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INVESTIGATION OF WEAR BEHAVIOR OF AL6061 BASED HYBRID COMPOSITE USING STATISTICAL TECHNIQUES

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ABSTRACT

Because of their exceptional strength-to-weight ratio, outstanding thermal conductivity, and resistance to corrosion, AMCs have become a viable material for lightweight structural and tribological applications. Hybrid AMCs reinforced with different reinforcements have drawn a lot of interest recently because they allow for cost and weight optimization while providing a balanced improvement in mechanical and tribological qualities. In this regard, the current study focuses on the creation and methodical characterization of a hybrid metal matrix composite based on Al6061 that is reinforced with ceramic particles of titanium dioxide (TiO_2) and coconut shell ash (CSA), a bio-filler obtained from agricultural waste.

The primary objective of this work is to investigate the synergistic influence of ceramic and bio-based reinforcements on the mechanical and tribological behavior of Al6061 alloy. The use of TiO_2 as a hard ceramic reinforcement is intended to enhance hardness, strength, and wear resistance, while CSA is incorporated to reduce density, improve sustainability, and contribute to tribological performance. Hybrid AMCs were fabricated using the stir casting method by varying the TiO_2 content while maintaining a constant CSA fraction. The fabricated composites were subjected to comprehensive microstructural, and tribological characterization. Dry sliding wear behavior was evaluated using a pin-on-disc tribometer under varying load, sliding speed, and sliding distance conditions. A Taguchi L16 orthogonal array was employed to design the experiments, followed by analysis of variance (ANOVA) and Response Surface Methodology (RSM) to identify the relative significance of wear parameters. The statistical analysis identified that reinforcement is the primary factor influencing wear behavior, where hybrid composites incorporating filler particles exhibit improved wear resistance. while load and speed contributed to increased wear through mechanical and thermal effects. Increased hardness and the combined effect of CSA and TiO_2 reinforcements were highly associated with the hybrid composites' enhanced wear resistance. The effective utilization of agro-waste–derived CSA alongside ceramic reinforcement not only improves tribological performance but also contributes to sustainable and cost-effective composite development, making the material a promising candidate for wear-resistant engineering applications.

Keyword: Al6061, Titanium Dioxide (TiO_2), Coconut Shell Ash (CSA), ANOVA, RSM.

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1. INTRODUCTION

The need for lightweight and durable materials that can withstand severe service conditions has increased in many advanced applications such as aerospace, automotive, marine, and sports industries. In recent years, studies have shown that aluminum metal composites reinforced with particulates are suitable materials for these applications. due to their improved physical and mechanical properties [1]

Ceramic particle–reinforced AMCs have become attractive materials for a wide range of applications due to their unique blend of properties they offer. These composites merge the ductility and toughness of aluminum alloys with the high strength and stiffness of ceramic reinforcements. As a result, AMCs exhibit a well-balanced set of mechanical properties. Extensive research carried out over the past few years has helped address several technical challenges related to AMCs. These include cost-effective processing methods, material design, characterization techniques, and control of the matrix–reinforcement interface.[2].

TiO_2 and CSA offer a special set of characteristics when used as primary and secondary reinforcements in aluminum alloys. TiO_2 is utilized extensively because of its desirable qualities, which include high hardness, superior wear resistance, and chemical inertness. In contrast, coconut shell ash is considered a solid waste by-product that is abundant and has a low density and cheap cost of reinforcing. An agricultural byproduct of the coconut processing industry is coconut shell.

Hybrid Metal Matrix Composites are advanced class of composite materials that contain two or more different reinforcements within metal matrix. This approach used to achieve improved mechanical, thermal, and tribological properties. By combining different reinforcements, hybrid MMCs leverage the strengths of each material while mitigating individual limitations. As a result, resulting hybrid MMCs exhibit superior functional performance than their conventional single-reinforced composites. Due to these improved properties they have widely used for structural engineering and functional device applications[3]

The physical, mechanical and tribological properties of Al6061/ TiO_2 composites carried out to by G B Veeresh Kumar et al. [4]. The powder metallurgy route was followed to produce the composites varying wt% of TiO_2 microparticles. The outputs of the experiments revealed that the AMC containing higher filler content displayed the superior physical, mechanical and tribological characteristics. With increase in TiO_2 fillers, the density of the composite increased and the mechanical properties was increased significantly with higher TiO_2 content in the matrix, with loss in ductility. The dry sliding wear studies showed greater wear resistance of Al6061-TiO_2 composite than Al6061 matrix.

C. Antony Vasanthakumar et al. [5] manufactured AMC with varying content of TiO_2 and constant SiC via powder metallurgy process. They examined the TiO_2 content effect (0, 4, 8, and 12%) on hardness and wear properties. Microstructure showed uniform distribution of TiO_2 particles throughout the Al matrix. Both microhardness and wear resistance enhanced with increasing TiO_2 content. This is attributed to high hardness of TiO_2 and increased dislocation density in deformed regions. EDS analysis confirmed presence of an oxide layer. This reduced the effective contact area between the sliding surfaces, in turn, lowered wear loss of hybrid composites. Delamination and adhesive wear are identified as dominant mechanisms.

Ravi Raj et al [6] developed an aluminum composite reinforced with silicon carbide-titanium dioxide for dry bearings, exhibiting low friction coefficient, high wear resistance, and improved durability, enhancing engineering system efficiency and reliability. Nagendran N [7] TiO_2-SiC

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reinforced in Al 6061 matrix by stir casting technique. The reinforcements were added in 2%, 4% and 6% of weight to Al6061 to fabricate the metal matrix composite. The study indicates that Al6061-TiO_2-SiC composites exhibit superior tensile strength and hardness compared to pure aluminum.

Prasad et al. [8] used SiC and RHA reinforcements in equal proportions to develop hybrid AMCs. Findings shown ultimate tensile strength and yield strength and UTS of Al/SiC/RHA hybrid composites increased as the wt.% of reinforcements increased, while the elongation decreased which attributed to the presence of hard ceramic phase in the composites, increasing the brittleness in the developed composites.

Isaac Dinaharan et al. [9] produced Al6061 AMCs reinforced rice husk ash (RHA) particles (0–8 wt %). The wear was assessed using a pin-on-disc wear apparatus with a heating facility, and the temperature was varied from 40 °C to 240 °C. The incorporation of RHA particles was beneficial in improving the wear resistance and reducing the COF values over the entire range of temperatures used. The temperature increase deteriorated the wear resistance of the composites. Al6061/(0–4 wt %) RHA AMCs showed a clear transition from mild wear to severe wear at a temperature of 200 °C. The RHA particle content increased the transition wear temperature. The wear changed from abrasive wear at 40 °C to adhesive material flow at 240°C.

The current research emphasizes how different forms of agro-waste reinforcements affect mechanical and tribological characteristics of the AMCs. Among those, studies on viability of employing coconut shell ash (CSA) - a biomass reinforcement for the development of sustainable Al6061 hybrid composites, have gained significant attention. hybrid composites integrating CSA with ceramic reinforcements in aluminum matrix offer a strategic pathway for achieving a balanced enhancement in mechanical, and tribological properties.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

2.1 Materials

Using a double stir casting technique, TiO_2 and CSA were added to aluminum alloy 6061 for reinforcement. Al6061, supplied by M/s PMC corporation, Bangalore, INDIA, was utilized as the matrix phase. Its composition was as follows: Mn: 0.07, Fe: 0.5, Mg: 0.11, Si: 0.61, Cu: 0.32, Zn—0.22, Ti—0.18, Cr: 0.24, and the remaining weight percentage of Al. There are numerous pertinent uses for titanium dioxide (TiO_2), a substance that is both adaptable and chemically inert. Internal synthesis of coconut shell ash was carried out using conventional protocols that have been previously described [10].

The Al6061 ingots are melted in a graphite crucible using an electric resistance furnace at a temperature of about 750°C and Reinforcements were preheated. The Al metal in the crucible is allowed to cool to the semi-solid slurry and is agitated for five to ten minutes at a moderate speed (400 rpm). Predetermined weight fractions of warmed reinforcing particles were gradually introduced to the melt's vortex after the stirrer had been spun to create a vortex. Mg (1 wt%) is now added to this semi-solid slurry. The amalgamated matrix and reinforcement mixture is poured into the heated molds and let to harden in the ambient environment once the stirrer has been removed. To improve solidification and remove moisture, the permanent die is warmed.

2.2 Wear Test

In particular, when supplemented with hard ceramic and agro-waste particles like TiO_2 and Coconut Shell Ash (CSA), wear testing is another crucial characterisation technique to

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assess the tribological behavior of Al matrix composites. The purpose of these reinforcements is to increase the composite's resistance to material loss in abrasive or sliding environments.
In this experiment, a pin-on-disc tribometer as shown in fig (1) (Make: Ducom, India, Model: TR20LE) was employed for the dry sliding wear tests. Cylindrical specimens were prepared as per ASTM G99 standards and tests were conducted. SEM was used to analyse the worn surfaces after the test in order to determine the main wear mechanisms. Vickers micro hardness numbers (VHNs) for the composite specimens varied from 57 to 79. The wear loss was determined by weighing the specimen both before and after the test. For this investigation, a digital scale with an accuracy of ±0.1 mg was employed.

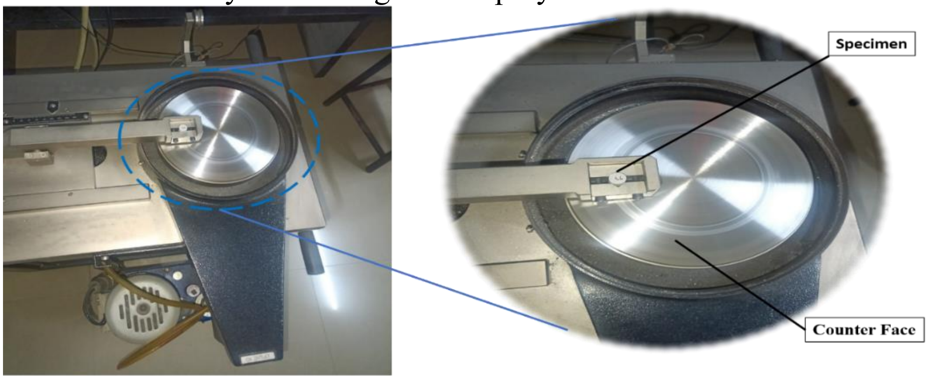

Fig 1: Wear testing of specimen

2.3 Experimental Design -Taguchi Analysis

The Taguchi method enables a systematic study of multiple factors with reduced experimental trials while maintaining statistical reliability. Based on the Control Factors and Levels chosen, an appropriate orthogonal array (OA) is selected. For this study, the control parameters and their respective levels chosen for experimentation are displayed in Table 3.8.

Table 1: Control factors and levels for wear test

Factor	Level 1	Level 2	Level 3	Level 4
A: Reinforcement (wt%)	0	5	7	9
B: Load (N)	10	20	30	40
C: Speed (rpm)	100	200	300	400
D: Sliding distance (m)	500	1000	1500	2000

An L16 orthogonal array was selected to accommodate four control factors, each at four levels, resulting in 16 experimental runs. Further, for statistical analysis Taguchi coupled with ANOVA, was done to systematically evaluate the impact of each process parameters and to identify the most significant factors influencing wear behaviour of the Al6061–TiO_2–CSA hybrid composites. Response Surface Methodology (RSM) was subsequently adopted to quantify interaction effects and to develop predictive mathematical models for the wear rate and COF.

3. Results and Discussions

The specific wear rate (SWR) was calculated from wear loss data and the results obtained are presented in Table 4.5. ANOVA results are presented in Table 2. Analysis of

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variance has been run on the experimental data to recognize significant parameters impacting the wear behavior of composites

Table 2: Wear test results of composites

Reinforcement (%)	Load (N)	Speed (RPM)	Sliding Distance (m)	SWR $x10^{-7}$ (mm^3/Nm)
0	10	100	500	1.775
0	20	200	1000	2.420
0	30	300	1500	2.770
0	40	400	2000	3.220
5	10	200	1500	1.745
5	20	100	2000	1.925
5	30	400	500	2.950
5	40	300	1000	2.650
7	10	300	2000	1.545
7	20	400	1500	2.420
7	30	100	1000	2.040
7	40	200	500	2.100
9	10	400	1000	1.880
9	20	300	500	1.610
9	30	200	2000	1.460
9	40	100	1500	1.740

Specific wear rate

Table 2 demonstrates that hybrid composites including filler particles shown enhanced wear resistance and a marked reduction in SWR relative to the unreinforced sample. The average SWR constantly diminished with higher reinforcement content, illustrating the advantageous impact of hybrid reinforcement on wear resistance enhancement. Figure 2 illustrates the principal effect plot of means for the computed SWR. This plot demonstrates the influence of each input parameter, highlighting those with the most substantial effect on the response, where lower values signify superior performance.

The response table for means (Table 3) and the main effects plot for SWR (Fig. 2) make it abundantly evident that sliding distance has a relatively small impact on the wear behavior of the Al6061–TiO_2–CSA hybrid composites, whereas reinforcement content, sliding speed, and applied load have a significant impact. The main factor affecting wear behavior, according to the results, is reinforcement; hybrid composites with filler particles show better wear resistance. TiO_2 filler provides the necessary hardness and load-bearing capacity, which lessens plastic deformation. Micro-ploughing resistance and tribo-film formation are facilitated by SiO_2-rich CSA particles. The wear rate steadily dropped as the filler content rose. The observed increase in wear resistance is due to the synergistic effect of adding hybrid fillers to the matrix phase. By increasing interfacial bonding and composite hardness, filler particles reduce wear. and material loss rates. Because of its cushioning effect, Satheesh et al. [11] found that adding CSA particles to Al6061-SiC composite decreased the wear loss of hybrid composites.

SWR rose proportionately with increasing speed, following a similar pattern. Wear was increased as a result of frictional heating and thermal softening of the Al matrix at higher speeds [12]. When compared to other factors, the sliding distance had the least variance in SWR,

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indicating that distance is not as important under the current test conditions. Additionally, it was observed that while the wear rate decreased with increasing distance, SWR initially increased significantly.

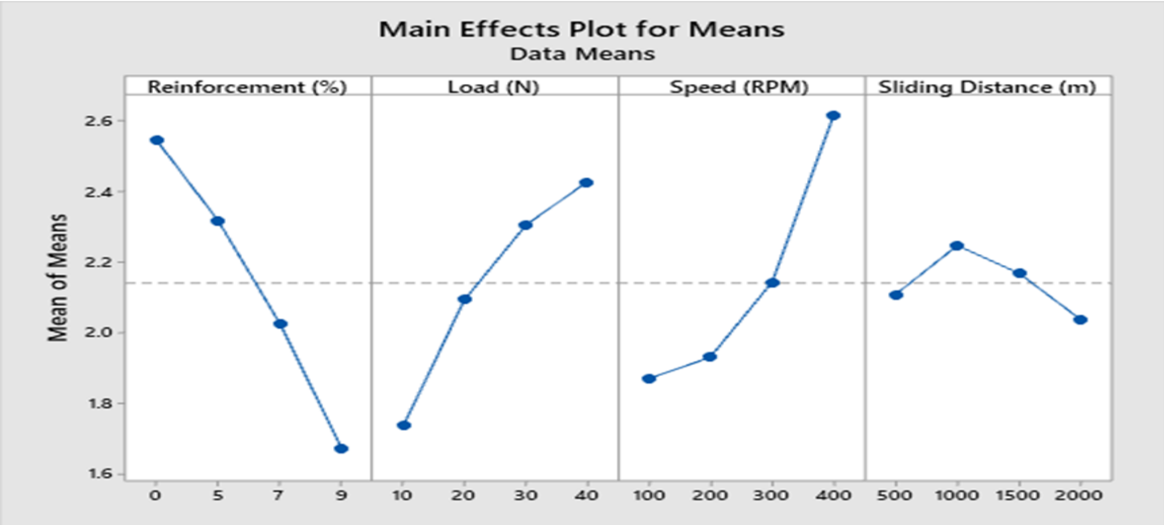

Fig. 2. Main effect plot of means - effect of control factor on SWR

Table 3 Response Table for Means-SWR

Level	Reinforcement (%)	Load (N)	Speed (RPM)	Sliding Distance (m)
1	2.546	1.736	1.870	2.109
2	2.317	2.094	1.931	2.248
3	2.026	2.305	2.144	2.169
4	1.673	2.428	2.617	2.038
Delta	0.874	0.691	0.747	0.210
Rank	1	3	2	4

At longer sliding distances, the abrasiveness is lessened by the presence of TiO_2+CSA filler particles in the matrix interface, which lowers the wear rate throughout the course of the longer test. Mukesh Kumar observed a similar decrease in wear rate for hybrid reinforcement systems at greater sliding distances [13]. A thin tribo-layer formed across the sliding surfaces as a result of lubricant particles being activated by an increase in temperature at the contact interface.

The findings from the main effects analysis are statistically supported by the ANOVA results for SWR shown in Table 4. The ANOVA findings specify that reinforcement as the most influencing parameter contributing 39.7% of the total variation in SWR, whereas sliding distance was the least significant component. With 31.9%, sliding speed was the second most

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influential factor, followed by load with 25.4% of the total contribution, confirming their significant impact on wear behaviour. Similar trends have been reported in TiO_2-reinforced hybrid composites by R. Jojith et al. [14], and Lohitesh et al. [15] in case of CSA-reinforced hybrid Al6061 composites.

Table 4 ANOVA for SWR

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
Reinforcement (%)	3	1.71216	1.71216	0.570719	75.86	0.003	39.74%
Load (N)	3	1.10013	1.10013	0.366710	48.75	0.005	25.54%
Speed (RPM)	3	1.37798	1.37798	0.459327	61.06	0.003	31.98%
Sliding Distance (m)	3	0.09546	0.09546	0.031819	4.23	0.134	2.22%
Error	3	0.02257	0.02257	0.007523			0.52%
Total	15	4.30829					100.00%

Response Surface Methodology (RSM) Analysis

The interactive effects of variables on wear rate are clearly visualized by the response surface plots. The individual and combined impacts of reinforcement content, applied load, sliding speed, and sliding distance on the wear behavior of the composite are depicted in the response surface plots of specific wear rate (SWR) in Figure 3. According to the reinforcement vs load curve in Figure 3 (a), SWR rises with applied load but sharply falls with increasing reinforcement percentage. Improved hardness, increased load-bearing capacity. Higher loads, on the other hand, result in a greater real area of contact and contact stress, which causes significant adhesive and abrasive wear.

SWR clearly increases with sliding speed, but SWR reduces with increasing reinforcement, according to the interaction plot of reinforcement vs speed in Figure 3 (b). Wear is decreased by reinforcement particles, which serve as barriers against material removal and encourage the development of a stable tribo-layer. Higher sliding speeds, however, produce more heat from friction, softening the matrix material and hastening wear. According to the reinforcement vs sliding distance plot (Figure 3 c), wear is continually reduced by larger reinforcement content, while SWR initially increases as sliding distance increases. Prior research has shown similar results, with greater reinforcement reducing wear and higher load and speed increasing wear even with enhanced material hardness [2].

Maximum wear occurs at high-load, high-speed combinations, as illustrated by the load versus speed plot in Figure 3 (d), which shows a strong synergistic influence of load and speed on SWR. Previous wear experiments have documented similar synergistic effects of speed and load, where high frictional energy at elevated operating conditions led to accelerated wear rates [16]. The load versus distance plot (Figure 3 e) demonstrates that the sliding distance controls the amount of wear exposure, whereas the load controls the degree of surface interaction via increasing contact stress.

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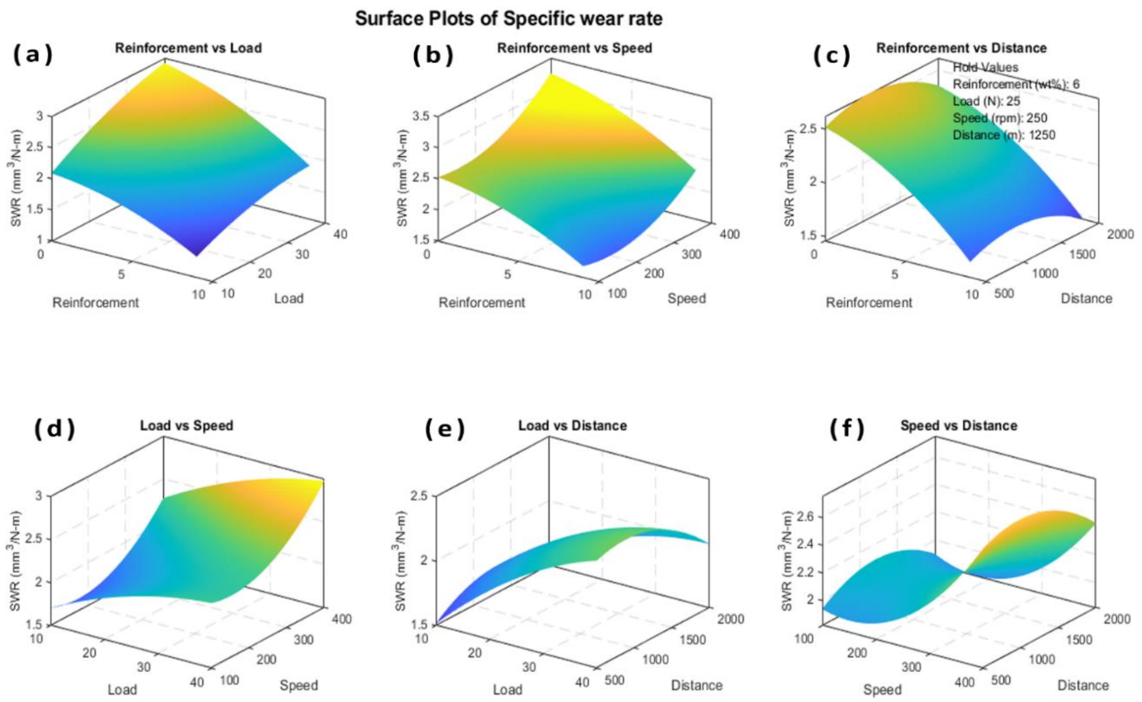

Figure 3(a-f) Surface plots of SWR

As the load vs speed figure in Figure 3 (d) demonstrates, maximum wear happens at high-load, high-speed pairings, indicating a strong synergistic influence of load and speed on SWR. Increasing load raises contact pressure, and increasing speed raises interface temperature, which promotes severe surface damage and faster wear. Figure 3 (f) indicates that SWR increases with both sliding speed and distance, exhibiting a noticeable interaction effect.

While load and speed contribute to increased wear through mechanical and thermal effects, the reinforcement consistently acts as the primary factor in reducing wear, according to previously published tribological studies on particulate-reinforced metal matrix composites.

The predictive equation for Specific wear rate in terms of factors is given by equation (1):

SWR = 1.13392 + 0.0579434*Load - 0.00364022*Speed + 0.000991541*Distance - 0.006696742*Reinforcement.^2 - 0.0004678482*Load.^2 + 1.24913e-05*Speed.^2 - 3.02511e-07*Distance.^2 - 0.00115244L*(Reinforcement.*Load) - 4.73536e-05S*(Reinforcement.*Speed) + 4.90851e-07D*(Reinforcement.*Distance) + 1.62554e-05S*(Load.*Speed) - 8.71501e-06D*(Load.*Distance) - 4.78607e-07*(Speed.*Distance)

Worn Surface SEM Analysis

In order to understand the primary wear mechanisms functioning under dry sliding conditions, the worn surfaces of Al6061 and TiO_2–CSA-reinforced hybrid aluminum matrix composites were examined using scanning electron microscopy (SEM). Figure 5.1-5.4 shows the SEM micrographs of the worn surfaces of the S1 (Al6061 alloy) and S4 (Al6061 + 6 % TiO_2 + 3 % CSA) samples that were evaluated at loads of 10 N and 40 N and at speeds of 100 rpm and 400 rpm.

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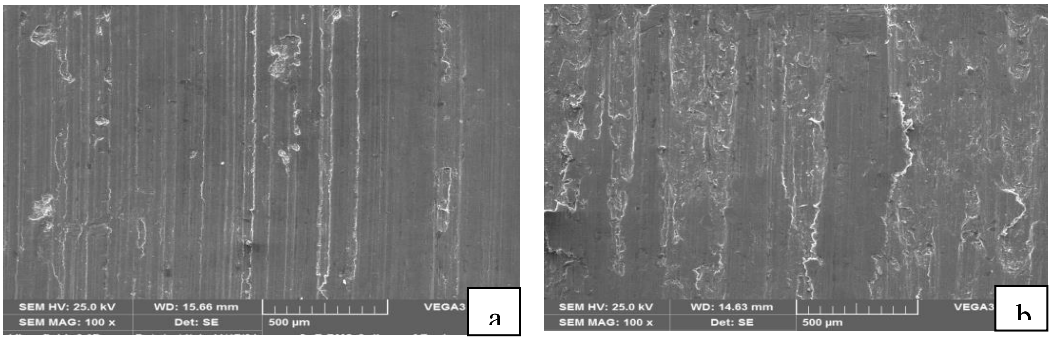

Figure 4.1. SEM image of (a) S1 (b) S4 sample at 10N

The SEM image of the S1 sample's worn surface at 10 N is displayed in Fig. 4.1 (a). Clearly visible abrasion marks and deep, continuous grooves running along the sliding direction are present on the surface. These characteristics show that abrasive wear is more common and is brought on by plastic deformation of the soft aluminum matrix and direct metal–counter face contact. Comparatively smaller grooves and less severe abrasion are seen in Fig. 4.1(b), which corresponds to the hybrid composite S4 at 10 N. Patches of shallow delamination are apparent, however they are much smaller in size than those seen in the base alloy. While CSA particles help with load sharing and prevent micro-cutting, the presence of hard TiO_2 particles increases surface hardness and resists surface wear. The worn surface of S1 Al6061 alloy seen in Fig. 4.1 (a) displays substantial surface degradation at higher load conditions of 40 N, which is characterized by extensive delamination, material peeling, and smeared regions along the sliding direction. Material softening and wear loss are accelerated by the increasing normal load, which also increases real contact area and frictional heating. On the other hand, narrower grooves and comparatively homogeneous wear marks with little delamination are shown in the hybrid composite S4 tested at 40 N (Fig. 4.2 b). Moreover, direct metal-to-metal contact is decreased when an oxide layer forms [5]. Consequently, even under extreme loading circumstances, the wear process changes toward controlled abrasive wear.

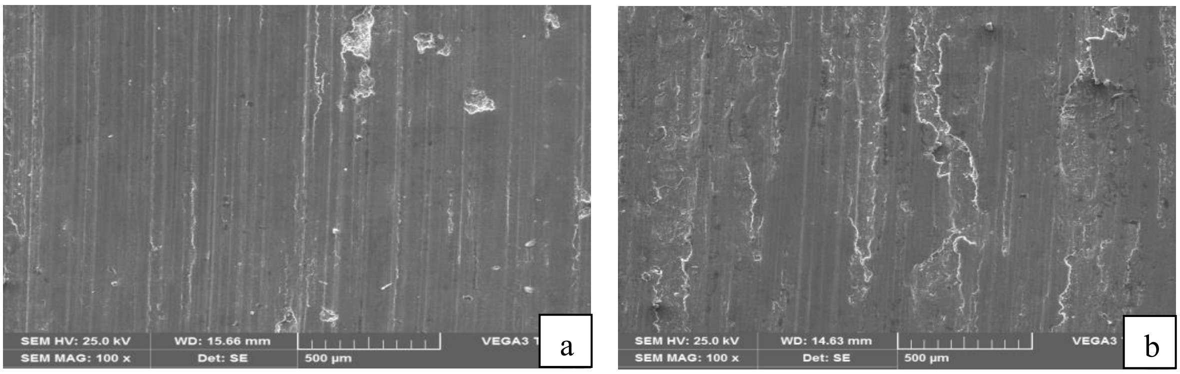

Figure 4.2. SEM image of (a) S1, (b) S4 sample at 40N

The worn surface of the S1 sample at 100 rpm is shown in Fig. 5.3(a). There are evident grooves lined along the sliding direction, and the worn morphology shows a combination of abrasion and delamination. The worn surface of S1 (Fig. 4.3a) exhibits increased delamination and smeared areas as the sliding speed rises to 400 rpm, indicating localized thermal softening

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of the matrix as a result of frictional heating. S4, on the other hand, has better surface integrity at both speeds. With limited and localized delamination and small, shallow grooves aligned along the sliding direction, the worn surface of S4 at 100 rpm is seen in Fig. 4.3(b), suggesting a mild abrasive wear regime. In comparison to 100 rpm, the S4 worn surface (Fig. 4.4 b) exhibits more apparent delamination patches and an increase in groove density and length when the sliding speed is raised to 400 rpm. Although groove density increases at 400 rpm, the depth and continuity of grooves remain relatively shallow and well-defined, without evidence of extensive plastic flow as compared to unreinforced alloy. Furthermore, the development of compressed tribo-layers with broken-up reinforcing particles adds to the protective layer. The formation of such a layer, coupled with enhanced hardness, explains the reduced wear rate of S4 even under severe sliding conditions. Frictional heating is reduced at lower sliding speeds, maintaining the interfacial connection between the reinforcements and the matrix as well as the matrix's hardness.

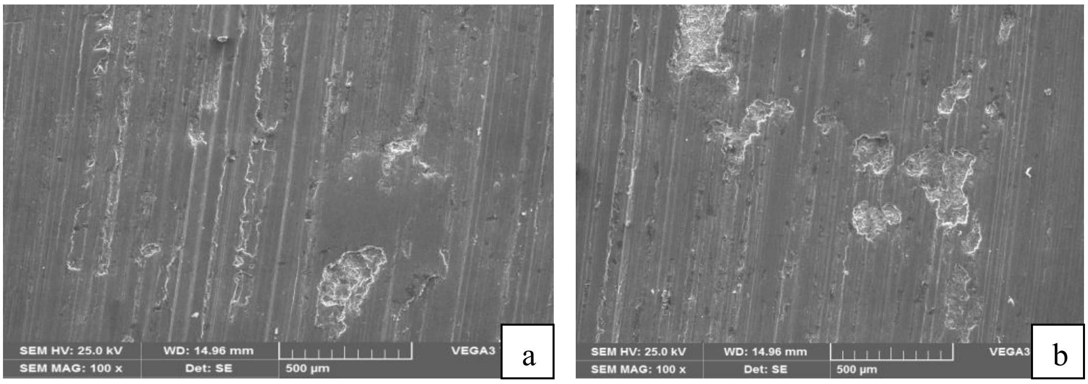

Figure 4.3. SEM image of (a) S1, (b) S4 sample at 100 rpm

Localized softening of the aluminum matrix is encouraged by the higher interfacial temperature caused by frictional heating caused by the faster sliding speed. At reinforcement–matrix contacts, this heat effect promotes the formation of subsurface cracks, which leads to delamination.

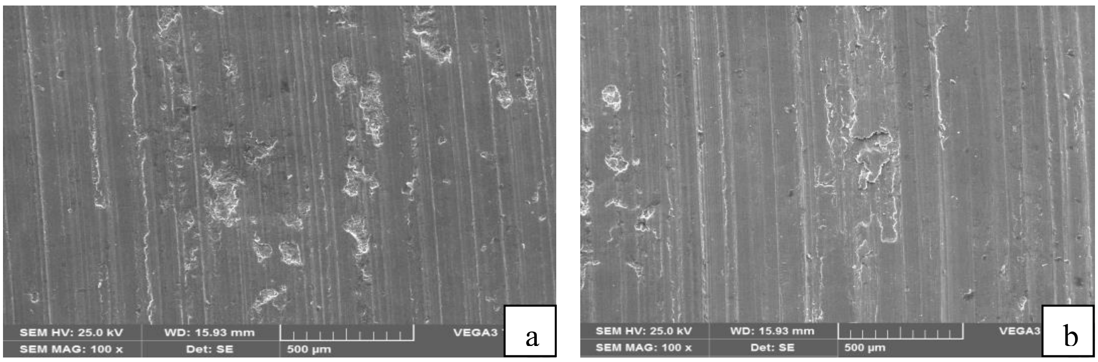

Figure 4.4. SEM image of (a) S1, (b) S4 sample at 400 rpm

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4. CONCLUSIONS

The impact of hybrid reinforcement on the tribological properties of the produced composites was methodically investigated in this work. The following deductions are made in light of the experimental findings and thorough analyses:

1. Across all evaluated loads and sliding speeds, dry sliding wear tests showed that the hybrid composites significantly reduced the specific wear rate and friction coefficient when compared to the basic alloy.

2. The beneficial impact of hybrid reinforcement in improving wear resistance is confirmed by the continuous decrease in SWR that occurs with a rise in reinforcement content. On the other hand, because of increased actual contact area, frictional heating, and matrix softening—all of which encourage severe adhesive and abrasive wear mechanisms—SWR rose with applied load and sliding speed.

3.Load was identified as the most influential parameter governing wear behavior, followed by sliding speed and distance. ANOVA and response surface analysis validated the statistical significance of these factors and enabled the reliable prediction of wear performance.

4. The SEM observations validate the efficacy of hybrid reinforcement synergy in improving the tribological performance under various loads and sliding speeds, and they substantially support the experimental wear results and statistical analysis.

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