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Experimental Investigation of Mechanical and Tribological Behavior of Graphite Reinforced Aluminum 6061 MMCs

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A B S T R A C T

The purpose of this work is to investigate the mechanical and tribological characteristics of Al 6061 Metal Matrix Composites (MMCs) reinforced with graphite. Al6061 MMCs were made using the stir casting method with graphite weight percentages of 5%, 10%, and 15%. The composite's microstructural analysis showed that the reinforcement in the matrix material was distributed uniformly. The microhardness of the aluminum (Al) MMCS's decreased with the increase in Graphite content. In a dry sliding environment, tribological investigations were conducted with a ball-on-disk tribometer. The findings indicate a tendency for the coefficient of friction (COF) and wear rate to decrease as the weight percentage of graphite increases. When compared to the base composition, the composition containing 5% graphite at 20N exhibits the lowest wear rate and COF value.

1. INTRODUCTION

MMCs have been investigated recently as viable engineering materials [1]. In MMCS, multiple distinct phases (one being a metallic phase) coexist and are evenly dispersed to give some critical qualities that can't be matched by any of the individual phases [2, 3]. MMCS are used in devices such as electronics, toys, military equipment, automobiles, aerospace etc. Al is the most common matrix for MMCs. Al alloys are both lightweight and strong. Their mechanical properties are enhanced by precipitation strengthening and solid solution strengthening. Al matrix composites (AMC) were studied effectively as early as the 1920s, and are now used extensively [4]. Al MMC provides an outstanding critical location or combination of grades which is unmatched by any other traditional substance. Al MMCs have traditionally been appreciated and employed in a wide range of structural, non-structural, as well as utility applications across several engineering disciplines. Performance, cost-effectiveness, and ecological advantages are the primary motivations for adopting Al MMC in numerous sectors [5]. Carbon reinforced Al metal matrices have extremely low COF and low wear rate properties. These composites have layered structures, and are heavily graphitized that provide solid lubrication. For this reason carbon composites are typically used to manufacture antifriction bearings, pistons, piston rings, cylinder liners, ship casings, frames, running gears, and other rigid critical component where high wear strength/friction performance and extreme operating environment are specification requirements [6].

Graphite is the most commonly used solid lubricant because of its low density. Graphite acts as a solid lubricant and forms a thin film between the composite and the counter surface, which reduces wear without any conventional solid or liquid lubricant [7]. Notably, the graphite-free composites were found to wear more readily than the graphite-containing composite grades among all composite series produced. Graphite is supposed to enhance the tribological performance by creating a solid lubricating film between the composite and the high-friction mating surfaces [8]. On the other hand, increasing the Gr content from 0.5 to 1.5 wt% decreased resistance to wear. The abundant availability of Al relative to other metals and the low and simple production costs compared to other composites have increased the demand for advanced Al MMCS [5]. Also, Al MMCs are known for a number of good mechanical properties. According to a study, stir-cast AA6061/Gr composites revealed that as the increase in filler percentage leads to the decrease in the material's density and hardness, and linear increase in its porosity and tensile strength. However, wear resistance increased at low wt.% of Graphite particles and decreased with additional increases in Gr content [9]. Gr particles were found to effect the wear behaviour positively in a different study that examined the tribological performance of Al7075/Al_2O_3 composites made via the route of liquid metallurgy. The study also found that the addition of Gr particles reduced the COF of the Al7075/Al_2O_3 composites and improved the durability against wear of graphite reinforced hybrid composites [10].

In an experiment, Al alloy reinforced with SiCp (SiC particles)-Gr, was explored for its sliding wear performance in dry condition. The unlubricated pin on disc wear test was performed to investigate the wear behaviour of the Al alloys and its composites. It has been found that graphite composites have minimum wear rate than matrix alloys and silicon carbide particle reinforced composites [11, 12]. Another experiment focused on liquid metallurgical techniques. Tribological experiments were performed on composites and matrix alloys by employing a pin-on-disc (POD) wear testing device with loads between 10 and 50N, sliding speeds from 1.25 to 3.05 m/s, and sliding distances varying from 0.5 to 3 km. Al6061 matrix, garnet particle reinforced composites have a greater wear resistance than unreinforced matrix alloy [13]. A study demonstrates that when the weight percentage and size of non-metallic particles were increase, the dry sliding wear resistance of 2014Al-Al_2O_3 also increases [14].

The wetting of reinforcement within Al matrix composites is a significant restriction in their manufacturing. In Al composites, a small film of oxide can inhibit surface wetting and react with ceramics, resulting in intermetallic phases that affect composite characteristics [15]. Hard ceramic compounds that have been effectively used as reinforcing materials include silicon carbide and boron carbide. In addition to financial benefits, graphite particles appear to have other benefits. There are numerous methods for creating MMCs [16] , but the stir casting method, also called as the liquid metal way, has special benefits for handling metals which have relatively low melting points like zinc and its alloys [17-20]. Therefore, in this study, graphite with varying wt% was used as reinforcement into the Al alloy and the composites were made by a mechanical stirring casting process. This study aims to explore the mechanical properties like hardness and density and tribological behavior like COF and wear resistance of graphite reinforced Al6061 MMCS.

2. MATERIALS AND METHODS

2.1 Materials

Here in, Graphite was used as reinforcement and Al 6061 alloy as the base matrix metal to make the composite by stir-cast process. Table 1 presents the the chemical composition of Al6061 alloy [21].

Table 1. Chemical composition (wt.%) of Al6061alloy [16].

Mg	Si	Fe	Cr	Cu	Mn	Al
0.89%	0.53%	0.2%	0.2%	0.3%	0.2%	Remaining

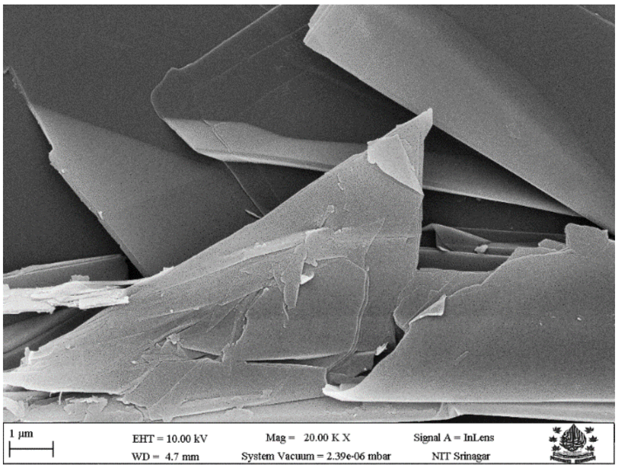


Fig. 1. Scanning electron microscopy (SEM) image of Graphite flakes used.

Samples were prepared using varying proportions of graphite particles (figure 1) (5 wt.%, 10 wt.% and 15 wt.%) using the vortex process. This method includes mechanical combination of warm reinforcement particles including Al_2O_3 and Gr into a molten metal bath. The mixture is transferred directly to a pre-developed mold and subsequently allowed to solidify. This approach offers the advantage of producing MMCs at significantly low costs. The matrix material employed in this investigation was Al6061 alloy, which has a theoretical density of 2.8 g/cm^3. Reinforcements included Al_2O_3 and Gr particles, each with an average particle size of 25 µm and densities of 3.97 g/cm^3 and 2.2 g/cm^3, respectively. A calculated weight of 1.95 kg of Al 6061 ingot alloy was deposited in a crucible within an induction furnace at 750°C. After being heated to 400°C, the alumina and Gr particles were added to the melt using the vortex. The metals were melted at 650–675°C and stirred automatically at 300–350 rpm for approximately 10 minutes in order to create the necessary vortex. The Al alloy melt was kept free of ferrous ions by using an aluminite-coated mechanical stainless steel stirrer. Particles of graphite and alumina were added, and the melt was agitated vigorously before solid hexachloroethane (C2Cl6) was used to degas it. Further, the flux was manually removed. Subsequently, the Al6061 metal matrix composite was ready for more testing. Figure 2 displays the casting equipment, furnace, and the final sample.

(a) Stir-casting setup

(b) Furnace used for fabrication of Al-Graphite MMC

(c) Cast of Al-Graphite

Fig. 2. Casting setup.

These samples were shaped into suitable specimens through machining and subsequently underwent a final grinding stage. Finally, the samples were polished to maintain the average surface roughness (Ra) for the disc samples in the range of 0.13-0.25 µm for all the compositions. This was measured by a 3D profilometer.

2.2 Methods

Vickers hardness testing equipment was used, to test the hardness of stir-casted composites, under a 100kgf force, with a dwell duration of 10 seconds and an indentation speed of 50µm/s. A general rule of mixtures was used to predict the density of the obtained material. The density of composites, denoted as ρ_c, were determined using the following equation:

$$\rho_c = \rho_f v_f + \rho_m v_m$$

n this case, the densities of the composite, filler material, and matrix material are represented by ρc, ρf, and ρm, respectively, while the volume fractions of the filler material and matrix material are indicated by v_f and v_m. Using the ball-on-disc approach, tribological experiments were performed on a sliding tribometer in dry sliding conditions. The material's COF and wear behavior were assessed using an EN08 steel ball with a 9.2 mm diameter and a 4.31 GPa hardness. Table 2 provides the chemical composition of EN08 steel.

Table 2. Chemical composition of EN08 Steel.

Element	Content (%)
Carbon (C)	0.36-0.44
*Manganese (*Mn)	0.6-1.00
Silicon (Si)	0.05-0.35
Phosphorous (P)	0.015-0.06
Sulphur (S)	0.015-0.06

Throughout the experiment a constant sliding distance of about 1200mm was maintained and varying load of 5N, 10N, 15N and 20N for a duration of 10 minutes. Before tests, microstructure analysis was done using SEM. Also energy dispersive spectroscopy (EDS) method was used to check the chemical composition on the sample surfaces after the tests were done.

3. RESULTS AND DISCUSSIONS

3.1 Microstructure analysis

Microstructural analysis shows the distribution of reinforcing particles in the fabricated composites. The SEM analysis, figure 3 displays a consistent distribution of graphite and Al_2O_3 particles all over the matrix alloy, together with robust interface bonding between the base metal and reinforcements. Also the presence of reinforcing particles can be observed as dark spots of the matrix phase. It has been observed that MMCs with higher hardness have reduced porosity. The matrix and reinforcement particles exhibit strong bonding, leading to improved load transmission from matrix to reinforcement materials. Cast Al composites exhibited particle clustering and porosity aggregation. This suggests that the reinforcement process was effective in dispersing the particles of graphite across the matrix. The Al matrix appears to be equiaxed which is typical of Al6061 that has been solution heat treated and quenched. The interface formed between the graphite particles and the aluminm matrix seems relatively well-defined. Also no significant porosity is evident within the microstructure.

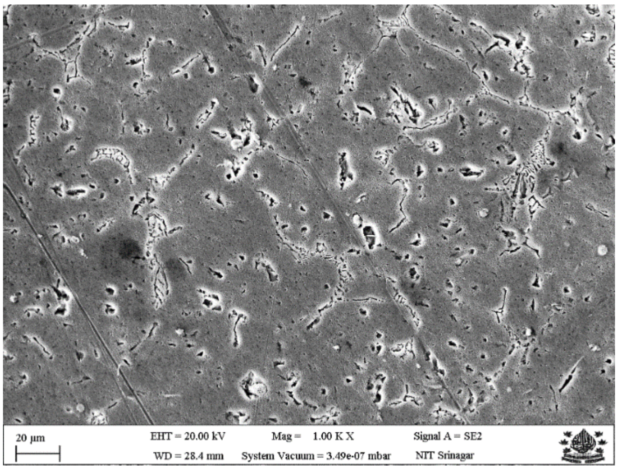


Fig. 3. Microstructure analysis of Al6061 MMC.

3.2 Hardness

The hardness of the obtained composite considerably depends on the reinforced particles as well as on the matrix phase [22]. Figure 4 depicts the results of Vickers microhardness tests. It is clear that with the increase of graphite content, microhardness increases upto 5wt% and thereafter falls. As a result, graphite at 5wt% has a higher hardness than other compositions. The reinforcing particles aid to maintain the contact stress, reducing deterioration and wear between the contact surfaces.

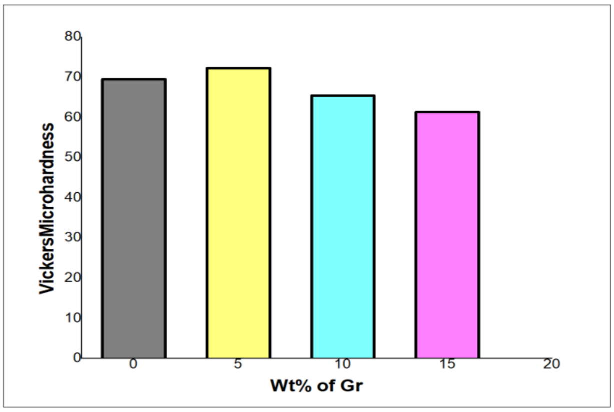


Fig. 4. Micro-hardness value for varying weight percentage of Graphite.

3.3 Density Results

The increase in weight percentage of graphite in base metal gives more porosity which in turn slightly decreases density of the composite. The graph shows the variation of theoretical density of Al 6061 MMCs with different weight percentages of graphite. As the graphite content is increased from 0% to 15%, the theoretical density of the composites reduces linearly from approximately 2.70 g/cm^3 to 2.63 g/cm^3. This is attributed to the lower density of graphite as compared to Al6061, which subsequently leads to the reduction in the overall density of the composite material.

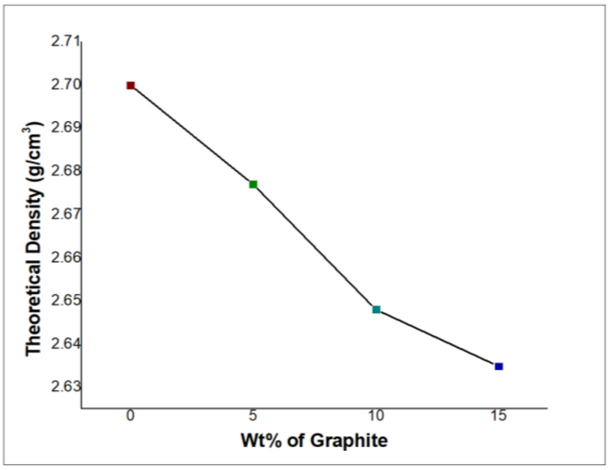


Fig. 5 Variation of theoretical density with different wt%age of Graphite.

3.4 Friction and wear Analysis

The results shows a trend of decrease in COF while increasing the wt% of Gr as shown in figure 6. At initial stage higher COF was observed due to direct metal to metal contact. With increase in wt% of graphite, the contact surfaces became smoother and the Graphite forms a lubricating film between the two contacting surfaces, which attributes to the decrease in COF. The composition with 5Wt% of graphite at 20N shows the lowest value of COF as compared to the base composition as shown in figure 7. Figure 8 illustrates that wear rate decreases as the weight fraction of graphite increases. For all graphite contents, the wear rate generally rises with higher applied loads, as indicated by the taller bars for 5N compared to 10N, 15N, and 20N. Increasing the graphite content reduces the wear rate. The wear rate is highest for 0% graphite and decreases progressively for 5%, 10%, and 15% graphite, particularly noticeable under higher loads. At 15% graphite, the wear rate is consistently low across all loads, showing the most significant improvement in wear resistance which illustrates that adding graphite to Al 6061 MMCs effectively reduces wear, with higher graphite content leading to greater improvements, especially under higher applied loads. Also the composition with 5Wt% of graphite at 20N shows lowest wear rate as compared with base composition as shown in figure 9.

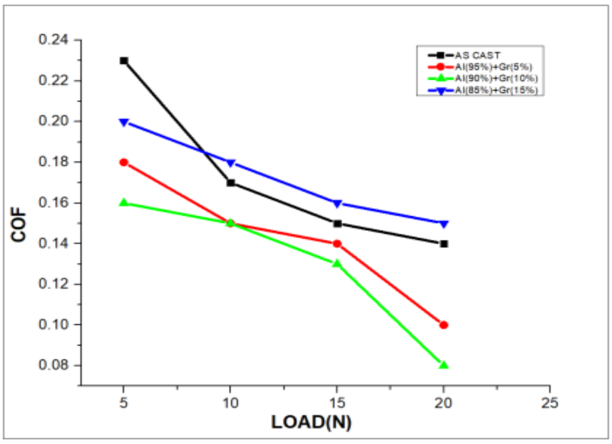


Fig. 6. Variation of COF of samples at different applied loads.

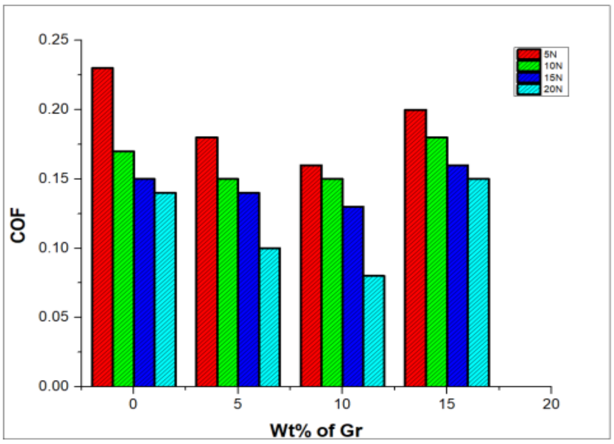


Fig. 7. Variation of COF of samples with different wt%age of Graphite.

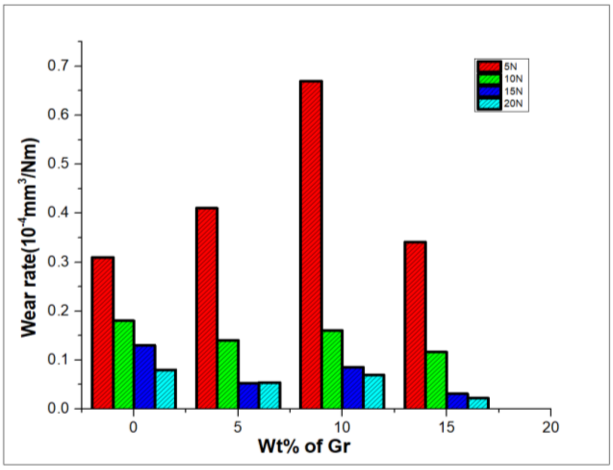


Fig. 8. Variation of wear rate with different wt%age of Graphite.

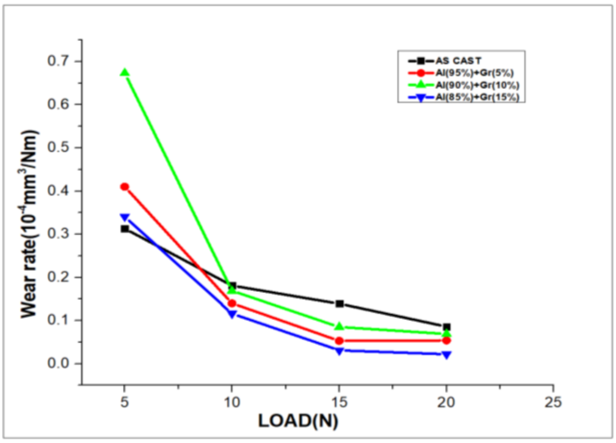


Fig. 9. Variation of wear rate at different applied loads.

3.5 Evaluation of Worn Surfaces

Figure 10 displays the SEM and EDS images showing morphologies of the wear scars of samples with 5%, 10%, and 15% graphite respectively at 20N load. The results clearly shows wear tracks were formed on the composite's worn surfaces, allowing for the study of the wear mechanism.

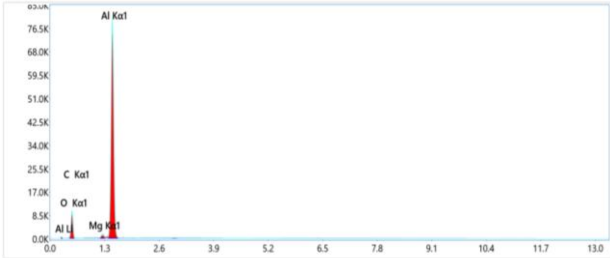
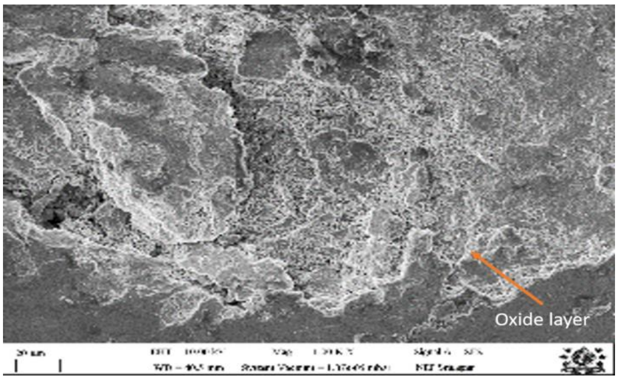
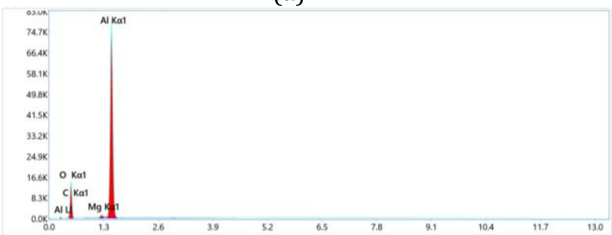


Fig. 10. SEM & EDS of Compositions tested for sliding distance at 20N load.

Figure 11 (a) shows 5wt% Graphite has formed an oxide layer proved by EDS analysis as peak of oxygen can be observed (figure 11(b)) on the worn surface, which plays an essential role in lowering wear rate and COF. The table 3 also presents the elemental composition of the components on the sample's surface.



(a)



(b)

Fig. 11. SEM (a) & EDS (b) of Al+Gr(5%) at 20N load.

Table 3. % composition of the elements on the surface of sample.

Element	Weight%	MDL	Atomic%	Net int.	Error%	R	A	F
C K	11.8	0.37	19.3	33.4	13.0	0.9056	0.0432	1.0000
O K	32.8	0.06	40.3	991.4	9.5	0.9152	0.1800	1.0000
Mg K	1.1	0.03	0.9	135.4	6.6	0.9311	0.5698	1.0271
Al K	54.3	0.03	39.6	7144.6	4.3	0.9346	0.6843	1.0016

4. DISCUSSION

This study found interesting aspects in the mechanical behavior of graphite-reinforced Al 6061 MMCS (MMCs). Al MMCs have greater mechanical properties than unreinforced Al alloy due to changed matrix microstructures [23]. The mechanical, tribological, thermo-mechanical, and physicochemical characteristics of Al MMCs are significantly impacted by reinforcements. Refined grain size, consistent dispersal of reinforced particles within the metal matrix, and improved matrix-reinforcement bonding are the main factors contributing to the enhancement in mechanical properties. Because of the dispersed particle's strengthening effect, the introduction of graphite particles led to a slight increase in hardness.

Under dry sliding circumstances, the tribological properties of Gr reinforced Al6061 MMCs were examined. As compared to the unreinforced Al 6061, the graphite particle addition decreased both the COF and the rate of wear. The drop may be attributed to the self-lubricating properties of graphite, which serves as a solid lubricant between the sliding surfaces. Better tribological performance is shown by the MMCs' stated lower friction coefficient, which is very desirable in industries like aerospace and automotive where wear and friction are big problems. The addition of graphite also facilitated the formation of a transfer layer on surfaces in contact, which in turn led to the decrease in wear and hence, improved the tribological performance of the composites as a whole [24]. An examination of the microstructure revealed that the Gr particles were evenly distributed throughout the Al matrix. The matrix and reinforcement exhibit effective dispersion and interfacial adhesion with minimal lumping or agglomeration. This consistent distribution is crucial for the mechanical integrity and tribological performance of the composite material [25].

5. CONCLUSION

To sum up, this study examined the tribological and mechanical characteristics of 6061 Al micromachine chips reinforced with graphite. Through stir casting, composites with varying graphite content (5%, 10%, and 15%) were fabricated and characterized. Microstructural analysis confirmed that graphite was uniformly distributed within the Al matrix. The micro-hardness of the composites revealed a decreasing trend with increasing graphite content, indicating a modification in mechanical properties. Tribological evaluations using a ball-on-disk tribometer under dry sliding conditions revealed the wear rates and COF were decreased with the increase in Gr content. Specifically, the composition with 5 wt.% graphite demonstrated the lowest COF and wear rate at 20N load, highlighting its enhanced tribological performance. The mechanical and tribological characteristics of Al 6061 MMCs were remarkably improved by adding graphite as a reinforcing element. This suggests that the material may find viable uses in industries that need better wear resistance and frictional behavior. Subsequent research endeavors may enhance the performance of the composite by investigating supplementary factors such particle size and distribution, therefore attaining customized material characteristics for particular uses.

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