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Wear Study of Al 6061 Hybrid Composite Reinforced with SiC and B4C Microparticles and Fabricated by Powder Metallurgy Method

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Abstract: The present study analysed the mechanical and wear characteristics of a hybrid composite material made from Al 6061 powder treated as a matrix material and reinforced with microparticles of SiC and B4C ceramics. A total of 12 samples were fabricated via the powder metallurgy (P/M) method. Among the twelve samples, one sample was A100 (100 Al6061), and the remaining samples were combinations of SiC and B4C from 0% to a maximum of 15%. The manufacturing methods included cold pressing, hot extrusion, and sintering. The results demonstrated that the composites consisting of only SiC particles presented the best strength, whereas the maximum hardness was attained when only B4C was used. Compared with those with more SiC, the composites made via the P/M method in the present study, containing a greater proportion of B4C, exhibited the most effective hardness performance. However, SiC had a greater impact on the tensile strength of the hybrid composite. This work offers useful insights into adjusting the composition of composites to improve their mechanical and tribological capabilities. As a result, these composites have the potential to be used in industries that require materials with exceptional performance characteristics. The Taguchi method was used to determine the relationships among the wear properties, such as speed, sliding velocity and loading force, via signal-to-noise ratio testing in the present study. This clearly shows that increasing the sliding velocity and rotation speed results in faster wear in the hybrid composite. Speed was the most crucial parameter for wear out the object and least crucial parameter was sliding distance to control the wear rate of the hybrid composite in which both micro particles have similar compositions. SEM images of the hybrid object was treated with 3D colour full scan analysis to show the clear impact of the micro particles on the composites surfaces.

Keywords: Hybrid composite; Al6061; SiC; B4C; Taguchi method; ANOVA; S/N ratio

1. Introduction

Metal matrix composites (MMCs) have attracted considerable interest in both academic and industrial fields because of their remarkable mechanical characteristics, such as superior strength, rigidity, and thermal conductivity, combined with low density[1,2]. MMCs have various advanced properties when compare with base materials and these properties make the MMC industry oriented materials[3]. Owing to their versatility and customizable traits, they are well suited for various industries, including aerospace, automotive,[etc.4,5]. Metal compistes made by various particulate materials most common like SiC, Fly ash and other ceramic materials[6]. MMCs incorporate a range of basic metals, including aluminum, magnesium, titanium, and their alloys, to provide a wide range of qualities that can be tailored to meet specific needs[7,8]. Among these options, aluminum alloys are notable for their plentiful supply, affordability, and exceptional ability to be shaped. The aluminum alloy 6061 has been extensively explored because of its well-balanced qualities in terms of strength, corrosion resistance, and machinability[9,10]. In some studies nano particles were also used to fabricate the MMC specially using Al alloys[11,31]. Reinforcement particles, such as SiC[12,13] and B4C[14,15], play important roles in metal matrix composites (MMCs), enhancing mechanical properties such as strength, stiffness, and wear resistance. SiC particles improve strength and stiffness, whereas B4C particles provide exceptional wear resistance and thermal stability, making them vital for applications that require high performance and lifespan.[18,32]. Hybrid combination[16,17] of SiC and B4C were discussed in various research papers and the detailed summary of these papers were present in table1.

Table 1. Summary of hybrid application of SiC and B4C fabricated MMC

Reference	Material System	Fabrication Method	Reinforcements	Key Findings
Kala, H. et al. (2014)	Al6061/SiC/B4C	Stir Casting	SiC, B4C	Improved mechanical and tribological properties; SiC provides hardness, B4C enhances wear resistance.
Rana, R. et al. (2012)	Al/SiC/B4C	Stir Casting	SiC, B4C	Overview of recent advancements in Al MMCs, with SiC and B4C noted for improving strength and wear resistance.
Chechi, P. et al. (2022)	Al-SiC/Flyash/Graphite	Stir Casting	SiC, Flyash, Graphite	Multi-reinforced hybrid composites showed superior mechanical properties.
Anand, A. et al. (2022)	Al-Zn-Al2O3	Stir Casting	Zn, Al2O3	Al2O3 reinforcement significantly enhances the mechanical properties.
Kumar Tripathy, S. et al. (2022)	Al/Hybrid MMC	CNC Turning	SiC, B4C	Optimization of machining parameters for enhanced surface finish and wear resistance.
Velavan, K. et al. (2021)	Al/B4C/Mica	Stir Casting	B4C, Mica	Significant improvement in mechanical properties with the addition of mica to B4C reinforced Al composites.
Mazahery, A. et al. (2011)	Al/NanoAl2O3	Stir Casting	NanoAl2O3	Nano-sized Al2O3 particles lead to enhanced mechanical properties of the composite.
Srivastava, A. K. (2020)	Al6063/SiC	Stir Casting	SiC	Enhanced mechanical properties with optimal SiC reinforcement.
Hekner, B. et al. (2017)	Al-SiC/Carbon	Hybrid Composites	SiC, Carbon	Enhanced wear resistance and mechanical properties through hybrid reinforcement.
Gode, C. (2013)	Alumix 123/SiC/B4C	Hot Pressing	SiC, B4C	Enhanced mechanical properties with combined SiC and B4C reinforcements.
Alam, M. T. et al. (2015)	Al-SiC	Stir Casting	SiC	SiC reinforcement leads to improved mechanical properties and wear resistance.
Keskin, G. et al. (2023)	AA7075/B4C/SiC	Powder Metallurgy EDM	B4C, SiC	Optimization of PMEDM process parameters for enhanced mechanical properties.
Halil, K. et al. (2019)	Al6061/SiC/B4C	Powder Metallurgy	SiC, B4C	Enhanced wear and mechanical properties with SiC and B4C reinforcement.
Tang, S. et al. (2021)	Al6061/SiC/SS	Hybrid MMC	SiC, Stainless Steel	Microstructural and mechanical behaviors enhanced with SiC and stainless steel reinforcement.
Sharma, H. et al. (2022)	Al6061/SiC	Stir Casting	SiC	Enhanced mechanical and erosive behavior with SiC reinforcement.
Maurya, N. K. et al. (2020)	Al6061/SiC	Stir Casting	SiC	Significant improvements in mechanical properties with optimized SiC content.
Knowles, A. J. et al. (2014)	Al6061/SiC Nanoparticles	Stir Casting	SiC Nanoparticles	Superior microstructure and mechanical properties with nano-sized SiC particles.
Mehta, K. M. et al. (2023)	Al-6061-B4C	Friction Stir Processing	B4C	Enhanced wear behavior with B4C surface composites.
Chenrayan, V. et al. (2020)	Al 6061/B4C	Hot Extrusion	B4C	Optimization of extrusion parameters for superior mechanical properties.

Lee, T. et al. (2023)	Al 6061/B4C	Directed Energy Deposition	B4C	Improved mechanical properties with core-shell powder application in directed energy deposition.
Maniraj, S. et al. (2022)	Al 6061/CNT/B4C	Hybrid MMC	CNT, B4C	Enhanced material properties with a combination of CNT and B4C reinforcement.
Srinivasan, R. et al. (2023)	Al/B4C	Friction Stir Welding	B4C	Investigation of mechanical properties with micro-sized B4C particles.
Ma, M. et al. (2023)	B4C/SiC	Reactive Sintering	B4C, SiC	Enhanced mechanical properties with in-situ high-pressure reactive sintering.
Liu, X. et al. (2024)	TiB2/Al	Mechanical Stirring & Ultrasonic Treatment	TiB2	Improved mechanical properties with mechanical stirring and ultrasonic treatment.
Dinaharan, I. et al. (2023)	Al-Zn/Al2O3	Friction Stir Processing	Zn, Al2O3	Enhanced mechanical properties with uniform dispersion of reinforcements.
Srinivasan, R. et al. (2022)	Al7075/TiC/Graphite	Gravity Stir Casting	TiC, Graphite	Improved mechanical properties with a combination of ceramic and carbon reinforcements.
Chechi, P. et al. (2022)	Al-SiC/Flyash/Graphite	Stir Casting	SiC, Flyash, Graphite	Multi-reinforced hybrid composites showed superior mechanical properties.

Aluminum alloy composites based on Al 6061 are widely employed in a variety of industries because of their superior properties[19,20)]. These composites are widely used in the airplane sector for structural components, the automobile industry for engine parts and chassis, and the marine industry for lightweight and corrosion-resistant structures.[21,33)]. Al 6061-based composites are used in sporting goods, electronic packaging, and industrial components because of their high strength–weight ratio, machinability, and corrosion resistance[22,23)]. These composites are significant in modern engineering because of their versatility and great performance, offering solutions for diverse problems in different sectors[24,25)]. Various researchers have investigated composites made from polymer and waste materials to help sustain the environment; in these studies, various mechanical tests were performed[28,29)]. Some researchers used the Agro waste to make the MMC level composite and this type of study help to make the sustainable development[30)].

In recent years, the integration of ceramic materials such as Silicon Carbide (SiC) and Boron Carbide (B4C) as reinforcements in aluminum matrix composites has gained significant attention due to their exceptional mechanical properties. SiC[47)] and B4C[48)] are known for their high hardness, excellent wear resistance, and superior thermal stability, making them ideal candidates for applications requiring enhanced performance under extreme conditions. Numerous studies have demonstrated the effectiveness of combining these two ceramics to produce hybrid composites with superior properties compared to those reinforced with a single ceramic material. The synergistic effect of SiC and B4C has been shown to improve the overall wear resistance, hardness, and mechanical strength of the composite, making them suitable for advanced engineering applications, including aerospace, defence, and automotive industries[22)].

Some special research work which was considerd as bases papers to make the present study was help to make the hybrid composite of Al6061, these references papers[43,44)] and[45)] were also made the hybrid of SiC and B4C materials.

Present study offers novel insights into the mechanical and wear characteristics of Al6061 hybrid composites reinforced with SiC[26)] and B4C microparticles. Unlike previous works that focused on individual reinforcements, this research systematically explores the combined effects of SiC and B4C within a single composite matrix. The study employs advanced manufacturing techniques, including cold pressing, hot extrusion, and sintering, to fabricate 12 distinct composite samples with varying reinforcement levels. This comprehensive approach highlights the differential impact of SiC and B4C on tensile strength and hardness, revealing that SiC predominantly enhances tensile strength, while B4C significantly improves hardness. Furthermore, the application of the Taguchi method to analyze wear properties under varying conditions of speed and load provides new insights into optimizing wear resistance. The integration of SEM analysis with 3D color mapping offers detailed visualization of reinforcement effects, underscoring the study's contribution to designing high-performance materials with tailored mechanical and tribological properties[38,39)].

The current study intends to investigate the mechanical and tribological properties of a hybrid composite material composed of an Al 6061 matrix reinforced with SiC and B4C microparticles. Composites were developed via the Taguchi technique and powder metallurgy (PM) procedures, with various mixes of SiC[27)] and B4C[40,41,42)] reinforcements. Using cold pressing, hot extrusion, and sintering processes, researchers have investigated the effects of different reinforcing quantities on strength, hardness, and wear performance. The results showed that composites with more SiC had superior strength, but those with more B4C had improved hardness and wear resistance. The study also looks at the relationship between wear metrics such as speed, sliding velocity, and loading force, using the signal–to–noise ratio and ANOVA tests. The findings of this study can be utilized to improve the composition of composites to meet specific industrial objectives, particularly in applications requiring superior mechanical and tribological performance.

Recent research underscores the significance of optimizing reinforcement materials in metal matrix composites. Keskin et al. (2023)[22] optimized PMEDM parameters for B4C and B4C+SiC reinforced AA7075 composites, emphasizing the importance of reinforcement distribution on mechanical properties. Halil et al. (2019)[27] demonstrated that hybrid Al6061 composites reinforced with SiC and B4C exhibit enhanced wear and mechanical properties, aligning with our findings. Gök et al. (2024)[43] reviewed various reinforcements like Al2O3, SiC, B4C, and MgO, reinforcing the need for precise processing techniques. Ma et al. (2023)[44] highlighted the benefits of high-pressure reactive sintering for B4C–SiC composites, while Karabulut et al. (2023)[45] compared the performance of Al6061 composites with different reinforcements, underscoring the need for optimized compositions. Surya (2022)[46] focused on the effects of SiC percentage and sintering duration, further validating the impact of reinforcement levels on mechanical behavior. These studies collectively support the novelty of our work in combining SiC and B4C in Al6061 composites and analysing their combined effects on wear and mechanical properties. The wear analysis was conducted with the help of the selected publications on the MMC[49,50].

2. Materials and methods

The current work used Al6061 powder as the matrix material with SiC and B4C ceramic powders to create a hybrid composite reinforcing material. The Al6061 powder, with particle sizes ranging from 100 to 150 micrometres, was purchased from a local vendor in Mumbai, ensuring consistency and perfection in the raw material. The acquisition of ceramic powders, which are critical for improving composite materials, necessitated their purchase from suppliers in Chennai and Mumbai.

This study provides a detailed explanation of the composite production procedure, including the exact combination of SiC and B4C powders shown in Table 2. This table shows the amounts or ratios of SiC and B4C powders used in the composite mixture. The comprehensive flow diagram of the fabrication process, as shown in Figure 1, illustrates the consecutive stages of the manufacturing process, providing a visual depiction of the approach.

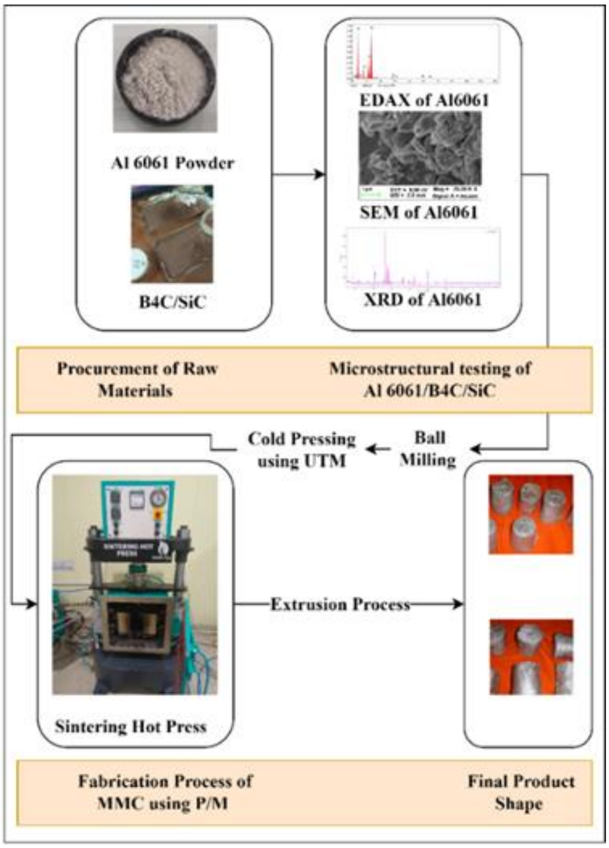


Fig. 1: Fabrication flow process to make MMCs

To guarantee the integrity and quality of the Al6061 powder, its chemical composition was recorded and is presented in Table 2. This table presents crucial data on the elemental composition of the matrix material, which assists in comprehending its properties and behavior during the fabrication process.

Table 2. Chemical composition of the Al 6061 powder

Element	Percentage Composition
Zn	0.23
Cu	0.21~0.36
Si	0.72
Mn	0.25~0.75
Ti	0.15
Fe	0.62
Cr	0.12
Mg	0.9~1.4
Al	Balance

The acquisition of materials from many suppliers in different geographical areas highlights the need to obtain superior raw materials and maintain uniformity in their characteristics. The careful and precise method of selecting and obtaining materials is essential for obtaining consistent and repeatable outcomes in the production of composites. The material and methods portion of this paper presents a thorough description of the raw materials utilized, their origins, and the manufacturing procedure employed to produce the hybrid composite. These specific pieces of information provide the basis for carrying out further mechanical and tribological investigations of the composite material, enhancing the scientific rigor and validity of the research results.

Table 3. Combinations (in%) of SiC/B4C in Al6061

Run	Base powder	Reinforcement particle	
	Al6061	SiC	B4C
1	100	0	0
2	85	1.5	13.5
3	85	3.0	12.0
4	85	4.5	10.5
5	85	6.0	9.0
6	85	7.5	7.5
7	85	9.0	6.0
8	85	10.5	4.5
9	85	12.0	3.0
10	85	13.5	1.5
11	85	15	0
12	85	0	15

As shown in Table 3, all the percentages required for mixing the base powder and particulate matter are presented, and the actual weights of all the ingredients are presented in Table 4.

Table 4. Mixing combination of SiC/B4C in the Al6061 powder by weight (gm)

Run	Base powder	Reinforcement particle	
	Al6061	SiC	B4C
1	250	0	0.0
2	212.5	3.8	33.8
3	212.5	7.5	30.0
4	212.5	11.3	26.3
5	212.5	15.0	22.5
6	212.5	18.8	18.8
7	212.5	22.5	15.0
8	212.5	26.3	11.3
9	212.5	30.0	7.5
10	212.5	33.8	3.8
11	212.5	37.5	0.0
12	212.5	0.0	37.5

As shown in Table 4, the maximum weight of the mixture was 250 g, and the mixing composition was determined according to Table 4. The particle size of the SiC and B4C was ranged in between 10 µm to 15 µm as selected by the researchers in their study[27].

In the present study, the Al6061 hybrid composite reinforced with SiC and B4C microparticles was fabricated using a controlled powder metallurgy (P/M) process. The sintering procedure was meticulously designed to ensure optimal bonding between the matrix and the reinforcement particles, leading to enhanced wear properties of the composite. The hybrid compacts, prepared by uniaxial compaction under a pressure of 400 MPa, were sintered in an inert controlled atmosphere to prevent oxidation. The sintering was conducted at a temperature of 550°C[27,46], which is below the melting point of Al6061 but sufficiently high to promote solid-state diffusion. This temperature was maintained for 2 hours, ensuring adequate diffusion of atoms across particle boundaries, leading to strong interparticle bonding and densification of the composite. The heating rate was controlled at 8°C/min to minimize thermal gradients and prevent the development of residual stresses. Following the sintering phase, the composites were allowed to cool slowly at a rate of 3°C/min within the furnace. This slow cooling process was crucial in avoiding thermal shock, which could otherwise introduce cracks or other defects into the composite. These sintering parameters were selected based on a series of preliminary trials aimed at achieving an optimal balance between density, mechanical properties, and microstructural integrity. The controlled atmosphere, precise temperature regulation, and careful cooling strategy collectively contributed to the formation of a dense, uniform composite with improved wear resistance[47]. Hot pressing was done at 835 K temperature and 400 MPa pressure. These boundary conditions helps to make the optimum density of the samples.

3. Mechanical Property Analysis

In the present study, mechanical and microstructural analyses comprehensively evaluated numerous factors required to understand the performance and features of the hybrid composite. The mechanical properties of the composite material were assessed methodically via criteria such as theoretical density, experimental density, tensile strength, hardness, and transverse rupture strength. SEM and XRD techniques were used to examine the internal structure, phase composition, and grain shape of the composite material. This dual method enables a full investigation of both larger-scale and smaller-scale aspects, improving the understanding of how the composite material behaves and performs under varied loads and environmental conditions.

3.1 Density analysis

In the present study, the theoretical density of the composite was compared with the experimental density. The formula[26] used for density calculation is presented here, and the densities of the Al6061 powder, B4C powder and SiC powder were 2.70 gm/cm3, 2.52 gm/cm3 and 3.10 gm/cm3, respectively[27].

$$\rho_{th} = \frac{1}{\left(\frac{W_{Al6061}}{\rho_{Al6061}}+\frac{W_{SiC}}{\rho_{SiC}}+\frac{W_{B4C}}{\rho_{B4C}}\right)} \qquad (1)$$

where W represents the weight fraction of the components mixed in the MMC and rho represents the individual densities of the powders. The experimental density was measured after complete fabrication of the MMC via the P/M methodology, and the comparison results are presented in Table 5.

Table 5. Comparison of theoretical and P/M sample densities

Run	Designation	Th. Density	P/M Sample Density
1	A100	2.700	2.682
2	A85/SiC1.5/B4C13.5	2.679	2.668
3	A85/SiC3/B4C12	2.687	2.654
4	A85/SiC4.5/B4C10.5	2.695	2.672
5	A85/SiC6/B4C9	2.704	2.689
6	A85/SiC7.5/B4C7.5	2.712	2.705
7	A85/SiC9/B4C6	2.720	2.716
8	A85/SiC10.5/B4C4.5	2.728	2.722
9	A85/SiC12/B4C3	2.737	2.731
10	A85/SiC13.5/B4C1.5	2.745	2.735
11	A85/SiC15	2.753	2.747
12	A85/B4C15	2.671	2.648

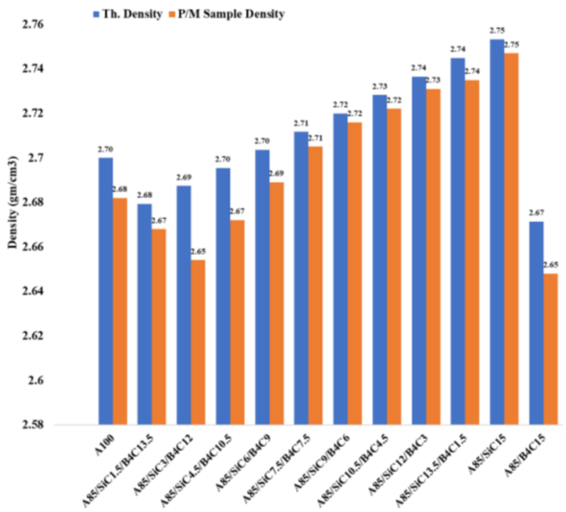


Fig. 2: Comparison of theoretical and experimental densities of the AL 6061 MMC

As shown in the Figure 2, the practical density was lower than the theoretical density, and the reason behind this behavior was due to practical limitations faced during the P/M fabrication method; however, the error content was lower than 10% for all samples of MMC. The discrepancies between theoretical and experimental densities observed in our study can be attributed to several factors inherent in the powder metallurgy (P/M) process. The theoretical density calculations assume a perfectly dense material, whereas experimental densities often fall short due to inherent porosity and voids formed during compaction and sintering. Variations in particle size and distribution also affect packing efficiency, with larger or poorly distributed particles contributing to lower actual densities. Additionally, variations in compaction pressure and sintering conditions can lead to incomplete densification. Measurement errors or slight inconsistencies in equipment calibration may further contribute to these differences. These factors are typical in P/M processes and explain why experimental densities are lower than theoretical values. Understanding these influences is crucial for optimizing material processing and achieving desired properties in hybrid composites.

3.2 Hardness and tensile strength

The examination of hardness and tensile strength revealed fascinating patterns inside the composite materials. The table data show that there were substantial variations in hardness values among the different compositions. The highest recorded hardness of 78.200 HB was observed in the A85/B4C15 composite. Curiously, as the proportion of SiC in the composite increased, the hardness steadily decreased. The ASTM E8M standard was used for the tensile strength measurement using UTM machine.

The inclusion of B4C generally led to an increase in hardness, with the greatest values found in compositions with higher B4C concentrations. The differences in tensile strength were less significant than those in hardness but are still worth mentioning. The range of tensile strength values varied from 171.6 MPa for the A100 composite to 189.6 MPa for the A85/SiC15 composite. In summary, these results emphasize the complex connection between the composition of composites and their mechanical properties. This highlights the possibility of customizing material design to obtain specific hardness and tensile strength features in hybrid composites.

Table 6. Hardness and tensile strength of the MMC made with Al6061

Run	Designation	Hardness (HB)	Strength (MPa)
1	A100	49.5	171.6
2	A85/SiC1.5/B4C13.5	76.4	172.5
3	A85/SiC3/B4C12	74.1	174.8
4	A85/SiC4.5/B4C10.5	70.4	177.1
5	A85/SiC6/B4C9	68.9	179.6
6	A85/SiC7.5/B4C7.5	67.3	181.7
7	A85/SiC9/B4C6	65.7	183.6
8	A85/SiC10.5/B4C4.5	62.8	186.3
9	A85/SiC12/B4C3	61.6	187.9
10	A85/SiC13.5/B4C1.5	58.5	188.5
11	A85/SiC15	53.9	189.6
12	A85/B4C15	78.2	173.2

Figure 3 shows the hardness parameter data, which clearly show that the presence of B4C had a greater impact on hardness than SiC particles in the metal matrix composite (MMC).

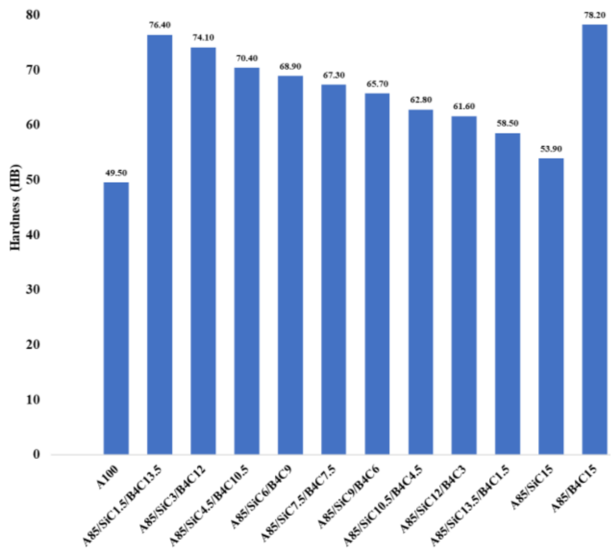


Fig. 3: Analysis of hardness of the different samples of hybrid MMCs

Figure 4 shows the tensile strength of the various samples, demonstrating that SiC particles had a stronger impact on the metal matrix composite (MMC) than did B4C particles.

3.3 Rupture strength of MMCs

The rupture strength of a metal matrix composite (MMC) varies significantly across different compositions. The rupture strength ranged from 360 MPa for composite A85/B4C15 to 416 MPa for composite A85/SiC15. The addition of SiC and B4C reinforcing particles frequently resulted in a higher rupture strength than did the base composite A100. The compositions of the hybrid combinations of Al6061, SiC and B4C materials, including increasing amounts of SiC and B4C, exhibited improved fracture strengths, with composite A85/SiC15 demonstrating the highest value. MPFI-411998 standards were selected for the rupture strength analysis.

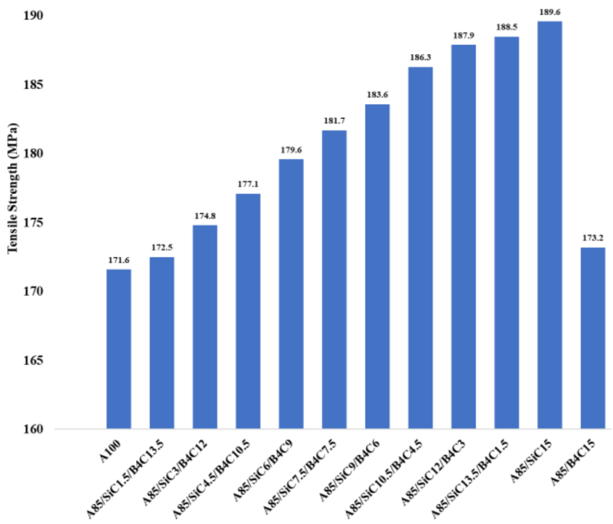


Fig. 4: Analysis of the tensile strength of the different samples of MMC

These findings highlight the critical role of reinforcing particles in increasing the mechanical properties of MMCs, specifically the rupture strength. This highlights the potential for customized composite designs to satisfy specific application needs.

Table 7. Rupture strength of hybrid MMCs made with Al6061

Run	Designation	Rupture Strength (MPa)
1	A100	366
2	A85/SiC1.5/B4C13.5	362
3	A85/SiC3/B4C12	370
4	A85/SiC4.5/B4C10.5	375
5	A85/SiC6/B4C9	380
6	A85/SiC7.5/B4C7.5	384
7	A85/SiC9/B4C6	389
8	A85/SiC10.5/B4C4.5	396
9	A85/SiC12/B4C3	407
10	A85/SiC13.5/B4C1.5	411
11	A85/SiC15	416
12	A85/B4C15	360

Figure 5 displays the rupture strength of all the samples created for the current study. The experimental results clearly demonstrated a positive correlation between the number of SiC particles in the MMC and its rupture strength. This increase in strength can be attributed to the inherent properties of the SiC particles. The results of the microstructural analysis of the clean A100, A85/SiC7.5/B4C7.5, A85/SiC15 and A85/B4C15 samples are presented in Fig. 6. The SEM images were processed with ImageJ software, and the images were converted to binary format to obtain a better understanding of the images.

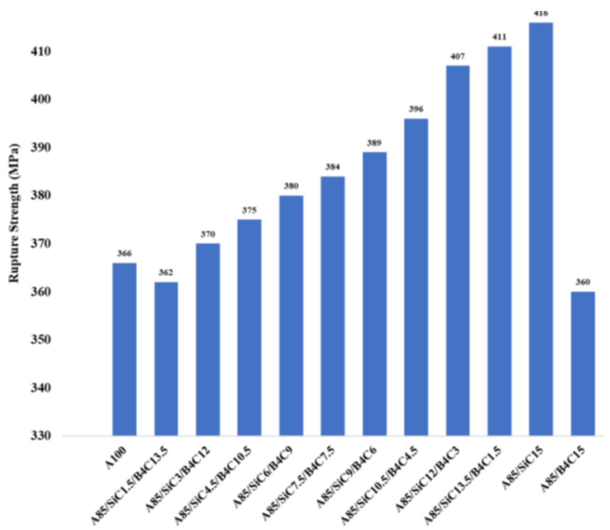
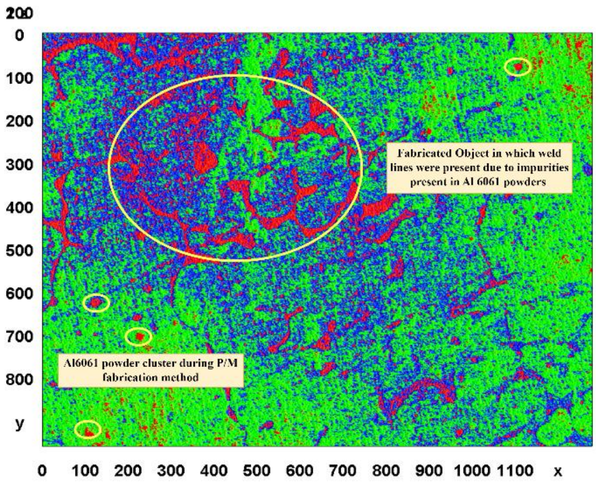
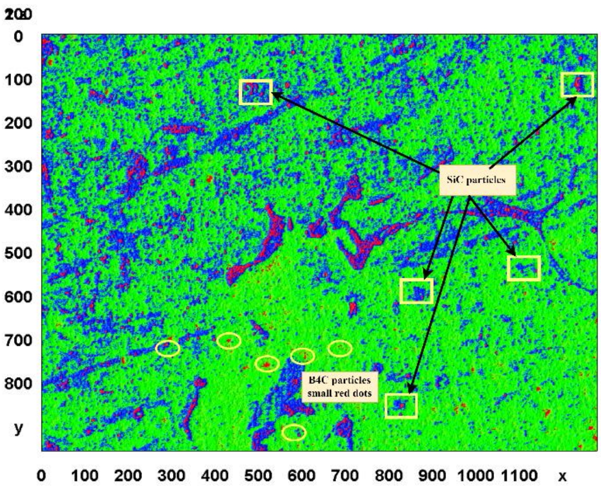


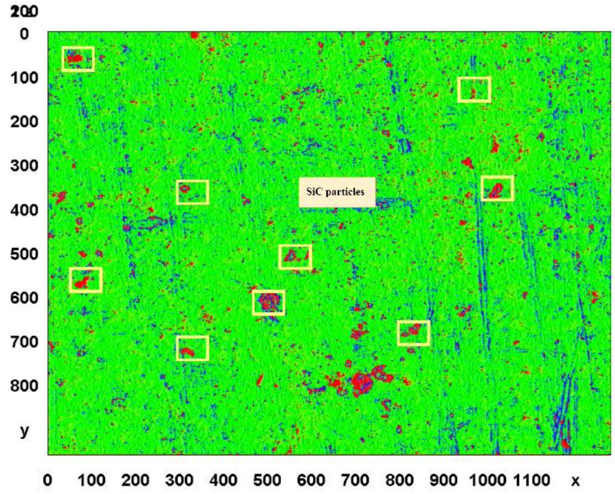
Fig. 5: Analysis of the rupture strengths of the different samples of MMCs



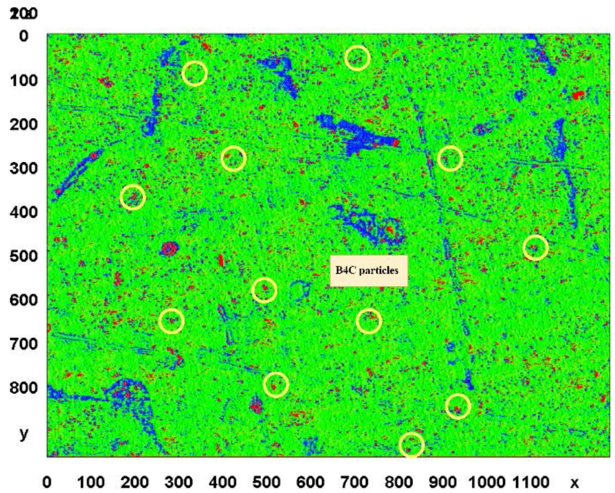
a) A100 (Al6061--100%) Scale 10µm



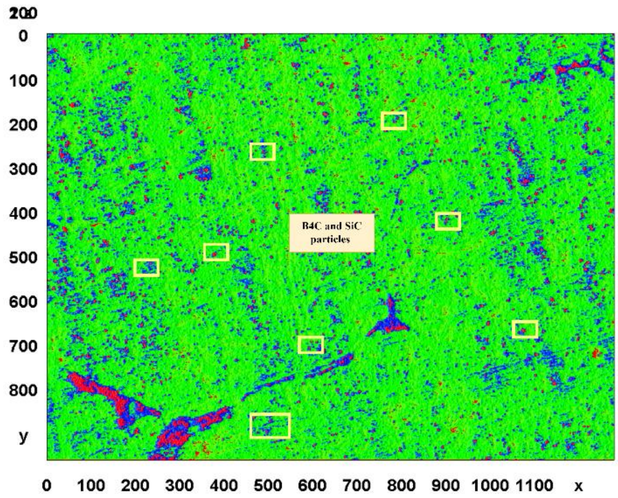
b) A85/SiC7.5/B4C7.5 Scale 10µm



c) A85/SiC15 Scale 10µm



d) A85/B4C15 Scale 10µm



e) A85/SiC4.5/B4C10.5Scale 10µm

Fig. 6: 3D scan images of an SEM sample of an MMC

Figure 6 displays the binary format of the SEM images for the base MMC (A100), the hybrid MMC with similar weight fractions of both reinforcement materials, and the individual particle components. The binary formation of the SEM images was performed via ImageJ software, which helps researchers perform image processing for advanced research studies.

The following figures effectively illustrate the influence of B4C and SiC on MMCs. Specifically, Figure 6 (a) highlights the presence of Al 6061 particles and surface cracks, which are represented by the black areas. However, when SiC was at the highest weight fraction (15%), as shown in Figure 6 (c), the white color was due to the SiC on the top of the surfaces. The same impact was shown for B4C in Fig. 6 (d). The XRD patterns for the present study was show in Figure 7 for pure A100, A85B4C15, A85SiC15 and A85SiC7.5B4C7.5. As seen in XRD plots it was observed that with referenced literature[48,49,50)] on the same work, the peaks for Al (111 and 200) were more high then B4C and SiC peaks in the composite material.

4 Wear Analysis of Hybrid MMCs

The wear study conducted via the Taguchi approach sought to examine the correlation between different parameters and the response variable, the wear rate. Three separate levels were considered for factors such as speed (RPM), load (N), and sliding distance (m). The Taguchi approach was used to create an experimental design matrix to investigate effectively the impact of these parameters on the wear rate while decreasing the number of experimental runs.

Table 8. Factors and levels selected for wear analysis

Factors/Levels	Unit	I	II	III
Speed	RPM	200	250	300
Load	N	5	10	15
Sliding Distance	m	150	300	450

The wear rate of the composite material was evaluated via statistical approaches such as the signal-to-noise ratio. These techniques aided in the discovery of critical parameters that determine the wear rate and allowed for the adjustment of the composite material's composition to improve wear resistance. The implementation of this strategy increased the material's efficiency and durability in practical circumstances.

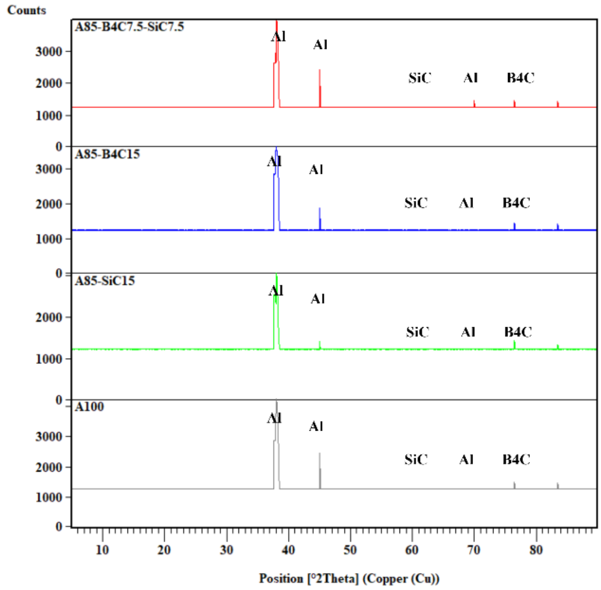


Fig. 7: XRD pattern for various composition of the B4C and SiC particles

The current work focused on analysing the wear characteristics of a hybrid composite sample consisting of 85% A material, 7.5% SiC, and 7.5% B4C. For this sample, both reinforcement materials had the same weight fraction. The orthogonal array used in this investigation is displayed in Table 9, along with the response wear rate.

Table 9. L9 orthogonal array developed for the present study for the wear rate (mm3/m)

Run	Speed	Load	Distance	Wear Rate	S N Ratio
1	200	5	150	0.0404	27.87
2	200	10	300	0.0344	29.27
3	200	15	450	0.0334	29.53
4	250	5	300	0.0244	32.25
5	250	10	450	0.0394	28.09
6	250	15	150	0.0274	31.24
7	300	5	450	0.0144	36.83
8	300	10	150	0.0204	33.81
9	300	15	300	0.0334	29.53
Unit	RPM	N	m	mm3/m	-

The signal-to-noise ratio analysis for the smaller option was better for the wear rate, and the rank of the wear rate for each factor is presented in Table 10.

Table 10. Signal-to-noise ratio analysis for the wear rate

Level	Speed	Load	Distance
1	28.89	32.32	30.97
2	30.53	30.39	30.35
3	33.39	30.1	31.48
Delta	4.5	2.22	1.13
Rank	**1**	**2**	**3**

The examination of the signal–to–noise ratio (SNR) for the wear rate provided significant insights into how various characteristics, such as speed, load, and sliding distance, affect composite material wear. SNR values represent the attractiveness of each factor level, with higher values indicating better performance. Speed had the greatest impact on the wear rate of all the characteristics, with level 3 (33.39) having the highest signal-to-noise ratio (SNR), followed by level 2 (30.53) and level 1 (28.89). This suggests that increasing the velocity improves the wear resistance. In contrast, speed had a greater effect on the wear rate than did load and sliding distance.

These findings highlight the importance of fine-tuning speed settings to reduce wear in real-world applications, as well as the possibility of further research into the complex interactions among various variables that influence wear performance in metal matrix composites. Figures 8 and 9 provide the plots for the S/N ratio analysis.

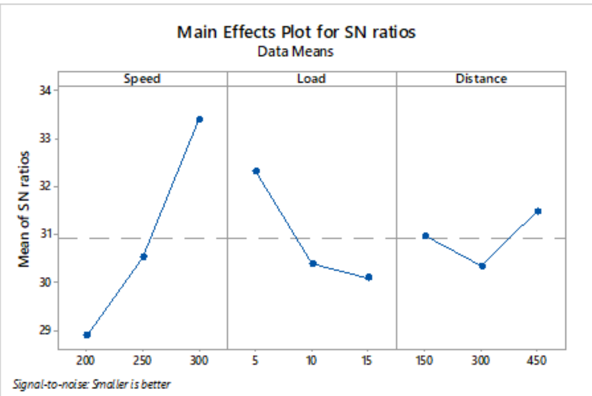


Fig. 8: S/N ratio analysis for the wear rate of a sample (A85/SiC7.5/B4C7.5)

The main effect plot for the response wear rate is shown in Fig. 9. The plot clearly shows that the speed was the crucial parameter controlling the wear rate of the sample (A85/SiC7.5/B4C7.5).

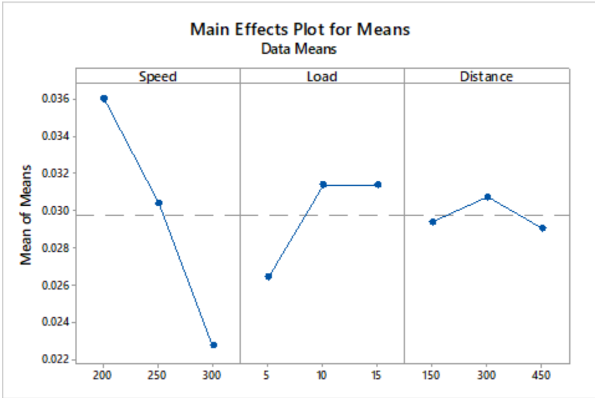


Fig. 9: Analysis of the main effects on the wear rate of a sample (A85/SiC7.5/B4C7.5)

4.1 Effect of load, speed and distance on wear rate

The contour plot (Fig. 9) illustrates the wear behavior of the Al 6061 hybrid composite reinforced with 7.5% SiC and 7.5% B4C microparticles, fabricated via the powder metallurgy method. The plot presents the relationship between the applied load and the resulting wear rate.

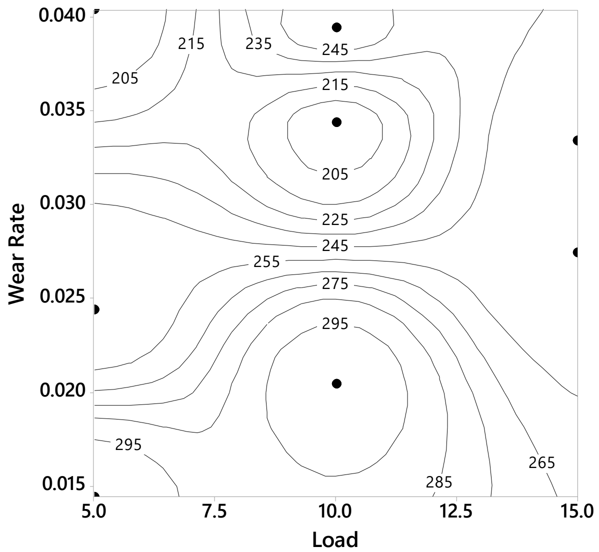


Fig. 10: surface contour plot for wear rate effect due to load and speed parameter(A85/SiC7.5/B4C7.5)

The wear rate exhibits distinct regions corresponding to varying load conditions. At lower loads (around 5-7.5 N), the wear rate tends to be higher, indicating the initial wear stage where surface asperities make contact, leading to material removal. As the load increases toward 10 N, the wear rate decreases, forming a distinct valley on the plot. This suggests a stabilization phase where the composite's reinforced structure effectively resists wear due to the uniform distribution and bonding of SiC and B4C particles.

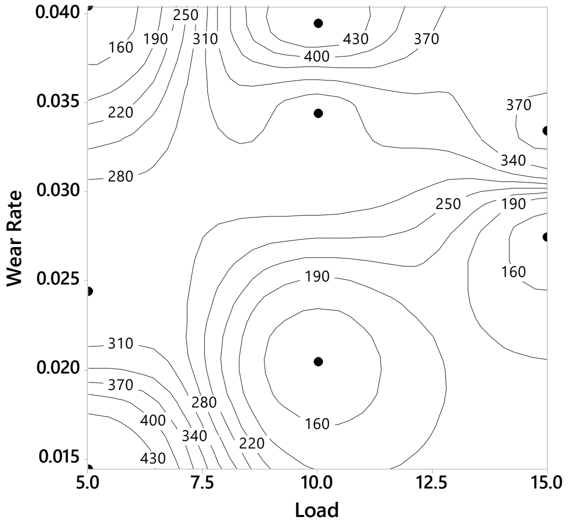


Fig. 11: surface contour plot for wear rate effect due to load and distance parameter(A85/SiC7.5/B4C7.5)

as the load further increases beyond 12.5 N, the wear rate rises again, reaching another peak. This is likely due to the breakdown of the protective tribolayer, where the applied load exceeds the composite's load-bearing capacity, leading to increased wear. The dual peaks in the contour plot emphasize the composite's sensitivity to varying loads, demonstrating the importance of optimizing load conditions to minimize wear in practical applications. This analysis highlights the Al 6061 hybrid composite's performance, where the reinforcement of SiC and B4C microparticles plays a crucial role in wear resistance, particularly under specific load conditions.

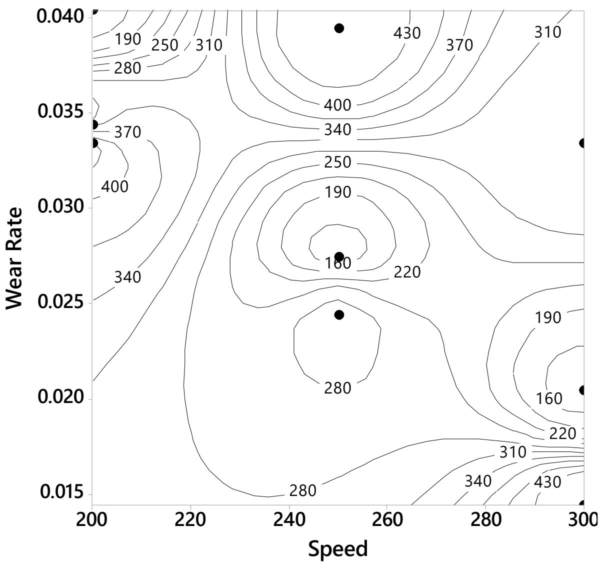


Fig. 12: surface contour plot for wear rate effect due to speed and distance parameter(A85/SiC7.5/B4C7.5)

The contour plot figure 10 show the relationship between the applied load and wear rate is depicted through well-defined regions on the plot, showcasing how the composite material responds to different mechanical stresses. At lower load values (around 5-7.5 N), the wear rate appears relatively high, particularly in the top left quadrant of the plot. This suggests that at lower loads, the initial interaction between the asperities on the composite surface and the counter surface leads to noticeable material removal. As the load increases to the 10 N range, a significant decrease in the wear rate is observed, forming a distinct low-wear zone in the plot's center. This indicates the effectiveness of the SiC and B4C reinforcement in stabilizing the material's resistance to wear by distributing the load more evenly across the surface.

The contour plot Figure 11, illustrates the wear behavior of the Al 6061 hybrid composite reinforced with 7.5% SiC and 7.5% B4C microparticles as a function of sliding speed. The plot provides a clear depiction of how wear rate varies with changes in speed, revealing important characteristics of the composite material under different operational conditions. At lower speeds (around 200-220 RPM), the wear rate is relatively high, as indicated by the tightly packed contour lines in the top left region of the plot. This suggests that at lower speeds, the composite surface experiences significant material removal, possibly due to insufficient lubrication or ineffective formation of a protective tribolayer. However, as the speed increases to around 240-260 RPM, the wear rate decreases markedly, forming a low-wear zone. This indicates that the reinforcement of SiC and B4C particles is effective at these intermediate speeds, providing a stable and protective surface layer that resists wear.

5 Conclusion

The current work extensively investigated the mechanical and tribological properties of a hybrid composite material composed of an Al 6061 matrix reinforced with SiC and B4C microparticles. A variety of analyses, including hardness testing, tensile strength testing, rupture strength testing, and wear rate assessment, provided useful information about the composite material's performance and features. The study of hardness and tensile strength revealed surprising patterns, since the addition of SiC and B4C reinforcing particles had different effects on these properties. SiC increased the hardness, although B4C had a greater influence on the tensile strength. These findings demonstrate that customized composite compositions can fulfil specified mechanical property goals for a wide range of application requirements.

The analysis of rupture strength revealed that the inclusion of SiC and B4C often resulted in an increase in rupture strength compared with that of the original composite. Compositions with larger levels of reinforcing particles showed even greater improvements in rupture strength. These findings emphasize the role of reinforcing particles in improving the mechanical properties of metal matrix composites, including their structural integrity and failure resistance. Wear analysis via the Taguchi technique revealed relationships between variables such as velocity, load, and sliding distance and the rate of wear of the composite material. These findings underscore the importance of speed in determining the rate of wear, as higher speeds are related to lower wear rates. This emphasizes the importance of increasing operational parameters to reduce wear and increase the durability of composite materials in real-world applications.

The current study provides valuable insights into the design and optimization of hybrid composites for a variety of technical applications. This study provides a foundation for future studies into the development of high-performance materials with precisely tuned mechanical and tribological properties. The implications of these findings are significant for industries that rely on materials with high mechanical strength, durability, and wear resistance.

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