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Effect of Graphite on Mechanical and Tribological Properties of Al6061/SiC Hybrid Composites

Mastan Rao Papabathina[1], Siva Sankara Babu Chinka[2], Nageswara Rao Putta[3], Murkonda Vijaya[4], Sneha. H. Dhoria[4*], Deva Raj Chilakala[4], Ranga Raya Chowdary Jarubula[4], Praveen Kumar Kancharla[4]

[1] Department of Mechanical Engineering, P V P Siddhartha Institute of Technology, Kanuru, Vijayawada 520007, India
[2] Department of Mechanical Engineering, Lakireddy Bali Reddy College of Engineering, Mylavaram 521230, India
[3] Department of Mechanical Engineering, Vasireddy Venkatadri Institute of Technology, Guntur 522508, India
[4] Department of Mechanical Engineering, R.V.R & J.C. College of Engineering, Chowdavaram, Guntur 522019, India

Corresponding Author Email: sneha@rvrjc.ac.in

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ABSTRACT

This study investigates the effects of incorporating graphite into a Al6061/SiC hybrid metal matrix composite on its mechanical and wear properties. The composites are fabricated using a stir casting technique, with SiC and Graphite particles added in different weight percentages ranging from 2-8%. Mechanical properties such as hardness, tensile strength, flexural strength, and compressive strength are evaluated. Results show that the composite with 6 wt.% of hybrid reinforcement exhibits significant improvement in hardness (30%), tensile strength (10.82%), compressive strength (68.14%), and flexural strength (85%) compared to pure Al6061 alloy. Furthermore, a wear test is performed using a pin-on-disc machine under dry conditions to assess the influence of parameters on the wear rate and coefficient of friction (COF). Tests are conducted at various loads (1-3 kgf), sliding speeds (150-450 rpm), and sliding distances (1000-2000 m). Among all reinforcements, the composite with 6% hybrid reinforcement exhibits the lowest wear rate and COF. Overall, this study provides valuable insights into the mechanical and wear properties of Al6061/SiC/graphite hybrid composites and highlights their potential for various industrial applications. These findings may pave the way for further research in the field of metal matrix composites and their applications.

1. INTRODUCTION

Aluminum alloy matrix composites (AMCs) are gaining increasing attention as high-performance engineering materials due to their enhanced quality and affordability. They offer improved thermal stability, corrosion resistance, fatigue resistance, durability, and rigidity making them a suitable alternative to monolithic alloys and other materials in various industries [1-3]. Among the AMCs, Al6061 is a widely used base material due to its beneficial characteristics, such as low density, superior strength, low electrical resistance, durability against corrosion, and excellent machining properties. However, its application has been limited by its comparatively lower wear resistance [4].

Stir casting is an effective method for creating composites consisting of Al6061 and various reinforcements, including inorganic materials (Al_2O_3, SiC, TiC, B_4C, etc.), organic materials, hybrid combinations, and nanomaterials, resulting in high hardness and young's modulus. Hybrid composites have been found to perform better than composites reinforced with a single material in terms of material properties [5, 6].

The tribological behaviour of AMCs, particularly Al6061 composites, has been widely studied. SiC particles have been found to enhance the mechanical strength and wear resistance of composites in the Al alloy matrix [7-9]. The inclusion of specific quantities of graphite in Al/SiC composites has been found to improve wear resistance [10]. Graphite-based aluminum composites can increase the mechanical characteristics and tribological behavior of AMCs.

Recent studies have made significant advancements in enhancing the mechanical and tribological characteristics of both fiber-reinforced and particulate Al6061 composites. Researchers have investigated the effect of graphite on the mechanical properties of aluminum composites. Their findings showed a downward trend in the mechanical properties as graphite was added to the Al6061 matrix [11].

In-situ powder metallurgy of Al6061/SiC/Gr hybrid composites containing SiC particles and uncoated graphite particles has been used to prepare samples, resulting in a uniform distribution of particles. Increased SiC size and graphite content improved compressibility but reduced hardness. Adding 5% graphite and increasing SiC size enhanced wear resistance [8]. Ultrasonic stir-casting has been found to significantly enhance the mechanical properties of AMCs produced with various fractions of SiC particles [12]. However, the addition of graphite content to Al2024 alloy has been found to decrease hardness and fracture toughness of composites, with a higher wear rate observed in Al/Gr composites that include 10 wt.% or more graphite particles compared to the base alloy [13]. The tribological behaviour of hybrid (Gr+SiC)/Al2024 MMC by powder metallurgy has been found to be significantly enhanced [14]. Hybrid aluminum matrix composites fabricated by stir casting have shown that tensile strength and hardness increase with SiC and

Graphite addition, with the wear rate rising with higher loads but declining after a specific sliding velocity [15]. AMCs reinforced with 2% nanoparticles exhibited the highest wear resistance [16].

Although numerous studies have been conducted to enhance the mechanical and tribological characteristics of Al6061 composites, limited work has been done on the fabrication of SiC and Graphite hybrid MMCs using Al6061 alloy. Therefore, this study aims to fabricate Al6061 Graphite/SiC hybrid MMCs with different weight percentages of reinforcements using stir casting. The focus is on evaluating the mechanical properties, including hardness, tensile strength, compressive strength, flexural strength, and elongation of the prepared samples. Additionally, tribological properties such as wear properties are evaluated under different applied loads and sliding velocities. This study aims to fill the research gap and provide insight into the mechanical and tribological behavior of Al6061 Graphite/SiC hybrid MMCs.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

In this work, Al6061 as a base matrix, SiC (Silicon Carbide), and Graphite particulates (2-8%) combinations (S1 to S5) as shown in Table 1 with average particle sizes of 50 and 30 μm are used as reinforcement.

Table 1. Composition of Al hybrid MMC

Samples	Al6061(wt.%)	SiC(wt.%)	Graphite(wt.%)
S1	0	0	0
S2	96	2	2
S3	92	4	4
S4	88	6	6
S5	84	8	8

2.2 Stir casting process

The stir casting technique plays a crucial role and is widely utilized in the development of Metal Matrix Composites (MMC) and metallurgical procedures. Figure 1 illustrates the schematic diagram of the stir casting process, highlighting its key components and operation. Additionally, Figure 2 provides a visual representation of the sequential steps involved in stir casting, offering a clear understanding of the process flow.

An electrical resistance furnace is used to melt Aluminium alloy for the manufacture of hybrid MMC. To enhance the wettability of particles with the matrix and eliminate casting flaws, molds are preheated to 250°C-350°C, and reinforcing particulates SiC and Gr are preheated to 400°C-500°C [17]. The Al6061 material is heated to its liquidous temperature, which is 750°C, and then held there until the metal melts. The wettability of molten magnesium powder had been added for enhancement [18]. Solid hex chloromethane [18] was used to degasify the mixture. Instead of introducing the reinforcement particles (SiC and Gr) all at once, they were added to the melt at varying intervals. The mixture was then thoroughly stirred for 10 minutes [19]. It was extremely difficult to mix the alloy with automatic equipment since it was semisolid. On the other hand, the slurry is heated to a total fluid condition for automatic mixing at 600 rpm for roughly 10-15 minutes [20, 21]. During this phase, the furnace temperature was kept constant at 750°C [17]. After that, the melt was poured into the molds. The heated stirrer was put into the crucible and mixed the melt at 250-300 rpm speed [17]. After bringing the molds containing the specimens to room temperature, the samples were removed from the molds as shown in Figure 3. The prepared specimens were also cut to ASTM standards and polished by a double disc polishing machine to ensure the prepared material's tribological response at predetermined values.

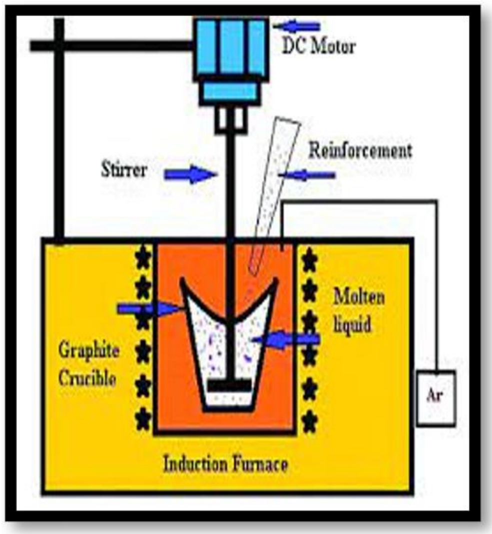

Figure 1. Stir casting process

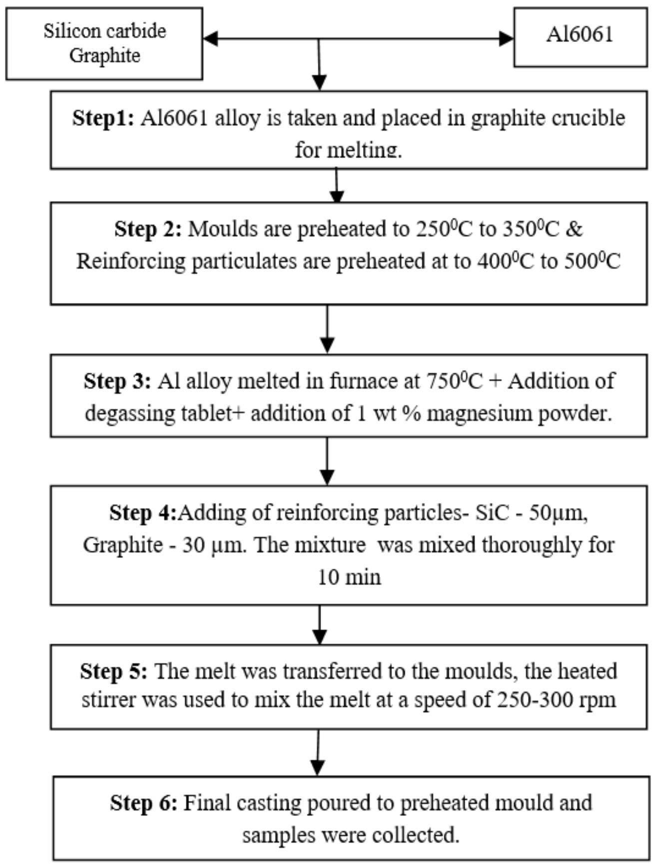

Figure 2. Steps of stir casting process

Figure 3. Al6061/sic/graphite hybrid composite

2.3 Mechanical properties

2.3.1 Hardness

The hardness testing of various samples was conducted using a Brinell hardness tester in accordance with the ASTM E10 standards. The hardness measurement involved the application of a 5mm ball indenter and a 250N load on the castings for a duration of 30 seconds. Figure 4 illustrates the Brinell hardness tester used in the experiment, providing a visual depiction of the equipment.

Figure 4. Brinell hardness tester

2.3.2 Tensile strength

To evaluate the tensile strength of the prepared specimens, a Universal Testing Machine (UTM) was employed. The UTM machine was utilized to perform the necessary mechanical tests on the samples. The equipment setup, as well as the appearance of the sample, can be observed in Figure 5a and Figure 5b, respectively. The tensile tests were conducted following the guidelines specified in ASTM A370, with a constant strain rate of 0.5mm/min. To ensure accuracy, three readings were recorded for each individual piece during the tensile test.

2.3.3 Flexural strength and compressive strength

The UTM (Universal Testing Machine) is commonly employed for evaluating the flexural strength of materials, utilizing a dedicated test fixture as illustrated in Figure 6. The sample was prepared in accordance with the specifications outlined in ASTM D790-10.

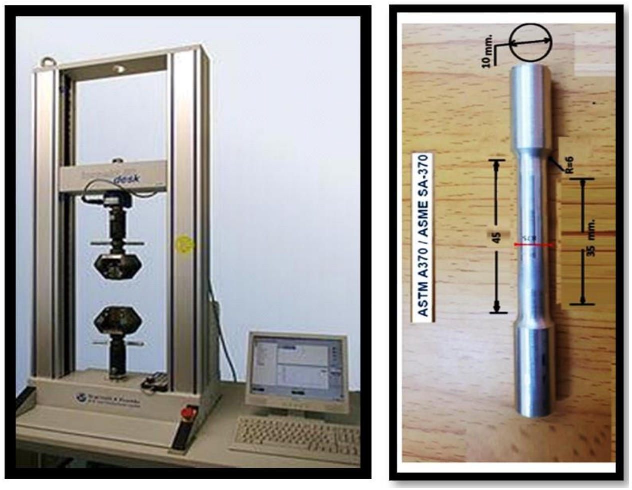

Figure 5. (a) UTM machine (b) Sample for test

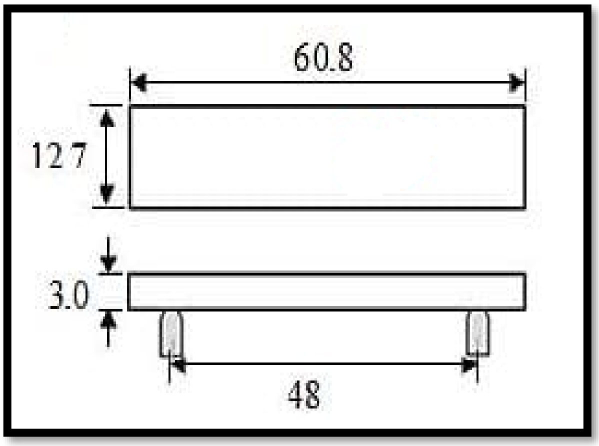

Figure 6. Flexural fixture

2.4 Tribological properties

2.4.1 Wear test

An experimental investigation was carried out to analyze the wear behavior of an Al6061 hybrid Metal Matrix Composite (MMC) in comparison to the wear properties of a base alloy. The wear tests were performed using a pin-on-disc machine, following the guidelines specified in ASTM G99 standards. The test samples had dimensions of ø6mm x 40mm. Prior to the experiment, the samples were polished to ensure a consistent surface finish. The impact of various factors, such as particle reinforcement, sliding speed(S), distances(D), and load, on the wear characteristics of the pins, was visually depicted and recorded in Table 2. A detailed procedure outlining the steps involved in the wear test is provided in Figure 7 and Figure 8.

Table 2. Control factors of wear

Parameters	Symbols	Units	Level1	Level2	Level3
Sliding Speed	S	rpm	150	300	450
Sliding Distance	D	m	1000	1500	2000
Applied Load	L	kgf	1	2	3

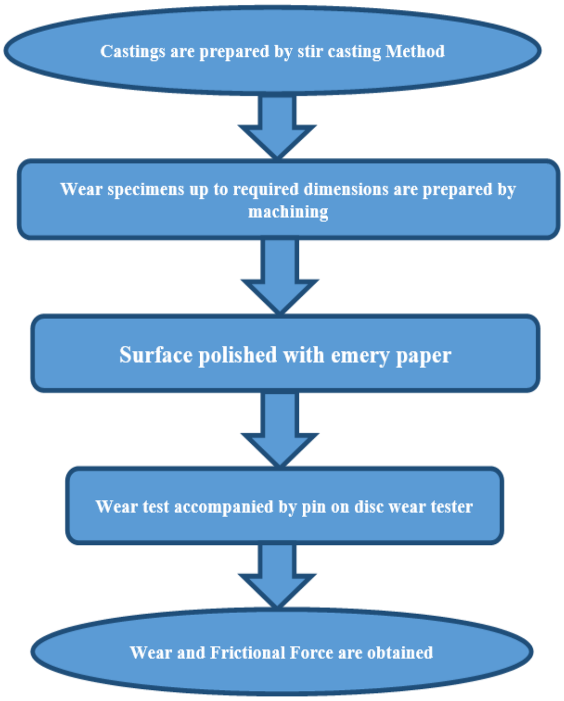

Figure 7. Wear test process

Figure 8. Pin on disc machine

3. RESULTS AND DISCUSSIONS

Mechanical properties:

Table 3 presents the mechanical properties of Al6061/SiC/Graphite composites produced through the stir casting process. The table provides a comprehensive overview of the various mechanical characteristics of the composites, including parameters such as tensile strength, flexural strength, compressive strength, hardness, and fracture toughness. These properties offer valuable insights into the performance and suitability of the Al6061/SiC/Graphite composites for specific applications.

Table 3. Mechanical properties of composite

Sample	Hardness (BHN)	Tensile Strength (N/mm^2)	% Elongation	Flexural Strength (N/mm^2)	Compressive Strength (N/mm^2)
S1	60	126	5.87	250	226
S2	68	158	4.2	442	356
S3	70	172	4	478	367
S4	78	198	3.9	496	380
S5	65	165	3.2	446	350

3.1 Effect of SiC and Graphite on hardness

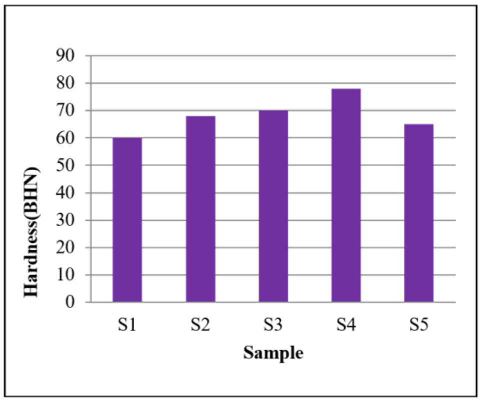

Figure 9. The hardness of hybrid composites

According to the findings illustrated in Figure 9, it is evident that the hardness of the material exhibits an increasing trend up to a reinforcement content of 6 wt.%. However, with further additions of graphite, the hardness begins to decline. This decrease in hardness can be attributed to the superior lubricating capabilities possessed by graphite [22].

3.2 Effect of SiC and Graphite on tensile, flexural, and compressive test

The Tensile strength of Al6061 hybrid composite is 198 N/mm^2. The tensile strength of Al6061 MMC is greater when compared with other Al series hybrid composites [23]. This is because of good bonding between the reinforced particulates [23]. The tensile, compressive, and flexural strength is also superior at 6 wt.% of hybrid composites. The strengths of the tensile, compressive and flexural is increased by 10.82%, 68.14% and 85% for the hybrid composite relative to the base alloy.

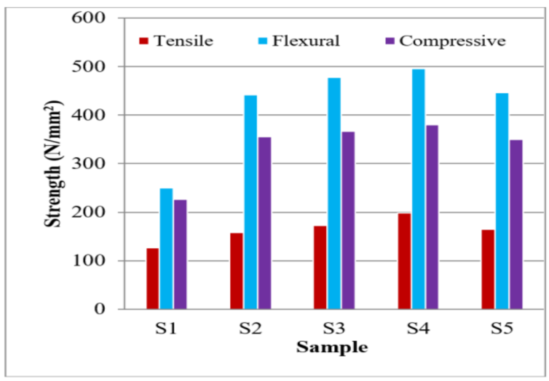

Figure 10. Tensile, flexural, and compressive strength of MMC

Figure 10 depicts the bonding between Al6061 alloy and reinforcement weight %. It reports that the strengths are monotonically increased up to 6 wt.% of hybrid composite. The tensile, compressive, flexural strength of hybrid composite is more when compared to base alloy due to the precise spacing between the reinforcement and the matrix [6].

3.3 Percentage of elongation

The percentage of elongation in hybrid metal matrix composites has been lowered by up to 8% due to the existence of SiC and Graphite. In the hybrid MMC depicted in Figure 11, the percent of elongation is lowered when compared to the SiC composite. It is also clear that the ductility of the metal matrix decreases as SiC/Graphite reinforcement is added. This is attributed to the beginning of a localized crack and the composite's better embrittlement impact [24].

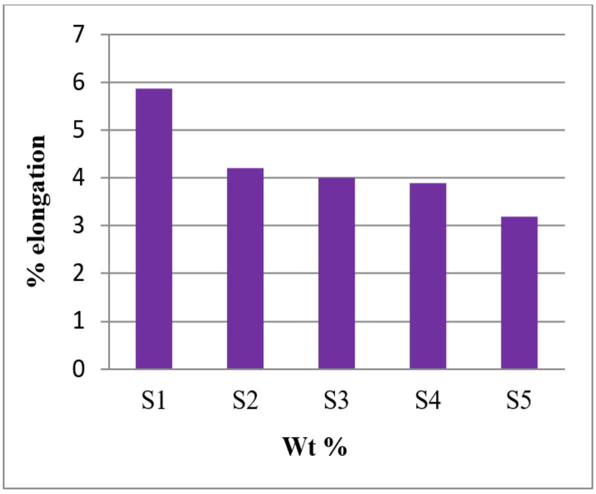

Figure 11. % Elongation of MMC

3.4 Microstructural studies

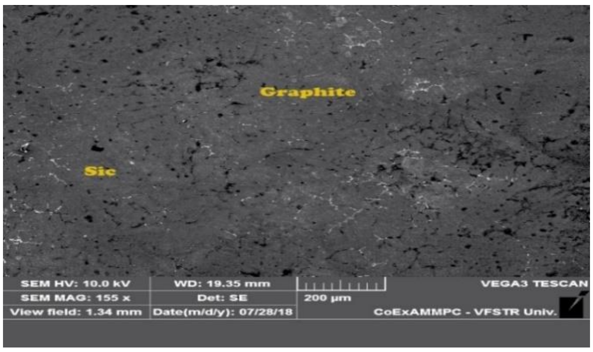

Figure 12. SEM of 6 wt.%

Microstructural studies were done for the best composition which is at 6 wt.%. To minimize height variations at interfaces and get rid of any geometric effects that result from the specimen surface, the sample needs to be polished into a smooth finish with emery paper. The studies were carried out using a Scanning Electron Microscope (SEM). Figure 12 shows the presence of SiC and Graphite particles are uniformly distributed. The dendritic structure was equally shaped and shows a uniform distribution, which indicates improvements in strengths up to 6 wt.% after that due to particle agglomeration the strength decreased [25].

4. WEAR AND FRICTION

4.1 Effect of load on the wear rate

Table 3. Wear rate values at load 1kgf, 2kgf, 3kgf

Load	Sliding Distance	% of Reinforcement				
		0%	2%	4%	6%	8%
1kgf	1000	0.87	0.0041	0.003	0.002	0.005
	1500	0.9	0.0041	0.0032	0.0022	0.006
	2000	0.9	0.0041	0.0033	0.0024	0.0062
2kgf	1000	0.87	0.0055	0.003	0.002	0.0074
	1500	0.9	0.005	0.0032	0.0025	0.0083
	2000	0.92	0.0056	0.0033	0.0027	0.0083
3kgf	1000	0.87	0.0041	0.003	0.002	0.005
	1500	0.9	0.0041	0.0032	0.0022	0.006
	2000	0.9	0.0041	0.0033	0.0024	0.0062

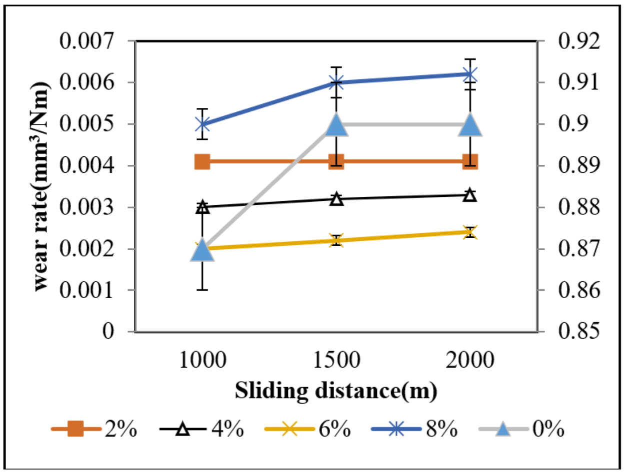

Figure 13. Wear rate at constant load of 1kgf

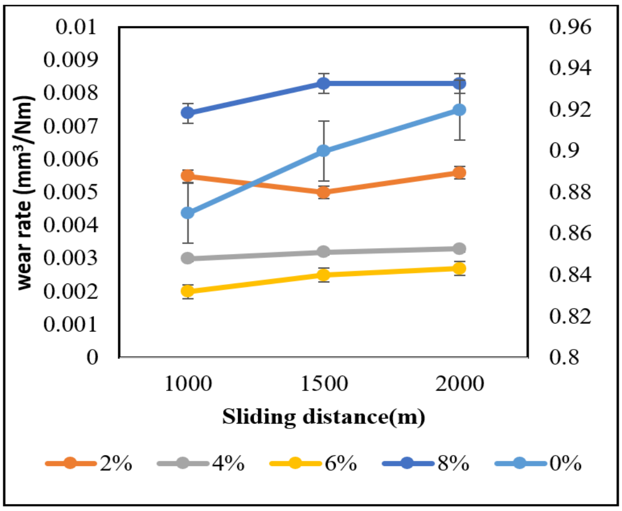

Figure 14. Wear rate at a constant load of 2kgf

The wear rate of Al MMC's and base alloy increased exponentially with increasing load and sliding distance, as shown in Figures 13-15. Hybrid composite, on the other hand, has a lower wear rate than the base metal. The Wear rate for different % reinforcements is as shown in Table 3.

In comparison to reinforced composites, the graphs show that the base alloy exhibits severe wear compared with others. Pins have a higher wear rate than other loads when applied at 3kgf and 2000m of sliding distance, as presented in Figure 15. With increased loads and sliding distances, however, the wear rate increases. In the comparison of wear rates at lower loads between alloy and composites, there is mildness due to decreased wear rates.

The composites, on the other hand, perform the base metal in terms of wear resistance. The results reveal that the wear-rate for base alloys and composites is lower at lower stresses, with the composites exhibiting significant wear resistance. The wear rate increases as the weight and distance increase promptly [25].

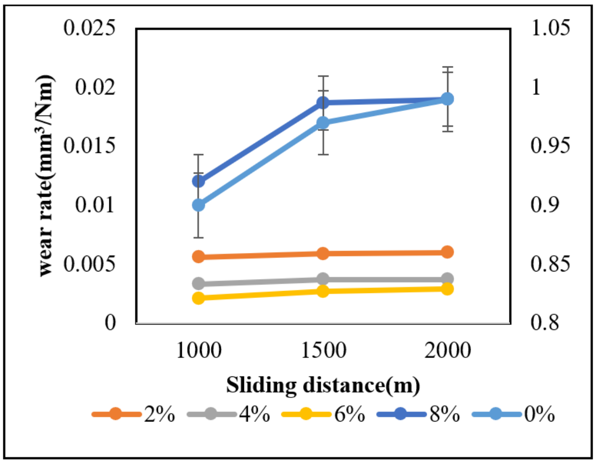

Figure 15. Wear rate at a constant load of 3kgf

4.2 Effect of load on the COF

The COF of Al MMCs and base alloy increased exponentially with increasing load and sliding distance as shown in Figures 16-18. The experimental values are tabulated in Table 4.

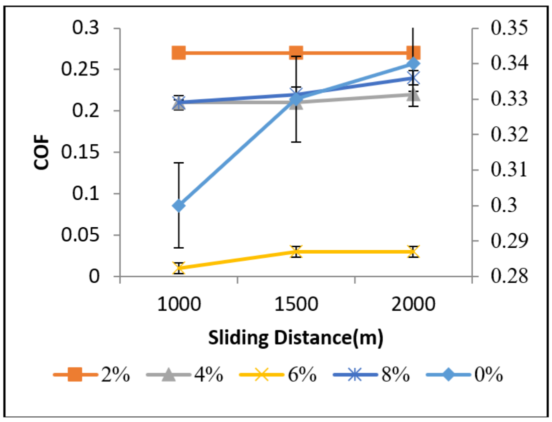

Figure 16. COF at load of 1kgf

Figures 16-18 show how different pins in hybrid composites have varying coefficients of friction at different loads. The sliding velocity and distance were kept stable during the experiment, at 150-450 rpm and 1000-2000 m, respectively. Frictional heat rises initially as a result of the increased contact area, which enhances the frictional coefficient. After that, it settles down to a specific value. As a function of sliding distance, it exhibits stick-slip-type frictional behavior at all weights. Different weight percentages of reinforcement showed a similar result. The COF increased as the sliding distances increased with the application of weights, according to the graphs [26, 27].

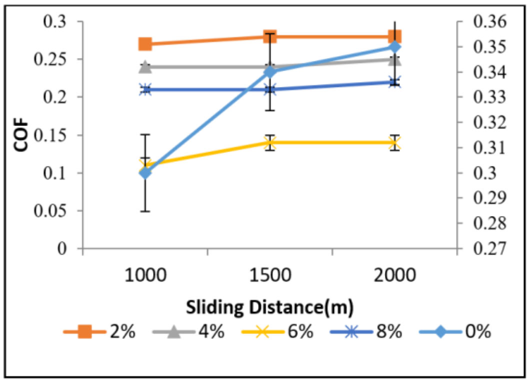

Figure 17. COF at load of 2kgf

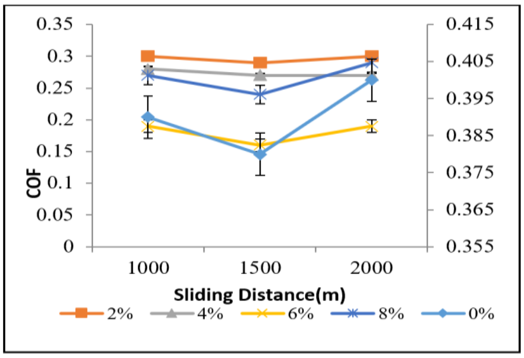

Figure 18. COF at load of 3kgf

Table 4. COF values at different loads

Load	Sliding Distance	% of Reinforcement				
		0%	2%	4%	6%	8%
1Kgf	1000	0.3	0.27	0.21	0.01	0.21
	1500	0.33	0.27	0.21	0.03	0.22
	2000	0.3	0.27	0.22	0.03	0.24
2Kgf	1000	0.3	0.27	0.24	0.11	0.21
	1500	0.34	0.28	0.24	0.14	0.21
	2000	0.35	0.28	0.25	0.14	0.22
3Kgf	1000	0.39	0.3	0.28	0.19	0.27
	1500	0.38	0.29	0.27	0.16	0.24
	2000	0.4	0.3	0.27	0.19	0.29

5. COMPARISON OF RESULTS WITH LITERATURE

Table 5 presents a comprehensive comparison between the current study and previous research conducted by other scholars focusing on Al6061 hybrid metal matrix composites. The findings indicate that the stir casting technique employed in this research aligns with the methodologies adopted in other literature. The investigation of mechanical properties, such as hardness, tensile strength, ductility, and fracture strength, was a common theme among the majority of the studies.

Table 5. Comparision of results

Author	Composite	Technique	Findings
Aruri et al. [28]	Al6061(8%SiC, 4%Gr)	Friction stir processing	Composite at 900, 1120 and 1400 rpm.UTS-219, 178, 157MPa Yield strength-185, 137, 115MPa, % Elongation-9.1, 6.4, 7.2
Vencl et al. [29]	A356, 10%SiC, Gr(1, 3%)	Compocasting	COF-0.64, 0.66, 0.69 Wear-5.86, 5.44, $1.37x10^{-4}$, mm^3/m
Kandagal et al. [30]	Al6061,3,6,9% SiC,6%Gr	Stir casting	SEM,XRD,UTS-115, 145, 195MPa % Elongation-6.8, 4.4, 3.4
Dwivedi et al. [31]	Al6061,Al_2O_3(2.5-15%) Flyash	Stir casting	Tensile, Hardness, Microstructure, Corrosion, Ductility
Present work	Al6061 2-8 wt.% of SiC, Gr	Stir casting	Mechanical and Tribological properties

6. CONCLUSIONS

In this work, the effect of reinforcement particles on mechanical and dry sliding wear parameters of Al6061/SiC /Gr hybrid composites was investigated using the stir casting process. The following inferences were made throughout the examination of the current work.

- Stir casting successfully produced Al6061 hybrid composites with up to 8% SiC and Graphite particles, resulting in the hardness, Tensile, compressive, and flexural strength of the composite being improved by 30%, 10.82%, 68.14%, and 85% respectively.
- Hardness increased up to 6% reinforcement content, reaching a maximum of 78BHN and 30% increase when compared to the unreinforced alloy.
- Graphite is a good reinforcement to use with an equal composition to enhance the tribological behavior of hybrid MMC.
- The wear rate of composites and unreinforced alloys increases dramatically as load increases. In any case, the composite samples wear rate is considerably lesser than that of the base alloy. At increasing loads, it was evident that a transition was required.
- At 2000m sliding distance and at 1kgf load of 6 wt.% Al hybrid composite have a 20% high wear rate than that of 1000m, 1kgf load.
- At 2000m sliding distance and at 1kgf load of 6 wt.% Al hybrid composite have an 18% high COF than that of 1000m, 1kgf load. At greater loads and distances, it was noticeable that a transition from mild to rigorous wear and COF was occurred.
- Among all the weight fractions 6 wt.% have superior mechanical and tribological properties.

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