Visual Abstract

Fabrication, mechanical and wear properties of Aluminum (Al6061)-silicon carbide-graphite Hybrid Metal Matrix Composites

G.B. Veeresh Kumar
Department of Mechanical Engineering, National Institute of Technology - Andhra Pradesh, Tadepalligudem, Andhra Pradesh, India.
veereshkumargb@nitandhra.ac.in

P. S. Shivakumar Gouda*
Research Center, Department of Mechanical Engineering, SDM College of Engineering & Technology, Dharwad, Visvesvaraya Technological University, Karnataka, India.
ursshivu@gmail.com

R. Pramod
Department of Mechanical Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Bengaluru, Karnataka, India.
ase.pramod@gmail.com

N.D. Prasanna, H.S. Balasubramanya
Department of Mechanical Engineering, Ramaiah Institute of Technology, Bengaluru, Karnataka, India.
baluhs.md@gmail.com

S.M. Aradhya
Department of Mechanical Engineering, Kalpataru Institute of Technology, Tiptur, Karnataka, India.

ABSTRACT. In recent times, the use of aluminum alloy-based Hybrid Metal Matrix Composites (HMMCs) is being increased in aerospace and automotive applications. HMMCs compensate for the low desirable properties of each filler used. However, the mechanical properties of HMMCs are not well understood. In particular, microstructural investigations and wear optimization studies of HMMCs are not clear. Therefore, further studies are required. The present study is aimed at fabricating and mechanical and wear characterizing and microstructure investigating of Silicon Carbide (SiC) and Graphite (Gr) added in Aluminum (Al) alloy Al6061 HMMCs. The addition of SiC particles was in the range from 0 to 9 weight percentage (wt.%) in steps of 3, along with the addition of 1 wt.% Gr in powder form. The presence of

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alloying elements in the Al6061 alloy was identified using the Energy Dispersive X-Ray Analysis (EDX). The dispersion of SiC and Gr particles in the alloy was investigated using metallurgical microscope and Scanning Electron Microscopy (SEM). The gain in strength can be attributed to the growth in dislocation density. The nature of fracture was quasi-cleavage. The microstructure examination reveals the uniform dispersion of the reinforcement. Density, hardness, and Ultimate Tensile Strength values observed to be increased with increased contents of SiC reinforcement. Besides, wear studies were performed in dry sliding conditions. Optimization studies were performed to investigate the effect of parameters that affecting the wear. The sliding wear resistance was noticed to be improved concerning higher amounts of reinforcement leading to a decrease in delamination and adhesive wear. The predicted values for the wear rate have also been compared with the experimental results and good correlation is obtained.

KEYWORDS. HMMCs; SEM; Ultimate tensile strength; Dislocation density; Siding wear; Optimization.

INTRODUCTION

Metal Matrix Composites (MMCs) have created a lot of interest among researchers all over the world owing to their excellent properties [1-3]. It is almost four decades since then MMCs have taken the right shape and have been found as a potential candidate material substituting for conventional metals and alloys in different applications owing to their properties withstanding strengths at elevated temperatures [4, 5]. The main constituents of MMCs are the metal or the alloy and other elements are embedded in the bulk metal usually referred to as the reinforcement. The reinforcement additions in MMCs may be in the form of powder, fine particulate, fibers or whiskers form, etc. These reinforcing materials exhibiting high strength, stiffness, improved wear resistance properties, lower weight, better thermal expansion coefficient [6]. In particular, ceramic reinforcing particulate silicon carbide (SiC) filled MMCs have improved impact and wear resistance, high electron mobility and thermal conductivity [7, 8]. Owing to these advantages, SiC filled MMCs have been used in automotive and motor components such as engine heads, pistons, cylinder embed rings, calipers, vibrator application parts, and space-related structures [9-10]. The liquid metallurgy route is employed to produce particulate MMCs successfully [11]. Because of their low density and excellent mechanical characteristics, aluminum alloys are desired components for mineral processing, marine, automotive, even aerospace applications. In recent years, aluminum alloy-based hybrid metal matrix composites are being widely used in aerospace, automotive and electrical applications [5, 12]. This is owing to advantages of HMMCs such as lightweight, good strength and stiffness, low coefficient of thermal expansion, design adaptability, good corrosion and wear resistance, etc. Among several Al alloys, the use of Al6061 is significant and is studied for its outstanding properties [13]. Al6061 is corrosion-resistant, easily formable and machinable, and possesses good strength [7]. As the matrix is reinforced with fine particulates, it forms excellent composites that can be used in elevated applications and reinforced with ceramic particulate. In comparison to other characteristics, material stiffness has a greater impact on the sliding wear of Al6061-Al2O3 reinforced composites [14]. The wear of Al6061 and Al6061-Titanium Dioxide (TiO2) filled composites has a significant impact on machine part damage [15, 16]. Wear is a phenomenon wherein the contacting rubbing surfaces experience friction leading to the surface damage of the mating surfaces [17, 18]. The study of wear now has gained importance and has found itself as a property to characterize materials, especially concerning the applications involving the surfaces in contact having relative motion examples such as bearing, engine components, agricultural implements, etc. [19]. It was demonstrated that the temperature and load affect the wear of Al6061 composites with SiC filler additions and reported to have reduced wear rate with increased load [20]. In the examination of wear performance of short fiber, Saffil filled Al6061 composites are noteworthy in increasing wear resistance [21]. MMCs made from 15 vol percent SiC and produced by powder metallurgy were found to have good wear resistance in sliding [22]. The friction and wear resistance of composites are influenced by the microstructure and wear parameters. During the wear test of Al2219 composites, extreme wear and fracturing of SiC particles were found to increase with increasing loads [23]. When combined with load and sliding direction, the sliding wear distance factor has the greatest impact on composite wear [24]. Due to an improvement in temperature of Al6061 alloy during dry sliding, a moderate to extreme wear transition was observed [25]. The Al6061-Albite and Al6061-Gr studies revealed that increasing the number of Gr filler resulted in higher elongation, ductility, and resistance at lower hardness while controlling the value of albite filler resulted in higher Ultimate Tensile Strength (UTS) and hardness with lower ductility [26]. Mechanical and wear characterization studies related to HMMCs are limited and not well understood. In particular, the optimization studies to identify the parameters which affect the wear performance are limited. Therefore, further studies are essential to fill this research gap. This study aims to fabricate Al6061-SiC-Gr HMMCs and investigate their density, microstructure, mechanical characteristics, and dry wear behavior with various percentages of SiC additions, as primary reinforcement while the secondary reinforcement Gr particulates of 1 wt.% was maintained constant. Microstructure examination, theoretical and experimental density, mechanical properties such as hardness, UTS measurements were carried out as per the ASTM Standards. The experimental data and optimization results presented in this study will be useful in developing aluminum alloy-based process models.

MATERIALS AND METHODS

Materials

The matrix Al6061 alloy in ingot form was acquired from Fennfee Metallurgical, Bengaluru. The Al6061 alloy chemical composition is specified in Tab. 1. The reinforcing materials selected were SiC with an average particle size of 50µm acquired from Dalli Electronics, Mumbai, India, and Graphite of particle size average of 50 µm supplied by Graphite India Limited, Bengaluru, India. Different properties of materials used in this study are given in Tab. 2.

Chemical composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al6061	0.61-0.62	0.23	0.22	0.03	0.84	0.22	0.10	0.01	Bal

Table 1: Al6061 alloy chemical composition by wt%.

Material	Elastic Modulus (GPa)	Density (g/cm³)	Hardness (HB500)	Tensile Strength (MPa)
Al6061	70-80	2.7	30	115
SiC	410	3.1	2800	3900*
Gr	8-15	2.09	16.67	20 – 200

* Compressive Strength,

Table 2: The base matrix and reinforcement materials properties.

Fabrication of HMMCs

The fabrication of HMMCs for the present work was done via the liquid metallurgy method through stir casting technique which produces the even distribution of the reinforcement was adopted for fabrication. Upon receiving the alloy in its molten form, catalysts along with Magnesium (Mg) chips, Hexachloroethane (C2Cl6) solid degassing tablets, and Coverall were used to improve wettability, separate gases from the molten alloy, and create a barrier between the atmosphere and the molten content. A manual stirrer with a ceramic-coated impeller was used to ensure optimal mixing for 10 minutes at a rotational speed of 400rpm. The molten aluminum was used at 720 degrees Celsius, and the molten composite was poured into preheated cast iron cylindrical mold cases. The incorporation of SiC in Al6061 was varied from 0 to 9 wt. percent in 3 wt. percent phases while keeping the Gr reinforcement stable at 1 wt. percent. Cast HMMCs of Al6061-SiC-Gr were received in solid and cylindrical-shaped tubes with dimensions of 22mm X 210mm.

EXPERIMENTAL DETAILS

The Al6061-SiC-Gr HMMCs test specimens were machined to the recommended specifications as per ASTM standards. The density of composites, the weight to volume ratio were measured using a micro-scale electronic weighing machine and the dimensions were measured by using electronic Vernier calipers. Micro-structural details, hardness, tensile strength, and wear behavior were studied using the samples.

MICROSTRUCTURE DETAILS

Microphotographs of composites were acquired using a NIKON 150 ECLIPSE metallurgical microscope and Field Emission Scanning Electron Microscope (SEM) with Energy Dispersive Spectroscopy (EDX): JEOL JSM-7100F at Center for Nano and Material Sciences, Jain University, Bangalore was used to study the SEM images of the composites.

MECHANICAL AND WEAR TESTS DETAILS

Hardness studies were carried out as per ASTM E-384 using Highwood micro Vicker's hardness tester. The tensile tests were conducted on different weight percentages of HMMCs as per ASTM – E8/E8M-08 standard by using a computerized universal testing machine (UTM) (TUE – 400C Fine Spavy Associates). Tension test specimens were machined to the required dimensions using a computerized lathe. The dry sliding wear resistance of the Al6061-SiC-Gr HMMCs was investigated. Dry sliding wear tests were conducted using a POD tribometer apparatus [Model: Ducom, Bangalore - INDIA make Model TR20]. Fully computerized Pin-on-disc dry sliding wear equipment was used to conduct wear tests. The composite cylindrical pin was 10mm diameter X 10mm height and the disc material was against EN31 steel. Wear height loss of the matrix and HMMCs pin was observed due to wear. An LVDT transducer-assisted LED display of the wear monitoring device reported the amount of height loss due to wear. A load of 10N, 20N, 30N, and 40N on the pin was varied and a sliding distance of 3000m was maintained. The pin and the surface roughness of the disc of 0.1μm Ra were preserved.

RESULTS AND DISCUSSIONS

Optical studies of Al6061 Matrix Alloy and its HMMCs

Fig. 1 shows the EDX analysis with the presence of Si and Mg content in Al received from the supplier approves standard of Al6061 base matrix used for the current studies. Al6061 alloy forms a major alloy that finds its application in the manufacture of components used in the transportation and automobile sector. The microphotographs of composites were obtained when inspected through a metallurgical microscope. Microstructure examination was carried out on the base alloy and the alloy with SiC and Gr reinforcement additions. A standard metallographic procedure involving surface grinding, polishing, etching was employed for structure examination. The optical micrograph of the Al6061 and the other one Al6061-SiC-Gr HMMCs reinforced with 9wt.% of SiC and 1wt.% of Gr shown in Fig. 2(a) and 2(b) respectively. Fig. 2(a) indicates that the microphotographs only include a small proportion of the alloy matrix of Al dendrites, while Fig. 2(b) indicates Al solid solution dendrites with a few randomly dispersed reinforcement components in the matrix. In Fig. 2(b), micrographs also clearly display the increase in filler contents in the composite. It is correspondingly apparent from the microphotograph that a minor amount of porosity was observed. It is described further that the lower porosity of HMMCs is always related to higher hardness [27]. Additionally, from the microphotograph, a decent bonding amongst the matrix and the filler particulates was noticed, hence enhanced transmission of load from Al6061 onto filler particles which, results in enhanced load-carrying capability of composites. The SiC particles are seen to be angular in shape and are dispersed uniformly in the matrix. Also, the good interfacial bonding of the reinforcing phase with the matrix phase will lead to higher hardness values. Furthermore, figures indicated that the consistency of the fabricated composites.

Physical Properties

Fig. 3 compares the density values determined by the law of mixtures and the weight to volume ratio of composites with different percentages of filled SiC contents and the density readings from the law of mixture and the weight to volume ratio density readings match, indicating that the liquid metallurgy method of fabrication is appropriate. The composite material's density rose by 1.1 percent. As the percentage of SiC particles in the composite material rose from 0 to 9 wt%, the density of the material increased by 1.12%.

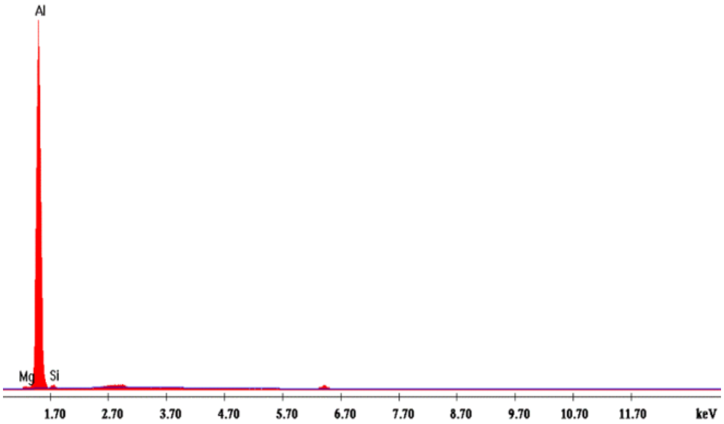


Figure 1: EDX image of Al6061 matrix alloy.

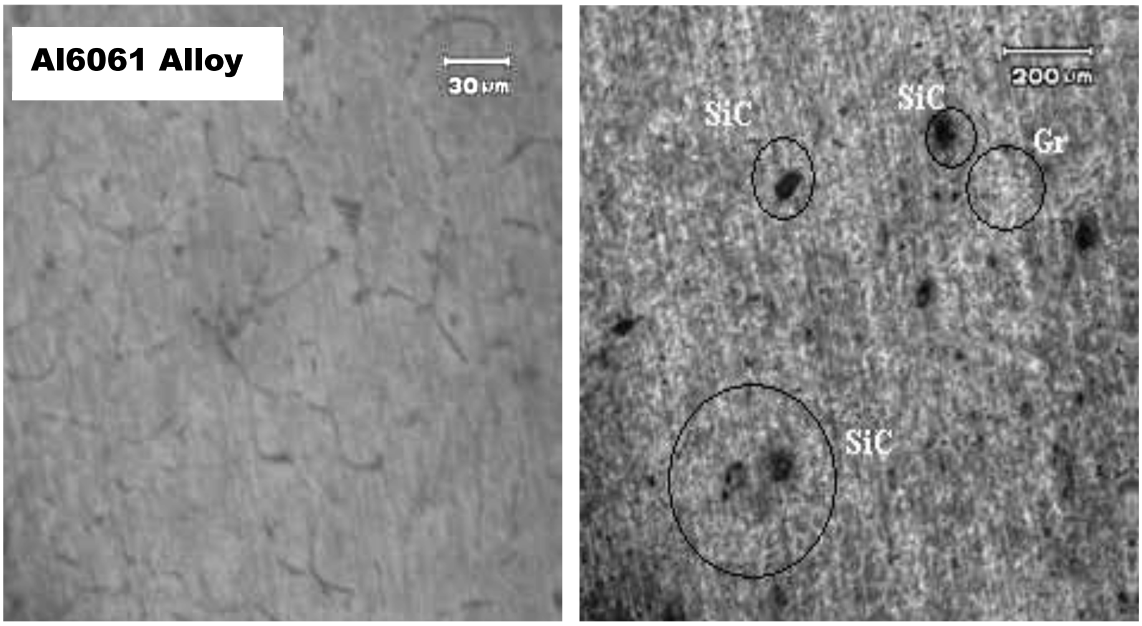


Figure 2: Optical micrograph of (a) Al6061 alloy, (b) MMC (Al6061-9wt.% SiC-1wt.% Gr).

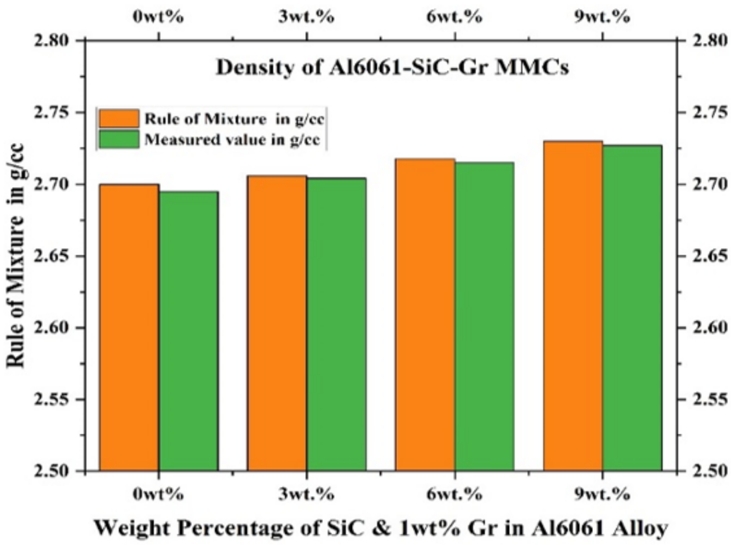


Figure 3: Density values of Al6061-SiC-Gr HMMCs.

The measured densities of the Al6061-SiC composites are greater than the base composites. The densities of the composites are expected to improve as the amount of SiC content added to the Al6061-SiC composites increases [28]. The higher densities of Al6061- 9wt.% SiC-1wt.% Gr HMMCs may be due to higher values of density of reinforcement material SiC[29]. The Al6061-SiC-Gr HMMCs with higher SiC reinforcement filler content shows greater higher density. The Density of composites Al6061-SiC-Gr rises by 1.19% with the increase in SiC content from 0 to 9 wt% [30]. Also, an increase in Al6061-SiC-Gr HMMCs density is due to lower porosity in the fabricated composites. Gas entrapment during the mixing process, shrinkage during solidification, hydrogen gas evolution, and the entry of air bubbles in the liquid composite or an air shell surrounding filled SiC-Gr reinforcement particulates can all be responsible for differences in porosity values in HMMCs. As a result, as the weight proportion of SiC-Gr reinforcement increases, the porosity increases as shown in Fig. 4.

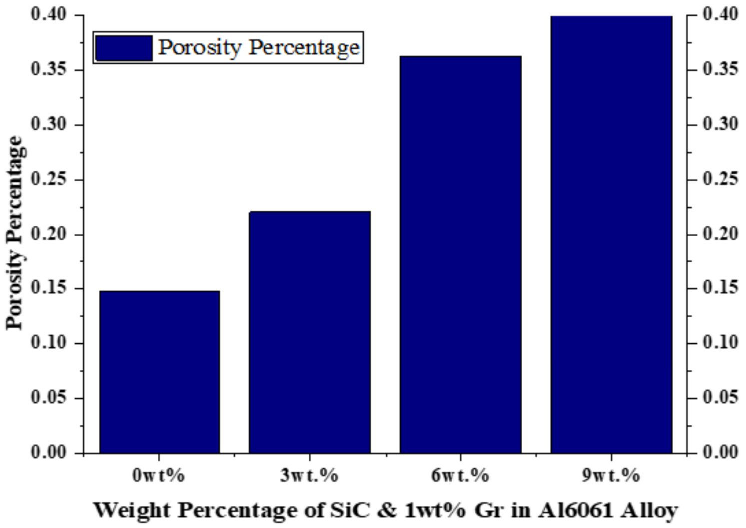


Figure 4: Variation in Porosity of Al6061-SiC-Gr HMMCs.

Mechanical properties

Standard procedures were employed to assess the tensile strength using computerized UTM and the hardness values using Vickers microhardness tester. Assessments were made for the base alloy and the Al6061-SiC-Gr HMMCs with reinforcement additions.

Hardness studies

Hardness accounts for one of the prime characteristics of composite materials which, directly affects the properties such as strength, toughness, fatigue, and resistance to sliding wear of alloy and HMMC materials. The resistance to plastic deformation - hardness test for alloy and HMMCs specimens were done with Highwood micro Vicker's hardness tester and was carried out as per ASTM E92 - 17 standard at room temperature on alloy Al6061 and its SiC-Gr filled composites. Fig. 5, shows the histogram drawn for the hardness values of Al6061 base alloy and its SiC-Gr reinforced HMMCs. It can be seen from the histogram that the base alloy exhibits the least hardness value. Increased hardness values are observed with the reinforcement additions. Al6061 alloy with 9wt.% addition of SiC has resulted in a higher hardness value. This may be attributed to the higher hardness of the SiC particles which is present in the matrix [13]. HMMC's hardness was observed to increase by an amount of 65% as the content of SiC particles rises from 0 to 9 wt%. Owing to the thermal imbalance between the Al6061 matrix alloy and the SiC-Gr reinforcement, increased reinforcement material in the matrix alloy contributes to higher dislocation densities upon solidification.

This causes significant internal stresses and strain mismatch, which affects the microstructure and strengthens the composites' mechanical properties. The matrix deforms plastically to satisfy the reinforcement particles' reduced volume growth, resulting in a higher density of dislocations. Increased dislocation densities result in increased resistance to plastic deformation with an increase in yield strength, as well as an improvement in composite stiffness as shown in Fig. 6.

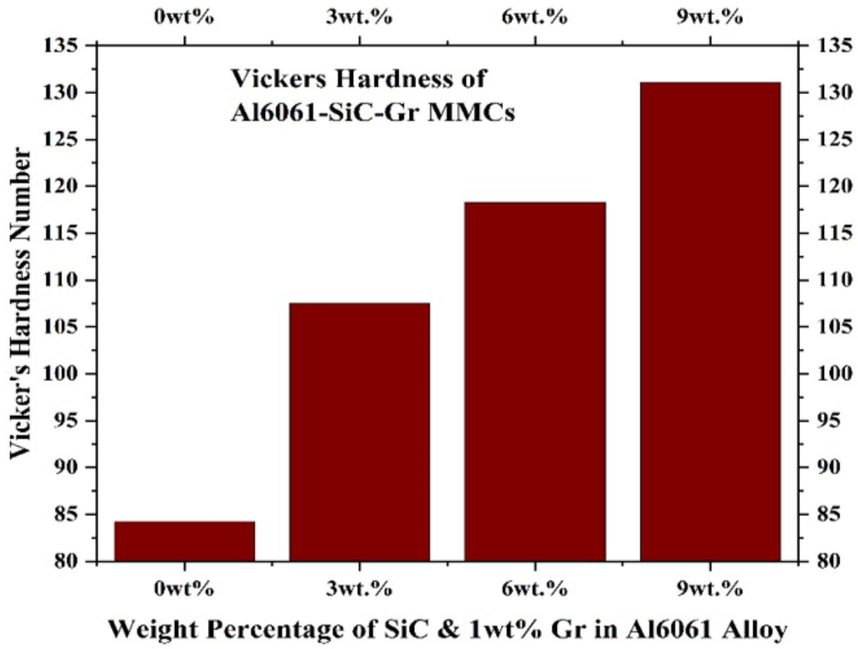


Figure 5: Hardness values of Al6061-SiC-Gr HMMCs.

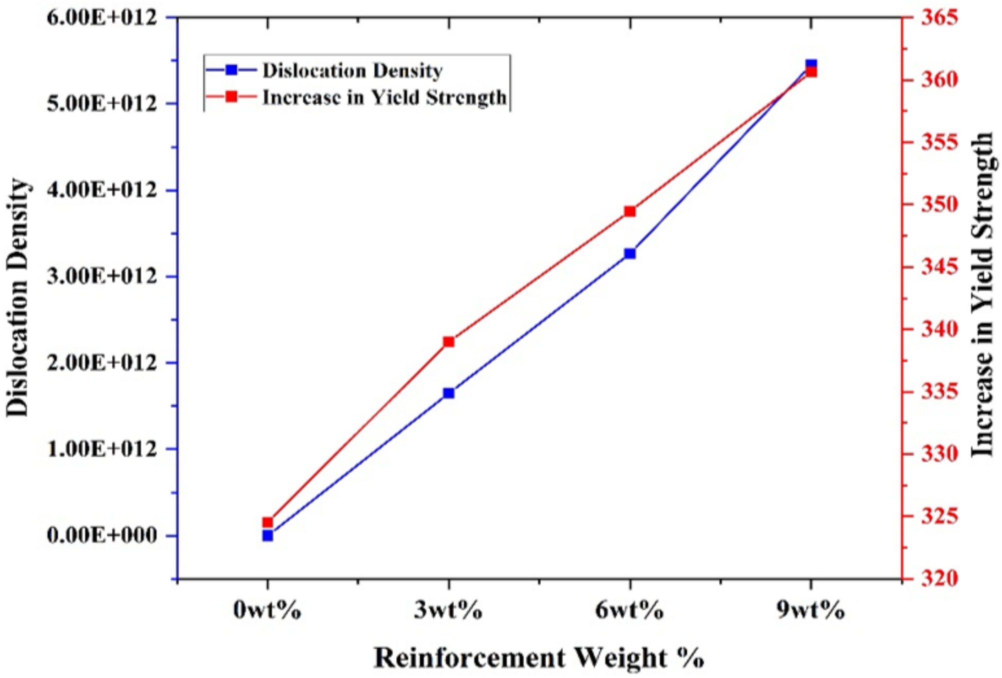


Figure 6: Dislocation Density and Increase in Yield strength of Al6061-SiC-Gr HMMCs.

Tensile properties

Fig. 7 shows the tensile properties (ultimate tensile strength (UTS) and %elongation) of different weight percentages of HMMCs. The variation in UTS of Al6061-SiC-Gr HMMCs with a growth in the percentage of SiC particles is observed from the figure. The UTS of HMMCs improved by a magnitude of 73.8% with the increase in weight percentages of SiC particles from 0 to 9 wt%. The increase in strength is due to the increase in hardness of the Al6061-SiC-Gr HMMCs with effective distribution of load from matrix to reinforcement particulates. The trial was conducted at room temperature, and the findings are in line with the observations of other researchers' studies [29]. However, the continuous decrease in %elongation with the increase in weight percentages of SiC particles is also observed. The ductility drops by 26% with the content of SiC varied from 0 to 9 wt%. The found results were in-line with the other scientists [31] who also noticed that the reduced ductility with higher SiC particulate content. This is due to change in failure mechanisms from ductile to brittle, with the increase in SiC particulate contents.

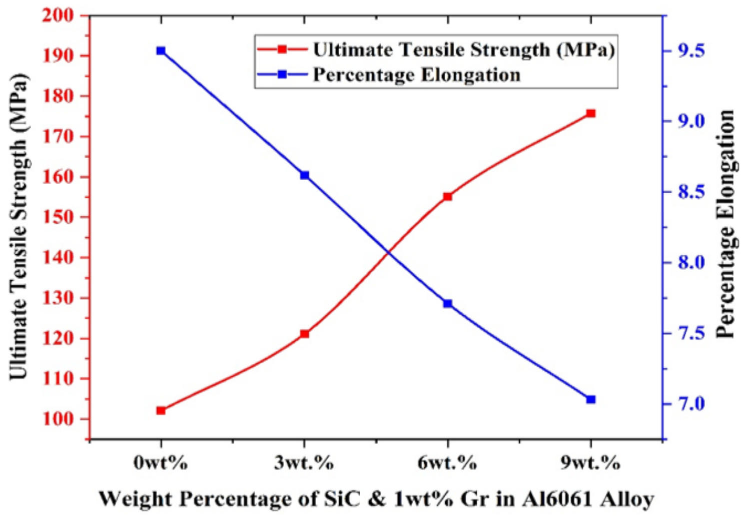
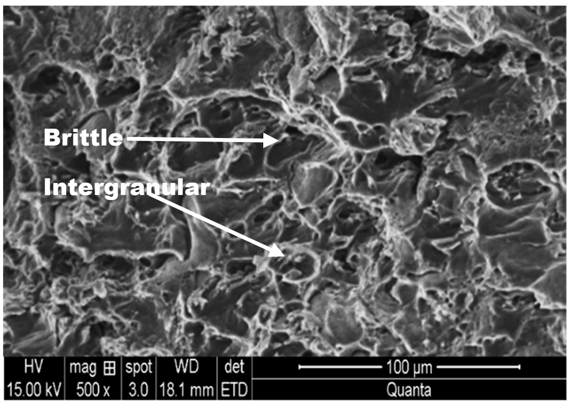
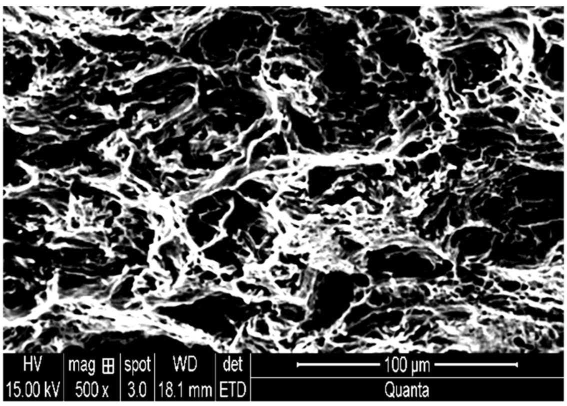


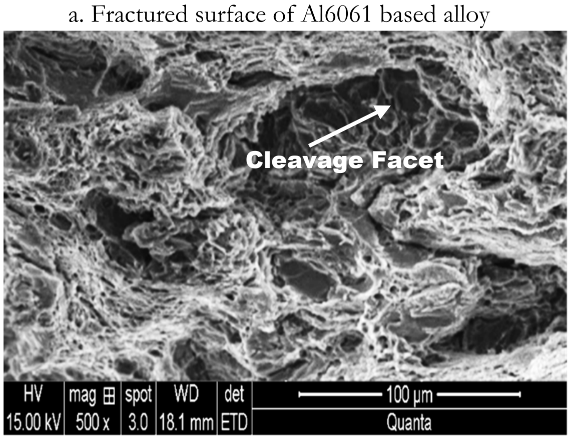
Figure 7: UTS and percentage elongation values of Al6061-SiC-Gr HMMCs.



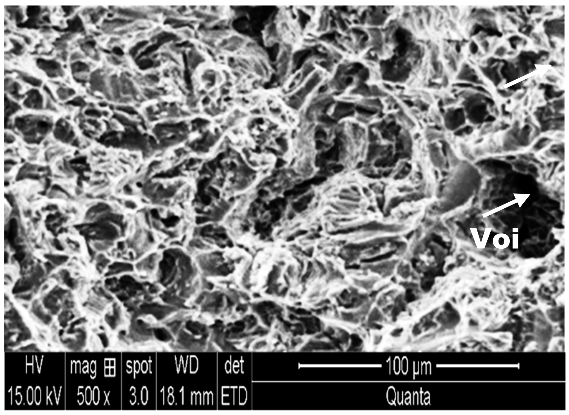
a. Fractured surface of Al6061 based alloy



b. Fractured Al6061-3wt% SiC – 1%Gr MMCs.



c. Fractured Al6061 - 6wt% SiC – 1%Gr MMCs.



d. Fractured Al6061- 9wt% SiC – 1%Gr MMCs.

Figure 8: a-d. SEM micrographs of tensile test fractured sides of Al6061 and Al6061- SiC - Gr HMMCs.

In Fig. 8 a-d, SEM micrographs show the fractured surface of Al6061-SiC-Gr HMMCs particulate reinforced composites. From SEM images, good bonding between the Al6061 base matrix and the reinforcements is observed. As expected, that the change of microstructure from ductile to brittle with the increase of weight percentages of particles in the base alloy. Similar kinds of results were reported elsewhere [32]. The loss of ductility with the increase in the hardness and strength characteristics are most commonly noticed in the ceramic reinforced Al-based HMMCs. These results were comparable to those obtained by numerous researchers [33]. The reinforcement particles have a considerable effect on the composites' mechanical properties, which is due to generation tension in the interface, which aids in the transfer and distribution of the load from the matrix to the reinforcement, resulting in improved elastic modulus and strength in the case of samples containing SiC-Gr particles, the fracturing mode is usually mixed, with dimple-oriented rupture and de-cohesive natured rupture. It's also possible to see quasi-cleavage fracturing in a few areas. Quasi-cleavage is a type of cleavage that has both cleavage and plastic deformation characteristics [34].

Wear studies

Numerous experiments were conducted on the Al-HMMCs to determine the dry wear characterizations of the composites and several researchers submitted reports related to dry sliding wear in the past couple of decades. In the current study, dry sliding wear tests were carried out at room temperature on the fabricated HMMCs. The ASTM standards followed for the dry wear test were according to standards of ASTM-G99 and constant sliding velocity was maintained. The weight-loss method was employed to assess the wear of the specimen. The specimen in the form of a pin (8mm dia x 30mm height) was made to slide against a standard EN19 wear disc. Wear parameters such as load, sliding distance, sliding speed were varied, which can be seen in Tab. 3.

Input Parameter	Levels			
	1	2	3	4
Normal Load (N)	10	20	30	40
Sliding Distance (m)	500	1000	1500	2000
Sliding Speed (RPM)	100	200	300	400
Composition	Al6061	Al6061+3%SiC +1%Gr	Al6061+6%SiC +1%Gr	Al6061+9%SiC +1%Gr

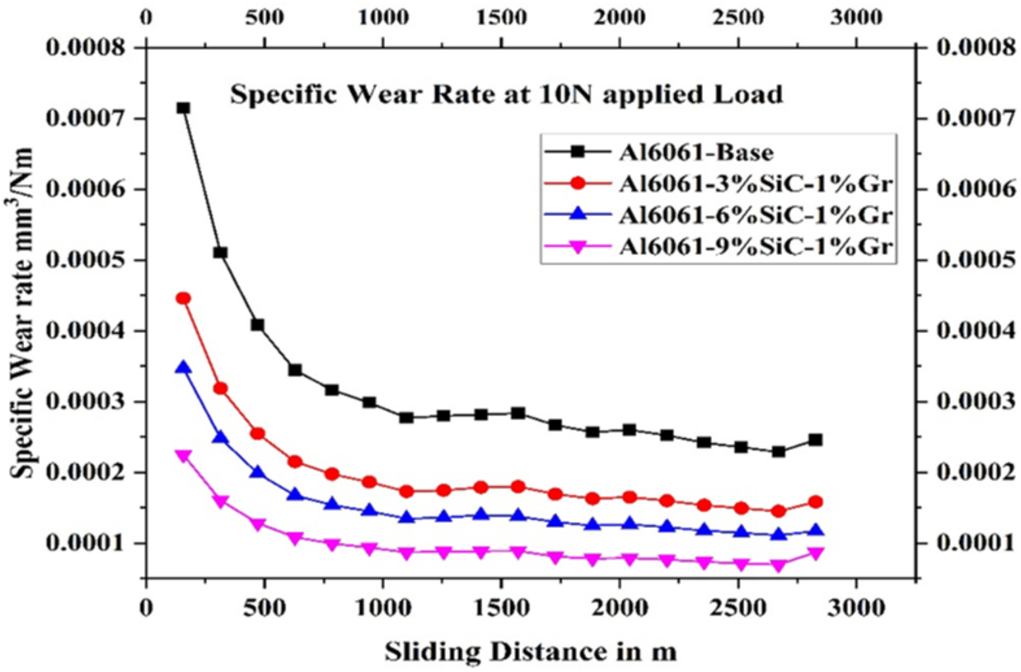
Table 3: Wear parameters at different levels.

From the dry sliding wear studies carried out on the base metal and with reinforcement addition, the results indicate that with an increase in the duration of testing height loss also increases. Severe wear is seen with the as-cast specimen (base metal) whereas less wear is seen with the specimen reinforced with SiC additions. Increased wear resistance is seen with the specimen reinforced with 9 wt.% addition indicating that the reinforcement addition increases the wear of the specimen. Specific wear rate was determined using the obtained data. The analysis was carried out using MINITAB 17 software. Signal to noise rations was considered for the analysis. ANOVA was used to study the effect of each input parameter on the wear behavior of the composite. Regression analysis was used to develop a mathematical model for the wear rate of each component of the specimen for confirmation.

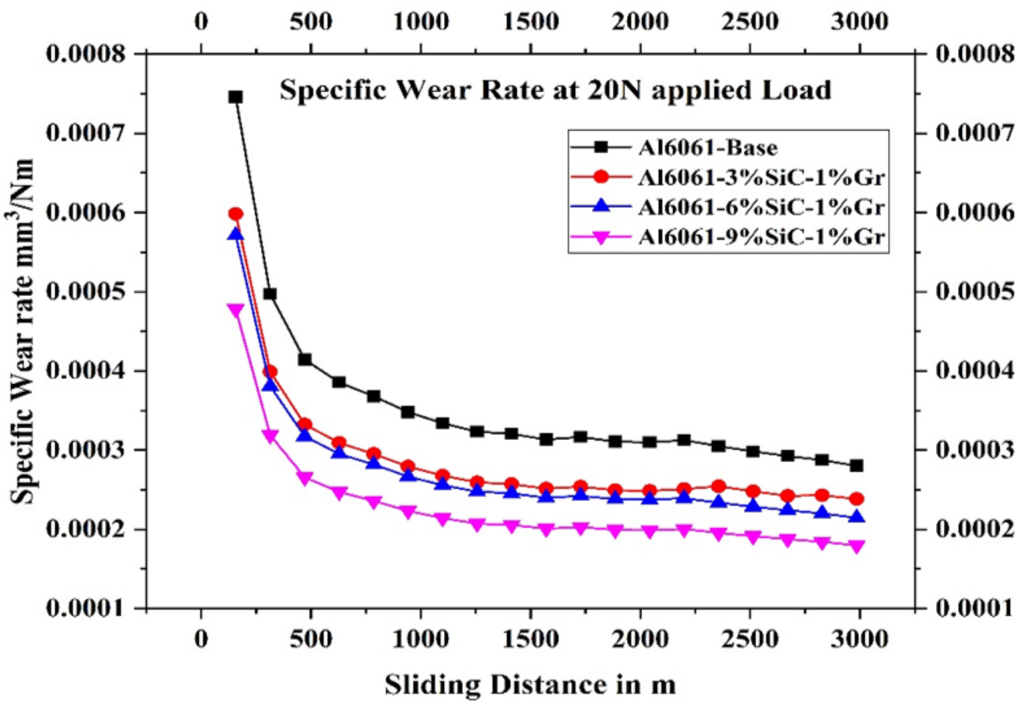
Studies on Dry sliding wear of Al6061-SiC-Gr MMCs

The Al6061 based MMCs were exposed to several tests, and the wear behavior of these composites was thoroughly investigated, as stated by many researchers over the past 25 years. On a wear test rig, the pin-on-disc dry sliding wear investigation was carried out at a velocity of 2.62m/s.Figs. 9 (a-d) show the basic wear rate of Al6061 and its SiC filled HMMCs at various sliding distances. The material wear loss of the Al6061 alloy and its HMMCs increases as the sliding distances increase, as seen in the graphs. As the sliding increases, the temperature of the sliding surface rises, softening the matrix and composites and promoting greater wear weight loss. Figs. 9 (a-d), the composites specific wear rate was lesser in contrast by matrix and reduce by higher SiC weight percentage particulate additions, further, maybe accredited to improved composites hardness and is directly proportional to increase in wear resistance. Also, the resistance to seizure of composite materials increases with the improvement in the hardness [35, 36]. The wear rate of base and HMMC's is influenced by the applied load, which is the most important factor regulating the wear. The wear height loss of the Al6061 matrix and HMMC's increases as the load increases. The wear loss of the HMMC's decreased as the weight percentage of SiC filler in the alloy increased, according to the estimates. Wear on the HMMC's is smaller than on the base Al6061 alloy.

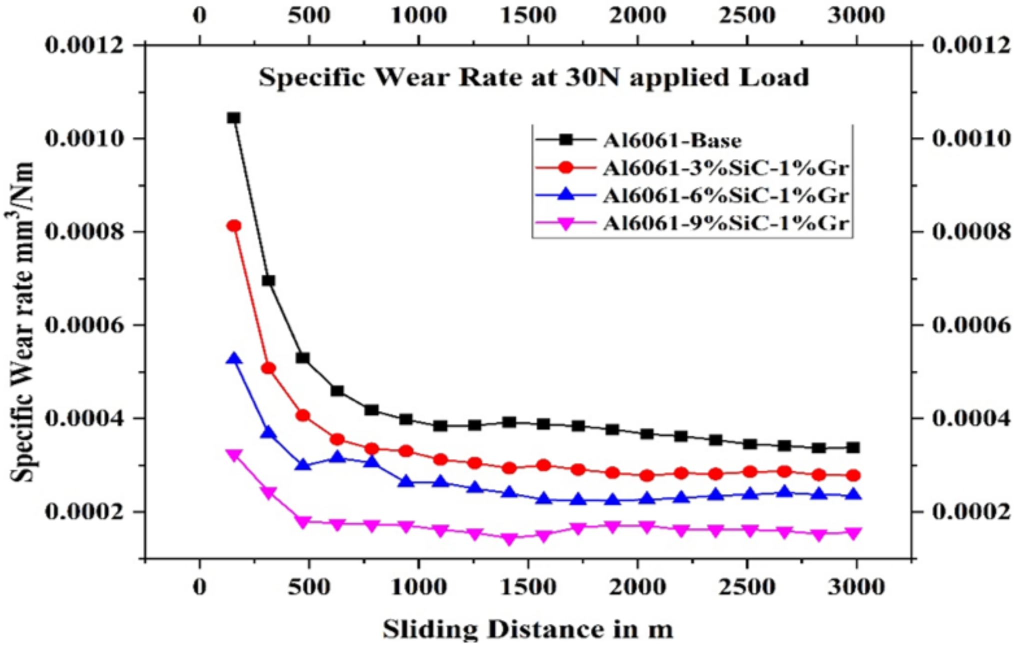
The increased wear resistance of composites due to particulates reinforcements addition resulting in higher hardness in HMMC's. Further, the Gr will also act as a solid lubricant, which in turn responsible for the reduction in the wear height loss of the Al6061-SiC-Gr filled composites [37, 38].



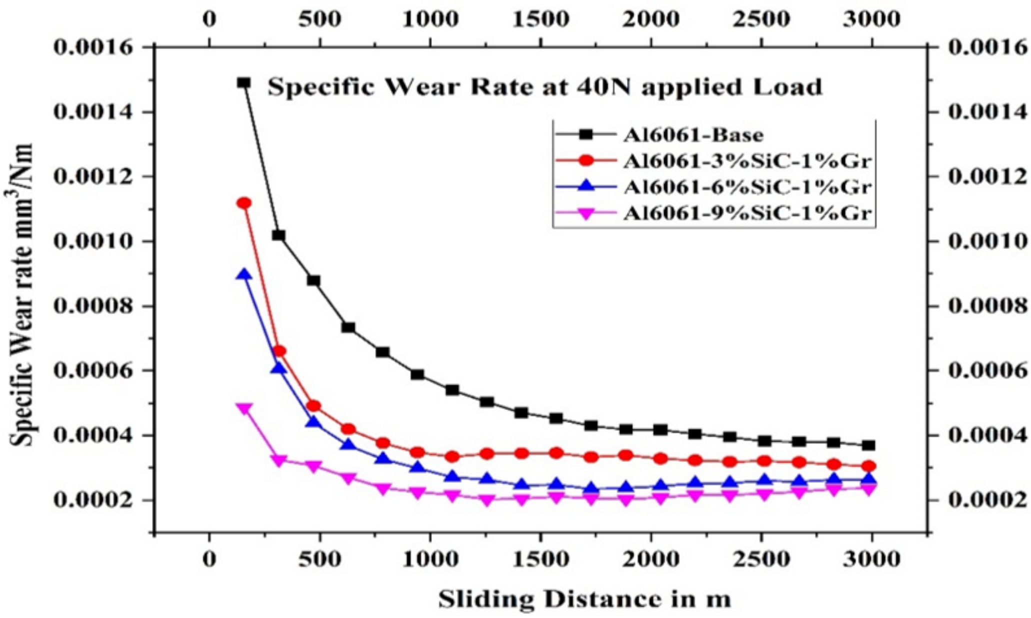
a. At 10N applied load.



b. At 20N applied load.



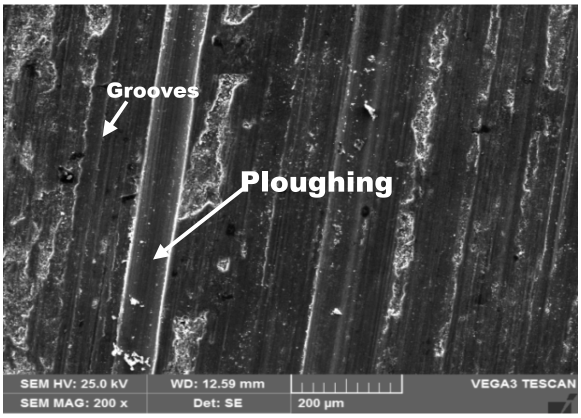
c. At 30N applied load.



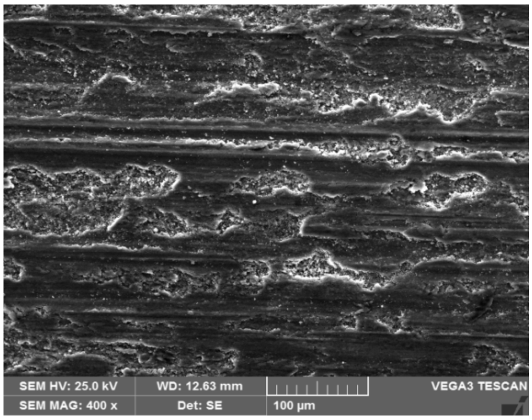
d. At 40N applied load.

Figure 9: a-d. The specific wear rate of Al6061 Alloy and SiC- Gr MMCs with a 3.0 km sliding distance at 10 – 40 N loads.

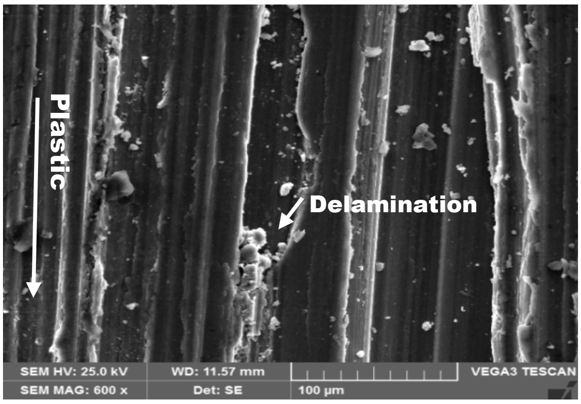
Fig. 10 presents the SEM photographs of worn surfaces of cast Al6061 alloy and its SiC and Gr filled composites at an applied load of 10N to 40N and a sliding distance of 3.0km. At 40N load, the composites of 9wt% SiC exhibits lower wear loss. The degree of grooves formed on the wear track of matrix alloys and composites containing lower volume fractions of SiC reinforcement is extremely large at higher loads, and the matrix alloys and composites containing lower volume fractions of SiC reinforcement undergo significant permanent deformation, resulting in serious wear. The volume of grooving in composites increased as SiC and Gr material increased. This phenomenon is quite evident from SEM photographs shown in Figs. 10a to 10d [35, 37].



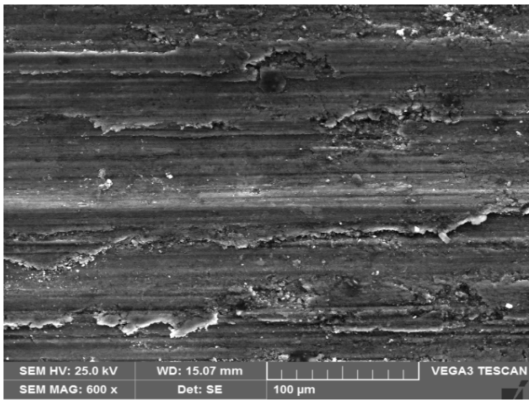
a. SEM Image of worn-out Al6061 alloy.



b. SEM of worn-out Al6061-3wt% SiC.



c. SEM of worn-out Al6061-6wt% SiC.



d. SEM of worn-out Al6061-9wt% SiC.

Figure 10: a-d. SEM photographs of worn-out Al6061 alloy and alloy with SiC and Gr additions

Sl.No	Applied Load, N	Sliding Speed, rpm	Sliding distance, m	Composition	Specific Wear rate mm^3/Nm	S/N Ratio
1	10	100	500	Al6061	0.00584	44.6717
2	10	200	1000	Al6061+3%SiC+1%Gr	0.000618	64.1802
3	10	300	1500	Al6061+6%SiC+1%Gr	0.000652	63.7150
4	10	400	2000	Al6061+9%SiC+1%Gr	0.000755	62.4411
5	20	100	500	Al6061+6%SiC+1%Gr	0.000261	71.6672
6	20	200	1000	Al6061+9%SiC+1%Gr	0.000289	70.7820
7	20	300	1500	Al6061	0.000489	66.2138
8	20	400	2000	Al6061+3%SiC+1%Gr	0.000434	67.2502
9	30	100	500	Al6061+9%SiC+1%Gr	0.000236	72.5418
10	30	200	1000	Al6061+6%SiC+1%Gr	0.000285	70.9031
11	30	300	1500	Al6061+3%SiC+1%Gr	0.000221	73.1515
12	30	400	2000	Al6061	0.000279	71.0879
13	40	100	500	Al6061+3%SiC+1%Gr	0.000243	72.2879
14	40	200	1000	Al6061	0.000204	73.8074
15	40	300	1500	Al6061+9%SiC+1%Gr	0.000195	74.1993
16	40	400	2000	Al6061+6%SiC+1%Gr	0.000219	73.1911

Table 4: Wear rate for different testing conditions.

OPTIMIZATION USING S/N RATIOS AND ANOVA

Analysis of variances (ANOVA) was utilized to find the factually huge parameters affecting the execution criteria during wear testing of composite example and to evaluate the rate commitment of each control factor on wear rate. Here the examination was done for the confidence level of 95%. The experiment is conducted for 16 trials as highlighted below. Wear rates obtained for L16 trials in Tab. 4.

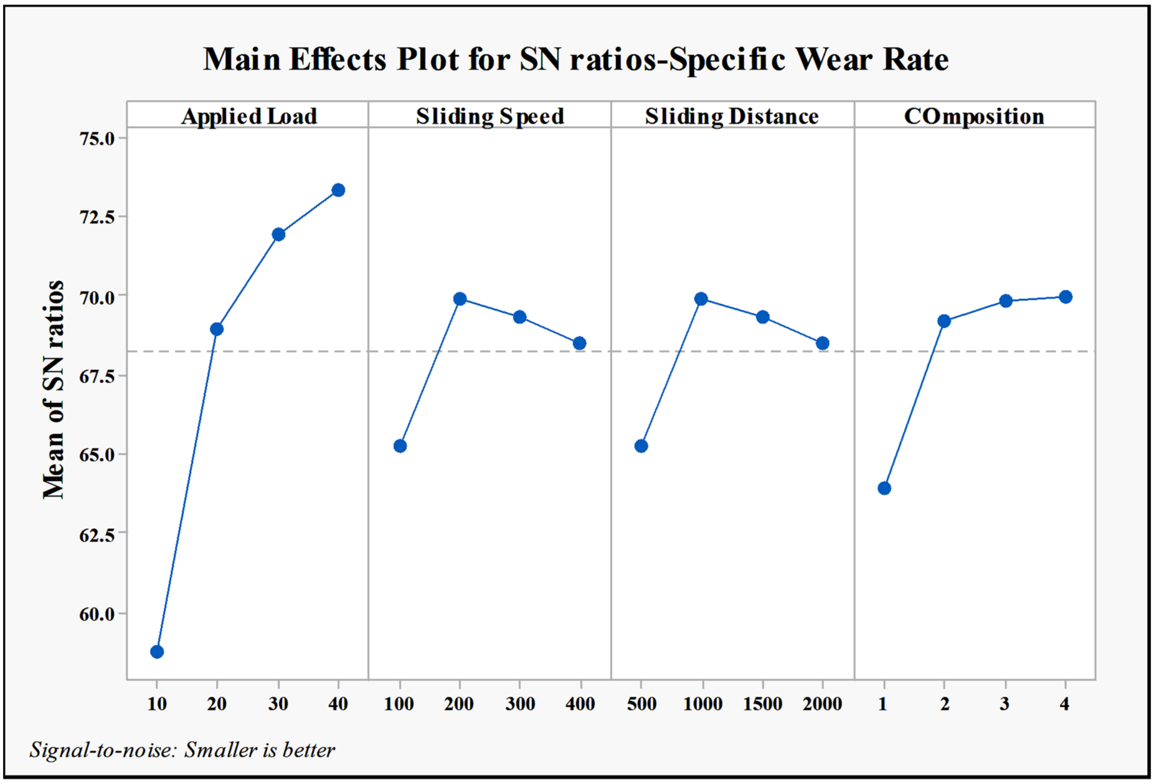


Figure 11: S/N ratios of Specific Wear rate

Fig. 11 shows the effect of parameters that affecting the wear performance. The difference in wear rate under the influence of each process parameter is illustrated. Wear rate increases with an increase in load, Sliding distance, and speed. The composite (Al6061-9wt.% SiC-1wt.% Gr powder) showed high wear resistance. The delamination wear process magnifies and speeds up the wear rate as the load is increased. Increased load causes higher local tension in the composite due to asperities, which speeds up wear by making deeper grooves. The wear rate of alloy increases as the slipping speed increases. The friction-induced temperature at the interface increases as the speed rises, resulting in the softening of the wear surfaces' surfaces and sub-surfaces. The composite outperforms Al alloy in terms of wear resistance. The inclusion of SiC strengthens the matrix. It also reduces the number of adhesive-wearing matrix interactions with the counter surface. As a result, delamination and adhesive wear are reduced. By comparing the wear resistance of the base material and the composite, the composites perform better than the base material [38].

CONCLUSIONS

The present work is aimed at fabrication, microstructure investigation, and mechanical and wear characterization of Al6061-SiC-Gr HMMCs. The important conclusions are summarized below:

(a) The stir casting route (liquid metallurgy technique) was successfully utilized in the preparation of Al6061-SiC-Gr HMMCs containing particles of SiC filler contents up to 9wt.% and Gr 1wt.%. Al6061-SiC-Gr HMMCs density values are found out and noticed to be improved than their matrix alloy.

(b) The EDX studies conducted on the matrix Al6061 confirm the presence of the alloying elements in the alloy and SEM microstructure examination reveals the uniform distribution of reinforcements SiC and Gr elements in the Al6061 alloy confirming the fabrication of Al6061-SiC-Gr HMMCs.
(c) The Al6061-SiC-Gr HMMCs hardness and tensile strength properties were found to be increased with increased filler content and Al6061-9wt% SiC-1wt% Gr composites displayed superior hardness and tensile strength values than the remaining HMMCs considered in the present study.
(d) The dry wear test results indicate that the Al6061-SiC-Gr HMMCs offered higher wear resistance than that of matrix alloy. Increased loads and sliding distances in the wear test resulted in higher wear loss. Tribological behavior of all compositions was studied for the different levels of process parameters selected. Experimental planning for wear performance was done using the Taguchi design of experiments method. L16 orthogonal array was selected. The optimal combination for wear rate has been found out using the main effects plot for SN ratio.
(e) Additionally, from the overall investigations and findings, it may be concluded that Al6061-9wt% SiC-1wt% Gr composites exhibit significantly improved physical, mechanical, and tribological properties in comparison with the other Al6061-SiC-Gr HMMCs considered in the present study. The experimental data and optimization results using ANOVA presented in this study will be useful to develop process-based models for aluminum alloy MMCs.

ABOUT RESEARCH DATA

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials. All the tests have been carried out as per ASTM standards.

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