces of hybrid composites under constant load and sliding distance with a sliding speed varying from 4.6 m/s to 6 m/s. Figure 13(a) shows that the worn surfaces are smooth because of the Gr content. The oxide layer can also be observed from the micrograph of these composites, leading to a low wear rate. The worn surface of the Al/SiC/Gr composite shows indistinct grooves and fine scratches. Figure 13(a) illustrates that the formation of grooves is low at a sliding speed of 4.6 m/s. However, as the speed increases (Fig. 13(b)), the grooves become deeper with greater plastic deformation of the wear surface. No subsurface deformation was observed in both of the cases; therefore, the transition from mild to severe wear did not occur in Al/SiC/Gr hybrid composites. In addition to the delay of the wear mechanism, the presence of Gr particles reduces the scuffing effect of ceramic particles against the counterface.

Thus, the micrographs indicated that the transition from mild to severe wear was delayed by the addition of Gr particles in the Al/SiC composites, because of the lubricating action of Gr particles. In addition to the delay in the transition in wear mechanism, the reinforcement of Gr particles in the Al/SiC composites enhances the resistance of the tribosystem as it reduces counterface wear.

### 5.2 Energy dispersive X-ray (EDX) analysis

The EDS spectrum of the worn surfaces of Al composites shows that the upper surfaces are rich in iron (Fe) and oxygen (O) [81]. This observation confirms the phenomenon of material transfer from the steel pin to the wear surface and the oxidation of this material. The worn surface of Al composites consists of the material from the composite and steel pin, thereby confirming the formation of a tribolayer on the wear surface. The presence of SiC particles and removal of small fragments of the steel pin during sliding action

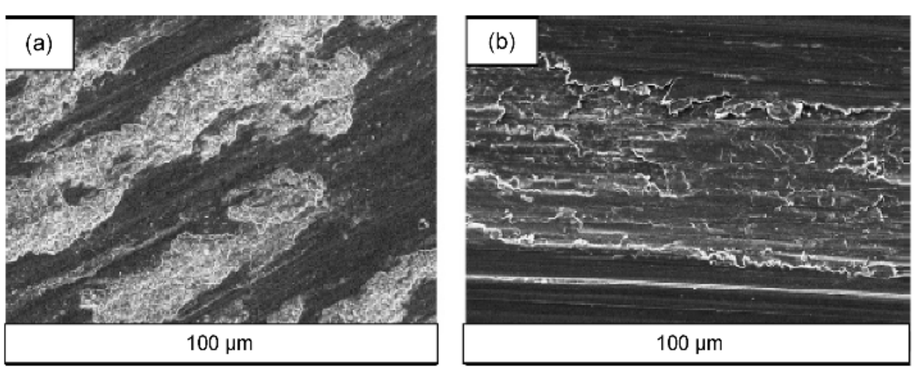


**Fig. 13** Worn surface of Al2219/15%SiC/3%Gr composite under an applied load of 40 N, sliding distance of 5,000 m, and sliding speed of (a) 4.6 m/s and (b) 6 m/s. Reproduced with permission from Ref. [70]. Copyright Elsevier, 2007.

lead to the formation of iron-rich transfer layers at the interface of the wear surface and counterface [82]. Therefore, Al/SiC particles result in increased material transfer from the counterface to the interface. In this scenario, the iron (Fe) peak in the EDS spectrum of Al/SiC composites is greater than those of the Al/SiC/Gr hybrid composite. Gr-rich films are formed on the wear surface of Al/SiC/Gr composites, which reduces the wear rate of the composites. The quantity of Fe at the interface of Al/SiC/Gr hybrid composites is also higher than that of the base alloy sample and Al/Gr composites.

In the study of Madhavi and Akhlaghi [51], XRD analysis of the worn surfaces of Al/SiC composites showed low intensity of Si peak and high intensity of Al peak (Fig. 14(a)). The high intensity of the Al peak indicates the plastic deformation of the Al/SiC composite, which must have occurred during sliding wear. The EDX spectrum of the worn surface of the Al/SiC/Gr composite confirmed the presence of a strong C peak and the low intensity of the Al peak (Fig. 14(b)). This finding confirms the increased smearing of graphite particles at the contact surface. However, a significant Fe peak is also noted because of the abrasion of steel counter surface material by the SiC particles of the hybrid composite.

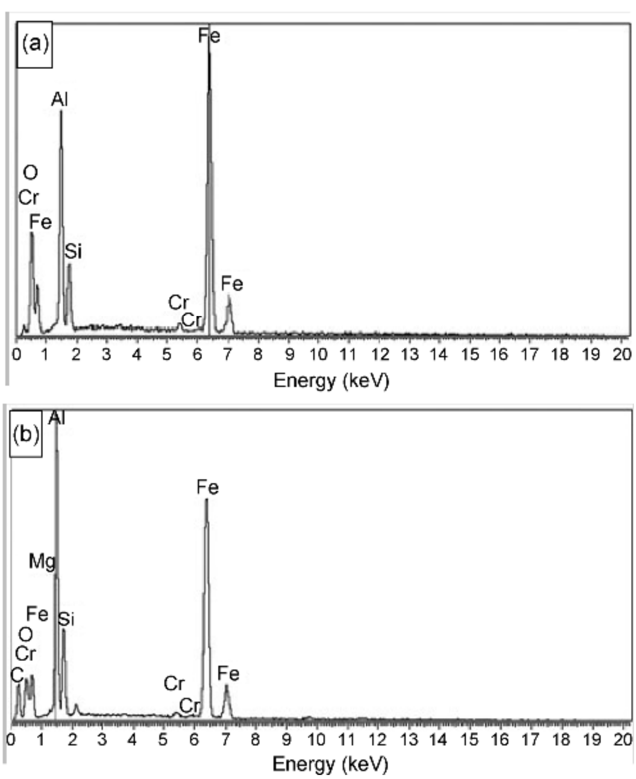


**Fig. 14** EDX spectrum of worn surfaces of (a) Al/SiC composite and (b) Al/SiC/Gr composite. Reproduced with permission from Ref. [51]. Copyright 2011 Springer.

Similar results were also obtained in the SEM and EDX analyses of Al composites by other investigators [50–52]. In the EDX results of Al composites, the presence of a small oxygen peak confirmed the formation of oxide layers at the interface. The increase in temperature and environmental conditions are the factors that lead to the formation of these layers at the interface.

### 5.3 Wear debris

Ravindran et al. [50] investigated the nature of wear debris generated in Al/SiC and Al/SiC/Gr composites (Fig. 15). Results demonstrated that the Al/SiC composite had undergone significant plastic deformation, resulting in the fracture of the ceramic reinforcements. Evidently, Figs. 15(a) to 15(d) show that the wear debris of Al/SiC/Gr composites is smaller than the debris of Al/SiC composites. The presence of graphite particles in the alloy matrix can minimize the mean size of the wear particles. However, the wear debris of the hybrid composite consists of a combination of fine and coarse powders with irregular shapes. In Figs. 15(c) and 15(d), the composite with 5% graphite has larger strip debris than the composite with 10% graphite because of a greater amount of graphite (self-lubrication) particles. Therefore, the morphology and size of the wear debris are controlled by the quantity of Gr particles in the Al composite.

These results were confirmed by other investigations [50–52, 64]; large wear particles (with uneven profile) are produced in pure Al alloy compared with Al composites. According to Mahdevi et al. [51], when two surfaces slide against each other, the soft material is sheared off by the hard asperities of the other. As the Al alloy is a soft material, sliding of the counterface against the alloy surface results in large plastic deformation. The cracks are initiated below the surface and then reach the surface under severe conditions. As the sliding contact proceeds, wedge-like debris are created on the wear surface of the Al alloy. However, the wear debris of Al/Gr composites are a mixture of fine and coarse powder. Moldovan

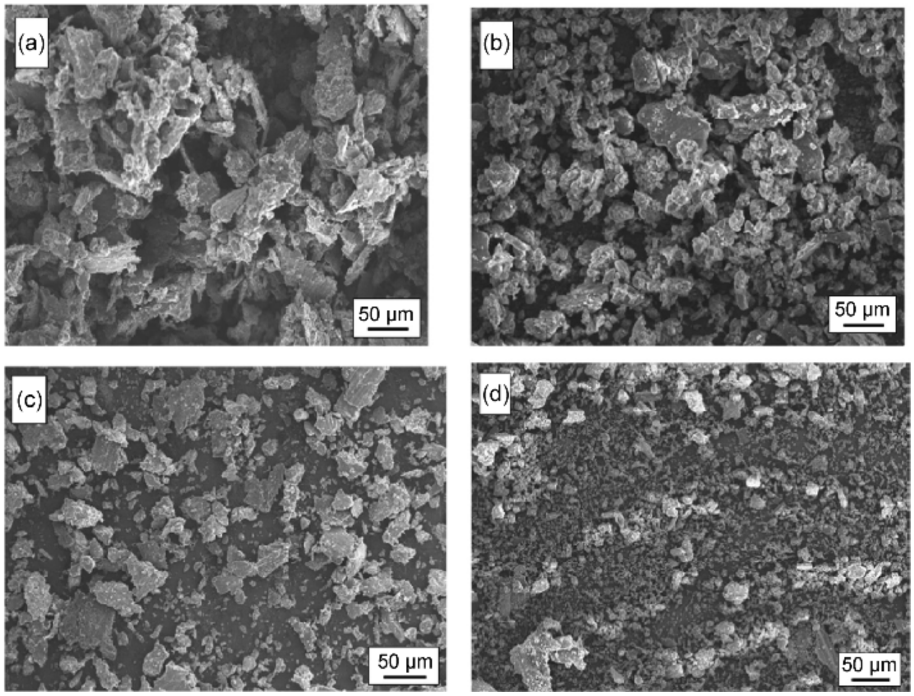


**Fig. 15** SEM micrographs of the collected debris from (a) nano-Al2024, (b) nano-Al/5%SiC, (c) nano-Al/5%SiC/5%Gr, and (d) nano-Al/5%SiC/10%Gr. Reproduced with permission from Ref. [50]. Copyright Elsevier, 2013.

et al. [83] and Jahanmir et al. [84] stated that the plastic strain and dislocation movements in the subsurface result in nucleation of microcracks at the subsurface. The material flow at the reinforcing-matrix interfaces results in stress concentration at the interface and initiates cracks at the subsurface. In Al/SiC and Al/SiC/Gr composites, the cracks propagate parallel to the direction of the sliding direction because of the decreased contact between the asperities of sliding surfaces. However, the presence of hard particles in the matrix alloy results in the generation of fine wear debris. The addition of Gr particles in Al/SiC composites reduces the mean size of wear debris.

### 5.4 Influence of Gr addition

The Al/SiC/Gr composites perform better than the Al/SiC composites under optimum working conditions (load, speed, and velocity) and reinforcement contents (solid lubricating particles) [45, 50–52]. Therefore, the reinforcement contents of the solid lubricating particles must be optimized. Ravindran et al. [64] studied the influence of reinforcement contents of solid lubricant particles (for fixed contents of SiC particles) in Al2024/5wt.%SiC/$x$wt.%Gr ($x = 0$, 5, 10) composites. During the morphological analysis of worn surfaces, the transfer layers were observed on the wear surfaces of the composites. Figure 16(a) shows the loose particles at the worn surface with oxide particles of aluminum, indicating severe deformation of the composite surface (Al2024/5wt.%SiC/10%Gr hybrid composite). By contrast, Fig. 16(b) shows very small microcrystals of graphite with a small amount of oxide particles at the worn surface of the Al2024/5wt.%SiC/5%Gr hybrid composite. Additionally, these loose particles were tightly packed among themselves and formed an adherent film over the contact surfaces. These conditions eventually led to a reduction in plastic deformation of the pin surface of the Al/5wt.%SiC/5wt.%Gr hybrid composite. As a result, the increase in temperature was partially reduced. The fine graphite grains were mixed with the other wear debris, and a smooth Gr-rich tribolayer was formed on the surface. The probability of severe wear in the Al/5wt.%SiC/5wt.%Gr composites is low, and abrasion and delaminating wear are the dominant wear mechanisms [52]. The results indicate that wear of hybrid composites initially decreases with increasing Gr contents up to 5 wt.% and then increases for

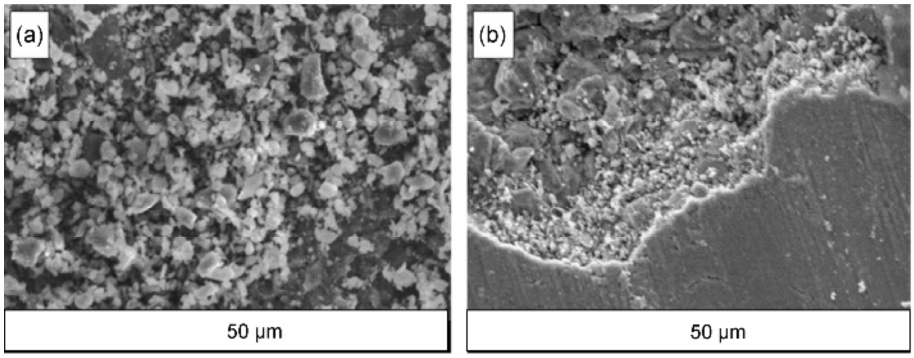


**Fig. 16** SEM image of mixed layer (a) Al/5%SiC/10%Gr composite at applied load of 20 N and (b) Al/5%SiC/5%Gr composite at applied load of 20 N. Reproduced with permission from Ref. [64]. Copyright Elsevier, 2013.

10 wt.% Gr contents (for fixed percentage of SiC) in the hybrid composites. Overall, the presence of Gr particles improves the tribological properties of Al-based composites [30, 79–81]. Notably, the wear rate of Al composites increases with increased load because of adhesive wear. Increased wear rate will improve the surface characteristics of the wear surface and enhance the application area of these composites in various advanced applications, such as power train, bearings, cam shafts, and brake arms.

## 6 Conclusion

In this study, various aspects regarding the fabrication and wear properties of Al/SiC/Gr hybrid composites have been reviewed. It has been revealed that the presence of Gr particles significantly enhances the wear properties under optimum conditions. The hybrid reinforcements can be successfully incorporated into the Al matrix (by powder metallurgy or casting method), so an isotropic set of properties can be obtained. The literature review also showed that the presence of SiC particles increases the hardness of the composites, whereas Gr particles maintain the minimum porosity in the composite. The wear resistance of Al/SiC/Gr composites increases with the addition of Gr contents. This phenomenon was attributed to the fact that the Gr particles act as the self-lubricating component and smear the counterface, thereby reducing the wear rate. Beyond a limit of reinforcement contents, the wear resistance of the hybrid composites decreases because of the high frictional force and the resultant interface temperature. SEM and XRD analyses of the worn surfaces of these composites confirmed the above mentioned results. This study demonstrated that the morphology and size of wear debris are controlled by the amount of Gr particles in the composite.

## Conflict of Interest

There is no conflict of interest.



## References

[1] Gurcan A B, Baker T N. Wear behaviour of AA6061 aluminium alloy and its composites. *Wear* **188**: 185–191 (1995)

[2] Macke A, Schultz B F, Rohatgi P. Metal matrix composites offer the automotive industry an opportunity to reduce vehicle weight, improve performance. *Adv Mater Processes* **170**(3): 19–23 (2012)

[3] Torabian H, Pathak J P, Tiwari S N. Wear characteristics of Al-Si alloys. *Wear* **172**(1): 49–58 (1994)

[4] Kuo S M, Rigney D A. Sliding behavior of aluminium. *Mater Sci Eng A* **157**: 131–143 (1992)

[5] Liu Y B, Asthana R, Rohatgi P. A map for wear mechanisms

in aluminum alloys. *J Mater Sci* **26**: 99–102 (1991)

[6] Zhang J, Alpas A T. Transition between mild and severe wear in aluminium alloys. *Acta Mater* **45**: 513–528 (1997)

[7] Ruiz-Andrés M, Conde A, de Damborenea J, García I. Wear behavior of aluminum alloys at slow sliding speeds. *Tribol Trans* **58**(5): 955–962 (2015)

[8] Umanath K, Palanikumar K, Selvamani S T. Analysis of dry sliding wear behaviour of Al6061/SiC/$Al_2O_3$ hybrid metal matrix composites. *Compos Part B: Eng* **53**: 159–168 (2013)

[9] Song B, Dong S , Liao H, Coddet C. Microstructure and wear resistance of FeAl/$Al_2O_3$ intermetallic composite coating prepared by atmospheric plasma spraying. *Surf Coat Technol* **268**: 24–29 (2015)

[10] Balasubramaniam I, Maheswaran R. Effect of inclusion of SiC particulates on the mechanical resistance behaviour of stir-cast AA6063/SiC composites. *Mater Des* **65**: 511–520 (2015)

[11] Chen H, Alpas A T. Sliding wear map for the magnesium alloy, Mg–9Al–0.9Zn (AZ91). *Wear* **246**: 106–116 (2000)

[12] Mondal D P, Das S, Rao R N Singh M. Effect of SiC addition and running-in-wear on the sliding wear behaviour of Al-Zn-Mg aluminium alloy. *Mater Sci Eng A* **40**(1–2): 307–319 (2005)

[13] Riahi, Alpas A T. The role of tribo-layers on the sliding wear behavior of graphitic aluminum matrix composites. *Wear* **251**: 1396–1407 (2001)

[14] Kowk J K M, Lim S C. High speed tribological properties of Al/SiC composites: I frictional and wear rate. *Compos Sci Technol* **59**: 55–63 (1999)

[15] Al-Rubaie K S, Yoshimura H M, Biasoli-de-Mello J D. Two-body abrasive wear of Al–SiC composites. *Wear* **233–235**: 222–454 (1999)

[16] Rao R N and Das S. Effect of SiC content and sliding speed on the wear behaviour of aluminium matrix composites. *Mater Des* **32**: 1066–1071 (2011)

[17] Sannino A P, Rack H J. Dry Sliding wear of discontinuously reinforced aluminium composites: Review and discussion. *Wear* **189**: 1–19 (1995)

[18] Rohatgi P K, Liu Y, Asthana R. Some issues in the construction of wear mechanism maps for metal matrix composites. In *Tribology of Composite Materials*. Rohatgi P K, Blau P J, Yust C S, Eds*.* ASM International 1990: 69–79.

[19] Rohatgi P K, Liu Y, Lim S C. Wear mapping for metal and ceramic matrix composites, In *Advances in Composites Tribology, Composite Materials Series (Vol. 8*). Pipes B, Ser. Ed, Friedrich K, Ed. Amsterdam: Elsevier, 1993: 291–309.

[20] Sajjadi S A, Zebarjad S M. Microstructural analysis and mechanical properties of aluminium matrix nanocomposites reinforced with uncoated and Cu-coated alumina particles. *Mater Sci Eng A* **607**: 81–88 (2014)

[21] Knowles A, Jiang X, Galano M, Audibert F. Microstructure and mechanical properties of 6061 Al alloy based composites with SiC nanoparticles. *J Alloys Compd* **615**: S401–S405 (2014)

[22] Huang B, Zeng J M, Hu Z L, He H, He C Y, Yan J L. Study on friction and wear behaviours of aluminium matrix composites reinforced with *in situ* formed $TiB_2$ particles. *Adv Mater Res* **900**: 794–797 (2014)

[23] Liu B, Huang W M, Wang H W, Wang M L, Li X F. Study on the load partition behaviours of high particle contents $B_4C$/Al composites in compression. *J Compos Mater* **48**(3): 355–364 (2014)

[24] Kanthavel K, Sumesh K R, Saravanakumar P. Study on tribological properties on Al/$Al_2O_3$/$MoS_2$ hybrid composite processed by powder metallurgy. *Alexaandria Eng J* **55**(1): 13–17 (2016)

[25] Baradeswaran A, Perumal A E. Wear and mechanical characteristics of Al 7075/graphite composites. *Compos part B* **56**: 472–476 (2014)

[26] Baradeswaran A, Perumal A E. Study on mechanical and wear properties of Al 7075/$Al_2O_3$/graphite hybrid composites. *Compos Part B* **56**: 464–471 (2014)

[27] Deaquino-Lara R, Soltani N, Bahrami A, Gutierrez-Castanada E, Garcia-Sanchez E, Hernandez-Rodriguez M A L. Tribological characterization of Al7075-graphite composites fabricated by mechanical alloying and hot extrusion. *Mater Des* **67**: 224–331 (2015)

[28] Wang T C, Fan T X, Di Z, Zhang D, Zhang G D.. The fabrication and wear properties of C/Al and (C + SiC)/Al composites based on wood template. *Mater Lett* **60**: 2695–2699 (2006)

[29] Basavarajappa S, Chandramohan G, Mukund K, Ashwin M, Prabu M. Dry sliding wear behavior of Al 2219/$SiC_p$–Gr hybrid metal matrix composites. *J Mater Eng Perform* **15**: 668−674 (2009)

[30] Suresha S, Sridhara B K. Effect of addition of graphite particulates on the wear behavior in aluminium–silicon carbide-graphite composites. *Mater Des* **31**: 1804–1812 (2010)

[31] Zeren A. 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 (2015)

[32] Kiran T, Prasannakumar M, Basavarajappa S, Viswanatha B M. Effect of heat treatment on tribological behavior of zinc aluminium alloy reinforced with graphite and SiC particles for journal bearing. *Ind Lubr Tribol* **67**(4): 292–300 (2015)

[33] Leng J, Jiang L, Zhang Q, Wu G, Sun D, Zhou Q. Study

of machinable SiC/Gr/Al composites. *J Mater Sci* **43**: 6495–6499 (2008)

[34] Omrani E, Moghadam A D, Meneze P L, Rohatgi P K. Influence of graphite reinforcement on the tribological properties of self-lubricating aluminium matrix composites for green tribology, sustainability and energy efficiency-a review. *Int J Adv Manf Technol* **83**(1): 325–346 (2016)

[35] Venkataraman B and Sundararajan G. Correlation between the characteristics of the mechanically mixed layer and wear behavior of aluminium, Al-7075 alloy and Al-MMCs. *Wear* **245**: 22–38 (2000)

[36] Li X Y, Tandon K N. Microstructural characterization of mechanically mixed layer and wear debris in sliding wear of an Al alloy and an Al based composite. *Wear* **245**: 148–161 (2000)

[37] Lu D, Gu M, Shi Z. Materials transfer and formation of mechanically mixed layer in dry sliding wear of metal matrix composites against steel. *Tribol Lett* **6**: 57–61 (1999)

[38] Chawla N, Chawla K K. *Metal matrix composites*. New York: Springer-Verlag, 2005.

[39] Lloyd D J. Particle reinforced aluminium and magnesium matrix composites. *Int Mater Rev* **39**: 1–23 (1994)

[40] Surappa M K. Aluminium matrix composites: challenges and opportunities. *Sadhana* **28**: 319–334 (2003).

[41] Lewandowski J J, Liu C, Hunt Jr W H. In *The Metallurgical Society of AIME (Edn) Processing and Properties for Powder Metallurgy Composites*. Warrendale PA, 1987:117–137.

[42] Kumar S, Balasubramanian V. Developing a mathematical model to evaluate wear rate of AA7075/$SiC_p$ powder metallurgy composites. *Wear* **264**: 1026–1034 (2008)

[43] Ted Guo M L, Tsao C Y A. Tribological behavior of aluminium/SiC/nickel-coated graphite hybrid composites. *Mater Sci Eng A* **333**(1): 134–145 (2002)

[44] Smith L N, Midha P S, Graham A D. Simulation of metal powder compaction, for the development of a knowledge based powder metallurgy process advisor. *J Mater Process Technol* **79**(1): 94–100 (1998)

[45] Kumar R, Dhiman S. A study of sliding wear behaviours of Al-7075 and Al-7075 hybrid composites by response surface methodology analysis. *Mater Des* **50**: 351–359 (2013)

[46] Mondal D P, Das S. High stress abrasive wear behavior of aluminium hard particle composites: Effect of experimental parameters, particle size and volume fraction. *Tribol Int* **39**: 470–478 (2006)

[47] Surappa M K, Rohatgi P K. Preparation and properties of cast aluminium-ceramic particle composites. *J Mater Sci* **16**: 983–993 (1981)

[48] Lloyd D J, Lagace H P, Mcleod A D. In *Controlled Interphases in Composite Materials - ICCM-III*. Ishida R Ed. London: Elsevier Applied Science, 1999: 359–376.

[49] Mahdavi S, Akhlaghi F. Effect of SiC content on the processing, compaction behavior, and properties of Al6061/SiC/Gr hybrid composites. *J Mater Sci* **46**: 1502–1511 (2011)

[50] Ravindran P, Manisekar K, Vinoth Kumar S, Rathika P. Investigation of microstructure and mechanical properties of hybrid aluminum nano composites with the additions of solid lubricants. *Mater Des* **51**: 448–456 (2013)

[51] Mahdavi S, Akhlaghi F. 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**: 1–12 (2011)

[52] Ravindran P, Manisekar K, Narayanasamy P, Selvakumar N, Narayanasamy R. Application of factorial techniques to study the wear behaviour of Al hybrid composites with graphite addition. *Mater Des* **39**: 42–54 (2012)

[53] Ramesh C S, NoorAhmed R, Mujeebu M A, Abdullah M Z. Development and performance analysis of novel cast copper–SiC–Gr hybrid composites. *Mater Des* **30**: 1957–1965 (2009)

[54] Chu H Y, Lin J F. Experimental analysis of the tribological behavior of electroless nickel-coated graphite particles in aluminum matrix composites under reciprocating motion. *Wear* **239**: 126–142 (2000)

[55] Zhan Y, Zhang G. Graphite and SiC hybrid particles reinforced copper composite and its tribological characteristic. *J Mater Sci Lett* **22**: 1087–1089 (2003)

[56] Rao R N, Das S, Mondal D P, Dixit G. Effect of heat treatment on the sliding wear behaviour of aluminium alloy (Al–Zn–Mg) hard particle composite. *Tribol Int* **43**: 330–339 (2010)

[57] Rao R N, Das S. Effect of matrix alloy and influence of SiC particle on the sliding wear characteristics of aluminium alloy composites. *Mater Des* **31**: 1200–1207 (2010)

[58] Leng J, Jiang L, Wu G, Tian S, Chen G. Effect of graphite particle reinforcement on dry sliding wear of SiC/Gr/Al composites. *Rare Met Mater Eng* **38**: 1894–1898 (2009)

[59] Ames W, Alpas A T. Wear mechanisms in hybrid composites of graphite-20 pct SiC in A356 aluminum alloy (Al-7 pct Si-0.3 pct Mg). *Metall Mater Trans A* **26A**: 85–98 (1995)

[60] Song J I, Han K S. Effect of volume fraction of carbon fibers on wear behavior of Al/$Al_2O_3$/C hybrid metal matrix composites. *Compos Struct* **39**(3–4): 309–318 (1997)

[61] Du J, Liu Y-H, Yu S R, Li W F. Dry sliding friction and wear properties of $Al_2O_3$ and carbon short fibres reinforced Al–12Si alloy hybrid composites. *Wear* **257**: 930–940 (2004)

[62] Liu Y B, Lim S C, Rayb S, Rohatgi P K. Friction and wear of aluminium–graphite composites: the smearing process of graphite during sliding. *Wear* **159**: 201–205 (1992)

[63] Moghadam A D, Ferguson J B, Omrani E, Rohatgi, Gupta N. Functional Metal Matrix Composites: Self-lubricating, self-healing, and nanocomposites─An outlook. *JOM* **66**(6): 872–881 (2014)

[64] Ravindran P, Manisekar K, Narayanasamy R, Narayanasamy P. Tribological behaviour of powder metallurgy-processed aluminium hybrid composites with the addition of graphite solid lubricant. *Ceram Int* **39**: 1169–1182 (2013)

[65] Bowden F P, Tabor D. *The friction and lubrication of solids: Vols I and II*. Oxford: Oxford University Press, 1964.

[66] Suh N P, Sin H C. The genesis of friction. *Wear* **69**: 91–114 (1981)

[67] Ramesh C S, Keshavamurthy R, Naveen G J. Effect of extrusion ratio on wear behaviour of hot extruded Al6061–SiC(Ni–P coated) composites. *Wear* **271**: 1868–1877 (2011)

[68] Manoj Kumar B V, Kim Y W, Lim D S, Seon S W. Influence of small amount of sintering additives on unlubricated sliding wear properties of SiC ceramics. *Ceram Int* **37**: 3599–3608 (2011)

[69] Deng J, Can T, Sun J. Microstructure and mechanical properties of hot-pressed Al/TiC ceramic composites with the additions of solid lubricants. *Ceram Int* **31**: 249–256 (2005)

[70] Basavarajappa S, Chandramohan G, Mahadevan A, Thangavelu M, Subramanian R, Gopalakrishnan P. Influence of sliding speed on the dry sliding wear behaviour and the subsurface deformation on hybrid metal matrix composite. *Wear* **262**: 1007–1012 (2007)

[71] Edalati K, Ashida M, Horita Z, Matsui T, Hirotaka K. Wear resistance and tribological features of pure aluminum and Al–$Al_2O_3$ composites consolidated by high-pressure torsion. *Wear* **310**(1): 83–89 (2014)

[72] Venkataraman B, Sundarajan G. The sliding wear behaviour of Al/SiC particulate composites—II. The characterization of subsurface deformation and correlation with wear behaviour. *Acta Mater* **44**: 461–473 (1996)

[73] Zhan Y, Zhang G. The role of graphite particles in the high temperature wear of copper hybrid composites against steel. *Mater Des* **27**: 79–84 (2006)

[74] Hassan A M, Alrashdan A, Hayajneh M T, Mayyas A T. Wear behavior of Al–Mg–Cu-based composites containing SiC particles. *Tribol Int* **42**: 1230–1238 (2009)

[75] Savaskan T, Bican O. Dry sliding friction and wear properties of Al–25Zn–3Cu–(0–5)Si alloys in the as-cast and heat-treated conditions. *Tribol Lett* **40**: 327–336 (2010)

[76] Singh J, Chauhan A. Overview of aluminium matrix composites for automotive applications. *Int J Appl Eng Resear* **9**(8): 959–966 (2014)

[77] Singh J, Chauhan A. A review on sliding wear behaviour of aluminium matrix composites with hybrid reinforcements for automotive applications. *Tribol Online* **9**(3): 121–134 (2014)

[78] Singh J, Chauhan A. Characterization of hybrid aluminum matrix composites for advanced applications─A review. *J Mater Res Technol* **5**(2): 159–169 (2016)

[79] Singh J, Chauhan A. Overview of wear performance of aluminium matrix composites reinforced with ceramic materials under the influence of controllable variables. *Ceram Int* **42**(1)A: 56–81 (2016)

[80] Ravindran P, Manisekar K, Narayanasamy P, Rathika P. Tribological properties of powder metallurgy -processed aluminium self lubricating hybrid composites with SiC additions. *Mater Des* **45**: 561–570 (2013)

[81] Sharma P, Khanduja D, Sharma S. Dry sliding wear investigation of Al6082/Gr metal matrix composites by response surface methodology. *J Mater Res Technol* **5**(1): 29–36 (2016)

[82] Bodunrin M O, Alaneme K K, Chown L H. Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. *J Mater Res Technol* **4**(4): 434–445 (2015)

[83] Moldovan P, Csaki I, Popescu G, Lucaci M, Lungu M, Butu M. Microstructure evolution and tribological properties for new AlSi9Cu3/5%Gr composite. *Compos part B Eng* **81**: 141–148 (2015)

[84] Jahanmir S, Suh N P, Abrahamson E P. The delamination theory of wear and the wear of a composite surface. *Wear* **32**:33–49 (1975)

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