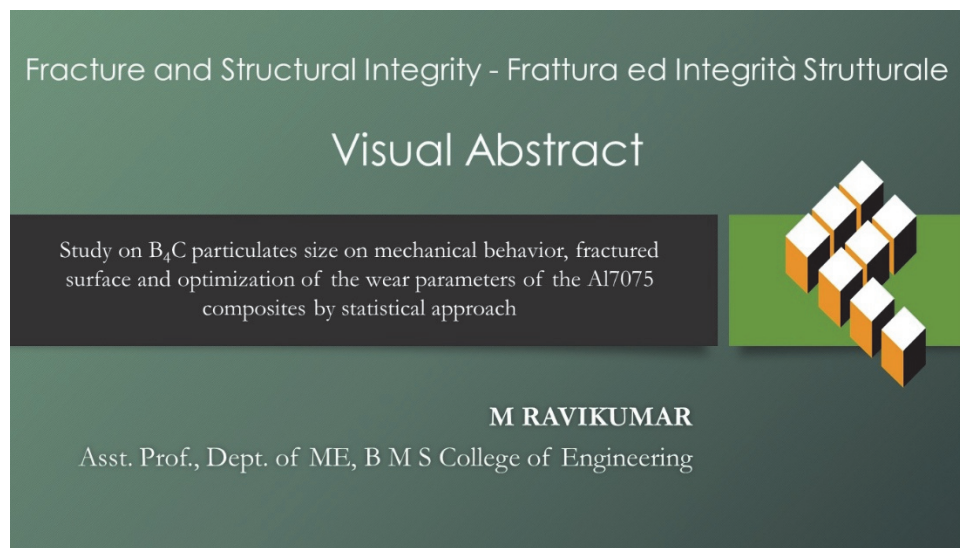




Study on B₄C particulates size on mechanical behavior, fractured surface and optimization of the wear parameters of the Al7075 composites by statistical approach

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KEYWORDS. Al7075, Particulates size, Microstructure, Mechanical behavior, Wear Characteristics, ANOVA, Fracture analysis.

INTRODUCTION

Metal Matrix Composites (MMCs) are a novel class of materials that can be applied to many different industries. By adding a robust ceramic reinforcement to a metal matrix, this class of materials enhances its properties, including specific strength, specific stiffness, wear resistance, better corrosion resistance, and high elastic modulus [1]. In other words, by fusing the metallic attributes of matrix alloys (ductility and toughness) with the ceramic qualities of reinforcements (high strength and high modulus), MMCs show improved strength in both compression and tension as well as higher service temperature capabilities. They are therefore extremely important in the fields of science, technology, and industry [2]. To improve alloy production and ultimate strength, micro-sized particles are commonly used. However, the ductility of MMCs significantly decreases as the concentration of ceramic particles rises. On the other hand, the ductility, fatigue strength, and high temperature creep resistance of metal-matrix composites are enhanced by the nanoscale inclusion of ceramic particles [3]. Due of its numerous technical properties, Al7075 is used for the addition of reinforcements. When necessary, one or more reinforcement particles can be added to the base material, Al alloy, to improve its various qualities. Compared to the base alloy, these particles are stronger. The properties of the material are improved via improved strengthening mechanisms in the MMCs. Aluminum alloys are referred to as the matrix phase in



Al composites. Another element that is frequently utilized to reinforce these alloys is hard ceramic reinforcement. When hard ceramic particles are added to aluminum alloy, the alloy frequently becomes stronger, more resistant to wear, has better corrosion resistance, and has a lower density than the base alloy. Continuous fiber reinforced composites are not advised due to their high cost and possible health risks. On the other hand, the anisotropic properties of short fiber reinforced composites make them effective. Therefore, it is necessary to produce particle-reinforced Al-based composites with low density, good formability, and isotropic properties. Stir casting is a reliable method that is widely utilized for both ferrous and nonferrous components. Many researchers followed the stir casting approach due of its commercial success in producing large-sized components, even if AMMCs are manufactured using other methods [4]. Furthermore, because of the swirling action that occurs when ceramic particles are added, the stir casting process has been shown to be an easy and successful method for particle bonding. The impact of reinforcement particle size on the microstructure and mechanical properties of Al composites was examined by researcher [5]. The findings were summarized as follows: (a) the matrix ligament size lowers with a rather uniform distribution of reinforcement when the particle size decreases; and (b) the composite's strength increases by around 50% when the reinforcement size decreases. Gangadharappa [2] looked at how the weight percentage of n-TiB₂ affected the Al7075/TiB₂ composite's mechanical and tribological properties. With a hardness of 82 VHN, it was determined that composites reinforced with 2.5 weight percent n-TiB₂ were the toughest. Maximum tensile robustness was noted for 2.5% of the nano composites reinforced with n-TiB₂, and tensile strength rose as the weight of n-TiB₂ particles was increased by 132 MPA. The impact of nanosized Al₂O₃ and Al₂O₃-SiC on the mechanical, wear, and fracture surfaces of Al7075 composites was investigated by Ravikumar [1]. When compared to base materials, it has been found that MMCs with n-SiCp reinforcement offer exceptional wear resistance. Prakash [3] investigated how formwork grade Al7075 composites' mechanical, wear, fracture, and machining characteristics were affected by nanoparticles (B₄C-Al₂O₃). It was noted that for samples reinforced with 4.5% B₄C + 2% Al₂O₃, the inclusion of nanoparticles and heat treatment significantly increased the hybrid composites' tensile strength, hardness, and wear resistance by 3%, 17%, and 10%, respectively. Ravikumar [6] investigated the effects of Al₂O₃ particles ranging in size from micro to nano on the mechanical, wear, as well as fracture behavior of Al7075 Metal Matrix Composites. It was found that the hardness and tensile strength values improved in tandem with the amount of reinforcement in the metal matrix. Nano composites have been found to be more robust than micro composites. Additionally, it was mentioned that the wear rate of composite and nano composite materials was higher than that of as-cast, and that wear loss decreased up to a certain weight percentage of reinforcement before remaining unaffected by a number of factors, including wettability and agglomeration of nano reinforcement particles, which at higher weight percentages of reinforcement content reduced the wear resistance of the nano composite.

In addition to creating extremely superior mechanical properties, the high cost of B₄C reinforcements is a major factor in the composites' increasing cost. The higher the weight-fraction and the finer the size of the reinforcing particles, the more expensive the AMMCs. To reduce the B₄C-associated cost of AMMCs, experiments with varying weight percentages of B₄C and size distributions are required. Investigating the combined effects of B₄C particle size and wt. % on the mechanical behavior and sliding wear mechanism of created composites is the aim of this work. Because of its simplicity, the pin-on-disc arrangement is frequently used in laboratories for wear tests; therefore, the pin-on-disc test method was employed in the current study in compliance with ASTM requirements. The purpose of the investigation was to find out how the sliding surfaces of Al7075 composites at a comparable time were affected by reinforcing the size and weight percentage.

MATERIALS AND EXPERIMENTAL PROCEDURES

The Al7075 alloy's high corrosion resistance makes it a popular choice for civil, automobile, aerospace, and marine engineering. In the production of Al7075 / B₄C composites, the basis material was Al7075 alloy, and the reinforcing component was micro-sized B₄C particles with an average mesh size of 100-125 and nano-sized B₄C particles with an average size of 25-30 nm. The developed MMCs' microhardness and tensile strength are increased by a B₄C particle that blocks dislocation moments in the matrix. The B₄C particles are distributed evenly throughout the matrix, forming hard phases that are resistant to plastic deformation. Increases the hardness, refines the structure's grain, and causes strain hardening in the matrix. The B₄C particles form a solid link with the matrix material, aid in efficient load transfer, and boost strength and hardness. According to the current study, the composites show enhanced mechanical characteristics and wear resistance when B₄C particles of micro and nano sizes are included into MMCs. Micro sized B₄C reinforced MMCs are extensively used in aerospace, automotive, energy, and engineering industrial sectors. It is due to the enhanced mechanical properties with stiffness to strength ratio. On the other hand, nano sized B₄C reinforced MMCs



show more noticeable improvements in mechanical properties, better wear and corrosion resistance and better damping properties. Stir casting is a crucial technique applied for fabrication of Al composites. This method can be used to melt metals such as copper, magnesium, and aluminum. This is one of the most widely used and effective methods for creating metal matrix composites [7]. The crucible used in the current investigation was preheated to 750 °C before B₄C particles were introduced to the molten melt inside the electric furnace. The weight percentages of micro and nanosized B₄C particles added to the molten metal were 1, 1.5, 2, and 2.5, respectively. While the furnace was heated to 800 °C, the stirring process was done for two minutes at 150 rpm in order to maintain a homogenous melt mixture. Stirring at high temperatures aids in the disintegration of agglomerates. The castings were finally removed from the mold box after molten metal was poured into a metal die and allowed to solidify. This procedure was carried out again utilizing various samples and weight percentages of micro and nano reinforcement, respectively. Vickers micro-hardness device was used to measure the material's hardness three places in order to eliminate the possibility of indenter testing on hard particles, which could result in an odd outcome. The microstructure of the surfaces was inspected after they were prepared with 1000 grit emery sheets and polished with 0.5 μm diamond paste. The composites' hardness was evaluated by applying a force of 10 kg for 30 seconds. Tensile tests were performed on the MMCs in accordance with ASTM E8 standards criteria in order to examine their mechanical strength. A Universal Testing Machine (UTM) with continuous loading at 10 N was used for the tensile test. In accordance with ASTM-G99 criteria, wear tests were performed on composite specimens measuring 25-30 mm in length and 6 mm in diameter. For the present research work, pin-on-disc tribometer was used under room temperature. To evaluate the wear behavior of the generated composites, a constant load of 10 N was applied for the course of the study. The wear surface was steel disc EN32, and weight loss method was used to calculate the wear rate. The amounts that controlled parameters were determined by the literature review, industry experts' opinions, and the early testing. The wear parameters are optimized using the L8 orthogonal array. The robust design of the L8 array helps to maximize the performance of developed MMCs' wear behavior while reducing the impact of wear parameters. Tab. 1 shows the wear parameters and its levels and Tab. 2 shows the L8 orthogonal array for the experimental work carried out during the wear test.

Sl. No.	Parameters	Levels
1	Particulates Size	Micro, Nano
2	Sliding Speed - (m/s)	3, 6
3	Sliding Distance - (m)	1500, 3000

Table 1: Input levels of process parameters.

RESULTS AND DISCUSSIONS

Microstructural analysis

The SEM images show the distribution of B₄C particulates in Fig. 1. The B₄C particles distributions in the matrix help to improve the stiffness, mechanical properties and high wear resistance. The B₄C particles create a strong bonding with matrix material and helps to transfer the load effectively and increasing the hardness and strength. In the current research, incorporating the micro and nano sized B₄C particles into MMCs, the composites exhibits improved mechanical properties and wear resistance. By combining Al7075 with B₄C particles, the micrographs clearly demonstrate a shift in dendritic size and distribution. It is evident that the application of the B₄C particles has decreased the length of the dendrites. The picture analysis demonstrates that adding micro B₄C particles or increasing the concentration of B₄C nanoparticles has reduced the average length of the dendrites. Additionally, it is clear that Micro B₄C refines dendrites more effectively than Nano B₄C.

In fact, B₄C particles' function as nucleants in Al7075 molten metal is responsible for their modifying effect. B₄C particles increase the amount of dendrites forming at a given time by acting as favored nucleation sites. The diffusion distance of solute atoms discharged into the surrounding melt decreases as the number of developing dendrites increases. As a result, the dendrites' average length is refined and their growth rate is weakened. According to this theory, the superior wettability of micro B₄C particles in the molten metal should be correlated with their efficiency. As previously stated, the high surface tension of nanoparticles and their low wettability with molten metals present the biggest obstacle to the production of NMMCs [8]. In their work on the Al7075-TiB₂ micro/nano composite, Akbari et al. [9] have reported similar results.

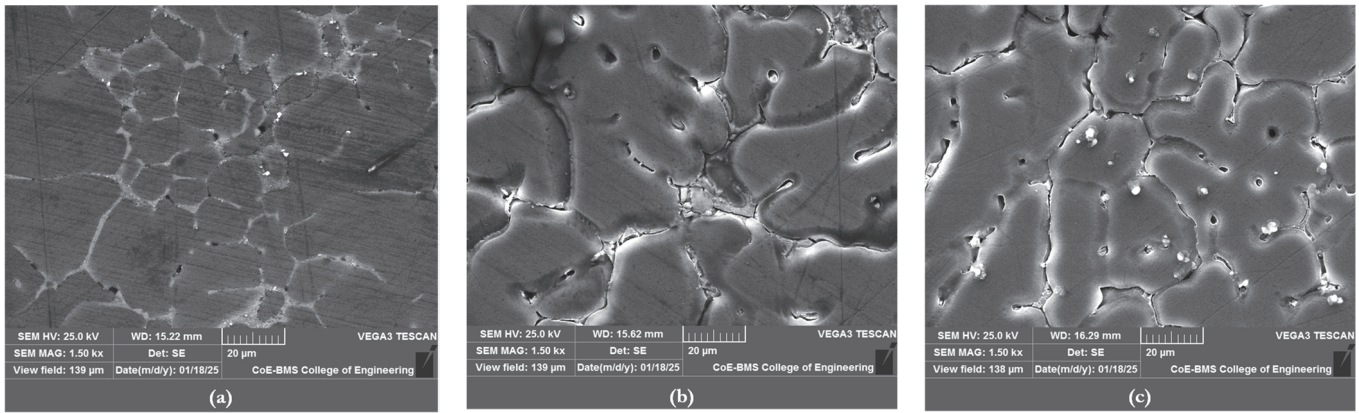


Figure 1: Microstructure of the (a) base alloy (b) micro composite and (c) nano composites.

Porosity

Fig. 2 illustrates how the porosity volume percent changes with the nano and micro B_4C volume percent. Because of their substantially larger surface area, which enables better dispersion and reduces the formation of voids or gaps within the material, nano-sized particles typically produce lower porosity when added to an aluminum matrix to create a composite; in other words, smaller particles can fill the spaces more effectively, resulting in a denser composite with less porosity [10].

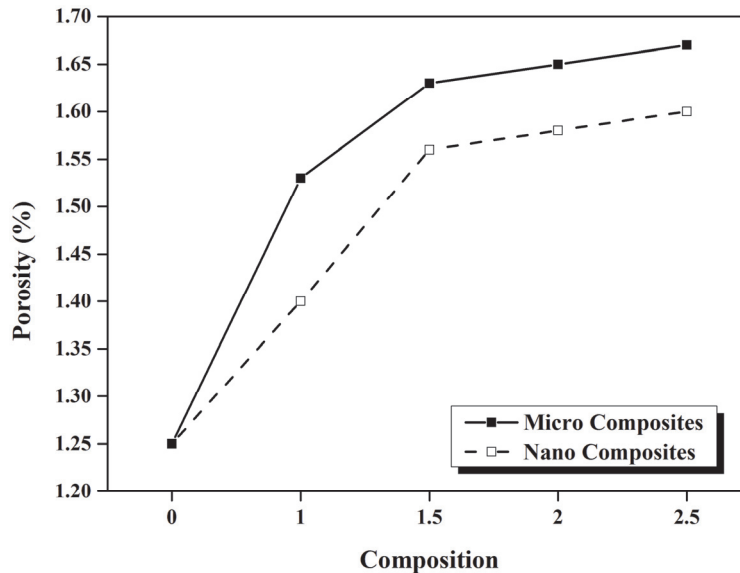


Figure 2: Porosity (%) of base alloy, micro and nano composites.

Hardness

Most researchers favored the Vickers hardness test because it had the broadest scales of any hardness test. As a result, Fig. 3 compares the hardness of all created micro and nano composites (as measured by the Vickers hardness test at a 10 kg force). The hardness of composite materials was increased by the combined action of hard ceramic particles and a denser matrix. From the Fig. 3, it is observed that, the hardness of the developed MMCs increased by 16.06% when compared to the base alloy. The obtained results indicate the higher hardness of MMCs leads to significant wear resistance with 2% of B_4C particles. Consequently, the hardness of the composites (nano composites) increased as their particle size decreased. The presence of nanoparticles caused the number of particles in the composite material to rise in a very comparable weight-fraction, which severely hindered material flow under stressed conditions. It also has wider interfacial regions between the reinforcements as well as the matrix to enable the reinforcements to absorb the external load applied by the matrices [11]. The B_4C particles create a strong bonding with matrix material and helps to transfer the load effectively and increasing the hardness and strength. In the current research, incorporating the micro and nano sized B_4C particles into MMCs, the composites exhibits improved mechanical properties and wear resistance. Larger B_4C particles (micro sized particles) make the matrices extremely ductile, but they also have a lower resistance to dent-deformation [12, 13].

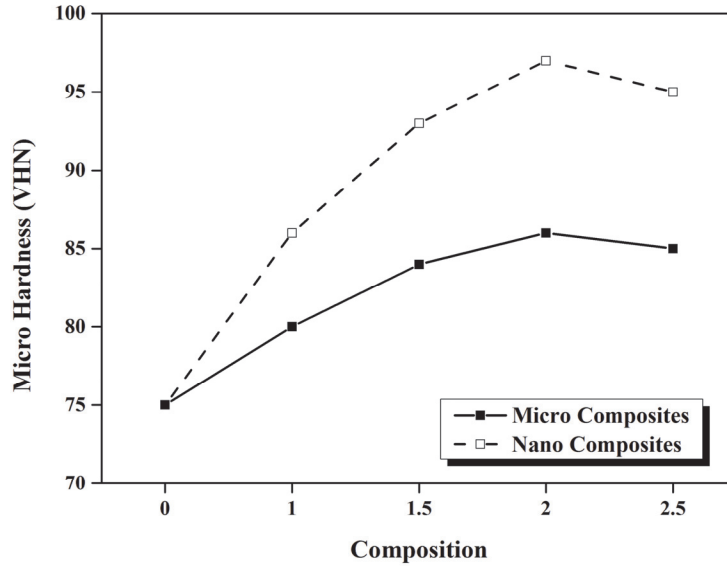


Figure 3: Hardness of base alloy, micro and nano composites.

Tensile strength

Fig. 4 shows the tensile strength of the generated micro and nano composites. From the Fig. 4, it is observed that, the tensile strength of the developed MMCs increased by 12.90% when compared to the base alloy. By incorporating nano B_4C particles into MMCs, the tensile strength and wear resistance will be significantly enhanced with efficient transfer load in the metal matrix and reducing the stress concentration. Nano B_4C particles refine the grain structure of the matrix and lead to increased tensile strength and wear resistance. It is due to the Hall-Petch relationship. It is well known that composites reinforced containing smaller B_4C particles (nanoparticles) have shorter interparticle spacing and a higher reinforcement/matrix surface energy. Shifting more stress from the softer matrices to the harder reinforcing material, increases the composite's tensile strength and work hardening. Due to the smaller interparticle gap and higher work-hardened rates, the experimental results show that decreasing the reinforced-size can lead to a finer morphology and improved mechanical performance for a given particle-weight percent.

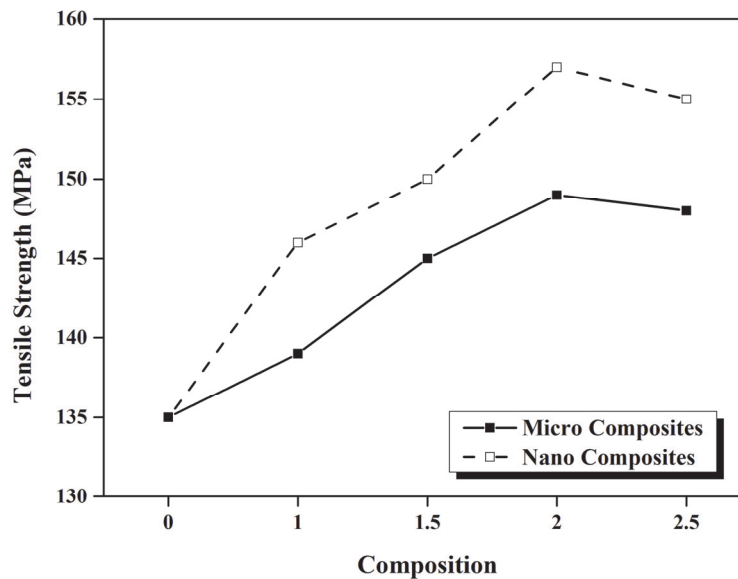


Figure 4: Tensile strength of base alloy, micro and nano composites.

The additional force can be transferred from the matrices to the B_4C particulates when the B_4C particle size decreases because the contact area between the matrix as well as the B_4C particles increases. Notably, a wide interfacial area may help the matrices create a lot of microcracks, fracture voids, and discontinuities, which improve mechanical performance.

However, during the tensile testing procedure, heavier particles (micro-sized particulates) collapse more quickly than microscopic particles (nano particles) for two significant reasons [14]. First, there is a greater stress-concentration because micro-sized particles have a larger interaction-area with the matrix. Furthermore, the particle's fracture toughness is influenced by its inherent flaws. Since the size of a particle determines the size of a fault, microparticles are more likely to fracture because they have a significantly higher statistical chance of creating a flaw or imperfection larger than the critical size [15]. Because the broken particles cannot withstand any stress and act as preferred failure sites, the composites with micro-sized B₄C particle sizes exhibit a decline in tensile strength [12].

Fractured Surface

The reinforced composites' fracture surfaces (Fig. 5a & b) show a distinct difference between the matrix's (dimple rupture) and the particles' (brittle rupture) modes of fracture. Because larger particles are more likely to crack, the composites reinforced with larger particles show several cracks in the image (Fig. 5(a)) [5]. It is suggested that the shear strength at the interface is greater than the particle fracture strength since the particle/matrix interfaces are still intact. Kumai et al. [16] have also noted comparable outcomes in 6061 aluminum alloy reinforced with SiC particles. With dimples placed on the reinforcement, the composite reinforced with smaller particles (Fig. 5(b)) exhibits nearly a ductile fracture.

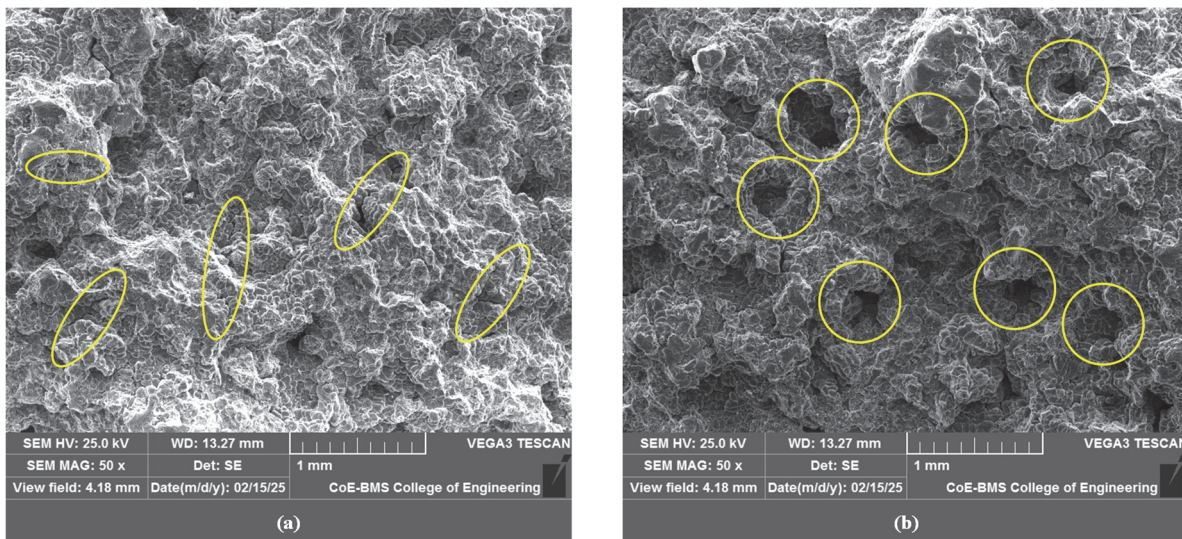


Figure 5: Tensile samples fractured surface of (a) Micro composite and (b) Nano composite

Influence of input parameters on specific wear-rate using RSM

Both the experiment design and the assessment of the data acquired during the investigation were done using RSM. RSM is a collection of statistical presumptions, mathematical tools, and empirical strategies that enable an effective experimental investigation of a system or process. RSM is a statistical method that uses quantifiable data from relevant research to determine and solve multi-variable equations concurrently. In several academic fields, this approach is frequently used to statistically analyze results. Analysis of Variance is used to summarize these tests (ANOVA). Furthermore, confirmatory tests, regression analysis, and interactions are examined for every ANOVA analysis. These graphs are used to analyze how various wear behaviors affect the wear loss and COF of the produced composites. Here, the three parameters (particles size, sliding speed, and sliding distance) at two different design levels were used to examine the impacts of control factors on wear loss as well as coefficient of friction, as indicated in Tab. 1. For every control parameter, the degree of freedom is one less than the number of levels. According to the rule, each control component and their interactions should have at least one additional experimental run than the total number of degrees of freedom. The L8 orthogonal array was used with three factors and two levels, as shown in Tab. 2. Eight trials were conducted using the run order produced by the Taguchi model. Coefficient of Friction and Wear Loss were the model's responses. The columns were organized in an orthogonal array according to the coefficient of friction and wear rate. The model's goal was to lower the coefficient of friction and wear loss. An ANOVA was performed on the results following the determination of the mean and Signal-to-Noise (SN) ratios.



Sl. No.	Particulates Size	Sliding Speed (m/s)	Sliding Distance (m)	Wear Loss (gms)	COF (μ)
1	Micro	3	1500	0.084	0.75
2	Micro	3	3000	0.075	0.90
3	Nano	6	1500	0.080	0.50
4	Nano	6	3000	0.060	0.60
5	Micro	6	1500	0.096	0.70
6	Micro	6	3000	0.091	0.75
7	Nano	3	1500	0.065	0.55
8	Nano	3	3000	0.060	0.70

Table 2: L8 Orthogonal array of experimental layout.

Using the "Smaller is better" theory, the signal-to-noise ratio was investigated. The influence of a factor is shown by the delta value in Tab. 3 and 4. The delta value is the difference between the averages of a factor's highest and lowest qualities. As the degree of variation increases, so will the delta value and the parameter's relevance to the responses. The parameter's relevance determines its rank. The rank makes it clear that the weight percentage of n-B₄C has a considerable impact on wear loss and the coefficient of friction, both of which are then influenced by the applied load and sliding speed.

Level	Particulates Size	Sliding Speed (m/s)	Sliding Distance (m)
1	0.08650	0.07100	0.08125
2	0.06625	0.08175	0.07150
Delta	0.02025	0.01075	0.00975
Rank	1	2	3

Table 3: Response Table for Wear Loss.

Level	Particulates Size	Sliding Speed (m/s)	Sliding Distance (m)
1	0.7750	0.7250	0.6250
2	0.5875	0.6375	0.7375
Delta	0.1875	0.0875	0.1125
Rank	1	3	2

Table 4: Response Table for COF.

Additional analysis and major effect plots are displayed after the DOE implements MINITAB software (Fig. 6 and 7). The appropriate level of each control parameter was determined using SN ratio charts. The major effects plot showed that a nanoparticle size, a 3000 m sliding distance, and a 3 m/s sliding speed produced the greatest results for the least amount of wear loss. Similarly, the main effects plot was used to determine the ideal amount of processing variables for particle size: nano, a sliding distance of 1500 m, as well as a sliding speed of 6 m/s produced the best results for the enhanced COF of the produced MMCs.

The effect of particulates size on wear rate is shown in Fig. 6 it is seen that, nano particulates reinforced Al composites shows the better wear resistance compared to micro particulates reinforced Al composites. The reason for this is probably that, in contrast to coarse and intermediate reinforcing particles, fine reinforcing particles are widely distributed throughout the matrix. Additionally, the disk that the specimen orbits is sliced by the sharp edges of fine (nano) particles. During this process, the abrading hard particles' sharp edges become dull. As a result, wear is decreased. Furthermore, when the load is applied, the sharp edge particles (nano particulates) are easier to insert into the matrix than micro particulates. The intermediate and coarse particles become fragmented and the wear rate rises because they are difficult to be absorbed into the matrix under these circumstances. This suggests that composites made with fine particles



(nanoparticles) are more effective than those made with microparticles. It also suggests that composites made with nanoparticles have better wear resistance than both unreinforced alloy and those made with microparticles.

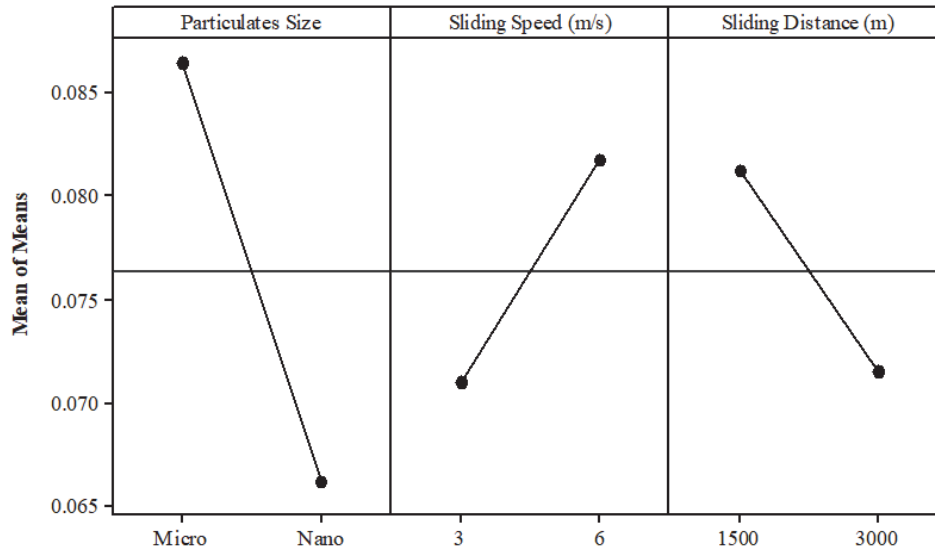


Figure 6: Main effect plots of wear loss.

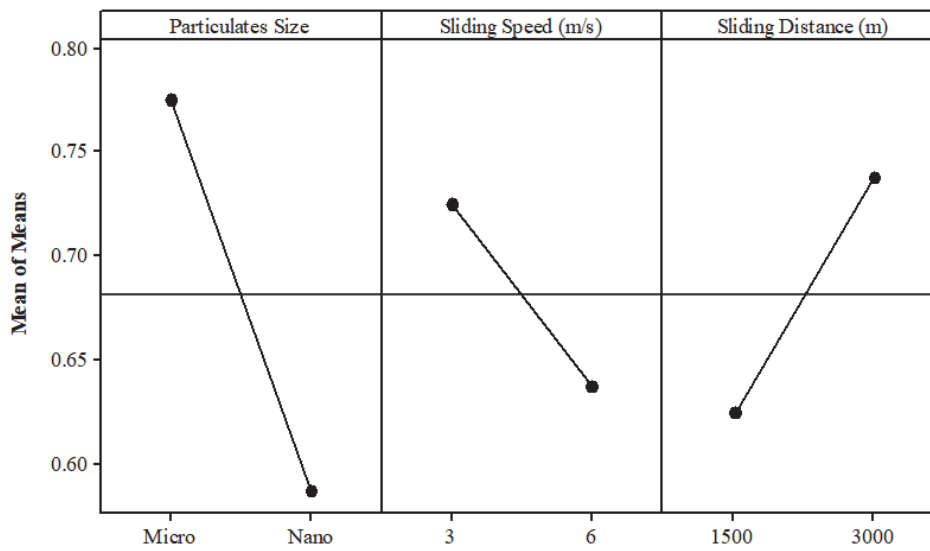


Figure 7: Main effect plots of COF.

The effect of sliding speed on wear rate is shown in Fig. 6, where it is seen that better wear resistance was found at higher sliding speeds. The rate at which material is worn away tends to increase as the relative speed between two surfaces in contact increases. This is mainly because of factors like increased friction heat generation, disruption of protective oxide layers, and the potential transition to more severe wear mechanisms at higher speeds. In general, increasing sliding speed causes an increase in wear rate. Similar results were found by another researcher, Odabas [17] and said that this is because rising sliding speeds are predicted to cause changes in strain rate and friction heating.

Fig. 6 shows the effect of sliding distance on wear rate, demonstrating that increased sliding distance led to better wear resistance. It was discovered that the rate of wear decreased with increasing distance between them due to the oxide layer that formed on the pin's surface. The film acted as a protective barrier by reducing the area of contact among the two surfaces. Furthermore, due to the mechanically mixed layer developed and was removed simultaneously, the rate of wear loss decreased as the sliding distance increased [18]. Priyaranjan Samal [19] reported that the wear rate of the composite decreased as the sliding distance increased. Two sliding surfaces make sharp contact during the first experiments, causing a lot of tension. With plastic deformation, these sharp edges broke and splintered, increasing the rate of wear. The wear debris filled the surface valleys as the sliding distance increased. As a result, there is less abrasive action, which lowers the



wear rate. In general, adhesion and ploughing are the two physical properties that cause friction. The ploughing component arises from the degree of plastic deformation between the surfaces of contact, whilst the adhesion component is formed by the adhesive force that exists between the contacting surfaces.

The effect of particulate size on the coefficient of friction (COF) is shown in Fig. 7. It is evident that the COF of the developed composites decreased as the particulate size was reduced. Micro sized particles can more noticeable asperities on the surface, increasing surface contact and friction forces, larger particles in aluminum composites typically have a higher coefficient of friction, which means that as the particle size increases, so does the friction between the surfaces. Higher friction when sliding against another surface results from larger reinforcing particles in an aluminum matrix producing more noticeable surface imperfections. Smaller particles can occasionally result in superior total wear resistance because of their capacity to embed more equally in the matrix and provide better load distribution, even though larger particles may initially have higher friction.

The effect of sliding speed on the coefficient of friction (COF) is shown in Fig. 7. It is observed that the COF of the developed composites was reduced by increasing the sliding speed. The coefficient of friction tends to decrease with increasing sliding speed, which means that friction force decreases with higher sliding speeds. This is mainly because heat is generated at the contact interface, which can soften the material and make sliding easier.

Figure 7 shows the effect of sliding distance on the coefficient of friction (COF). The COF of the developed composites increased with increasing sliding distance. The primary effect plot for COF shows that when the sliding distance is increased, the COF rises. The higher frictional forces between the rubbing surfaces could be the cause of this COF rise. Longer running distances leads to more wear debris between rubbing surfaces, which raises friction forces and raises COF [20].

The experiment data were analyzed using ANOVA, which ranked the importance of the variables that could have influenced wear loss. Tab. 5 and 6 display the results of the ANOVA. We used ANOVA data to explain the effect of wear loss and COF. These findings also provide light on how each of these components affects the overall wear characteristics of the finished composites. The significance of wear loss on the overall composite image is seen from the ANOVA results in Tab. 5. Of all the process components, the "particulates size" is the most significant, accounting for the biggest percentage (61.29%). As a result, wear loss is less affected by the size of the particles. Conversely, the results for sliding distance (14.20%) and speed (17.27%) were the least significant. Including a number of contributing factors, the total inaccuracy is 7.21%. The factors affecting the significance of COF were evaluated using an ANOVA analysis of the investigation's results. "Particulates size" had the largest percentage (61.30%) of all the components in Tab. 6, indicating their significant influence on COF. However, it was shown that, with respective contributions of 22.07% and 13.35%, sliding distance and speed had the least significance. When other contributing factors are considered, the overall inaccuracy (error) is 3.26 percent.

Sources	DoF	Seq. SS	Adj. SS	Adj. MS	F – Value	P - Value	% of Cont.	Remarks
Particulates Size	1	0.0008201	0.0008201	0.0008201	33.9948	0.0043114	61.29	Significant
Sliding Speed	1	0.0002311	0.0002311	0.0002311	9.5803	0.0363899	17.27	Significant
Sliding Distance	1	0.0001901	0.0001901	0.0001901	7.8808	0.0484508	14.20	Significant
Error	4	0.0000965	0.0000965	0.0000241			07.21	
Total	7	0.0013379	0.0013379				100	

Table 5: ANOVA results of wear loss.

Sources	DoF	Seq. SS	Adj. SS	Adj. MS	F – Value	P - Value	% of Cont.	Remarks
Particulates Size	1	0.070312	0.070312	0.0703125	75.0000	0.0009781	61.30	Significant
Sliding Speed	1	0.015313	0.015313	0.0153125	16.3333	0.0155853	13.35	Significant
Sliding Distance	1	0.025312	0.025313	0.0253125	27.0000	0.0065334	22.07	Significant
Error	4	0.003750	0.003750	0.0009375			03.26	
Total	7	0.114687					100	

Table 6: ANOVA results of COF.

When compared to sliding speed and sliding distance, the particles size exhibits the biggest contribution, according to the ANOVA findings, which also reveal the percentage contribution of each parameter and if the component is significant in the wear process. It is due to the effect of particles size (61%) contribute to the overall strengthening of the composite materials and high wear resistance, similarly the COF shows the particles size (61%) has significant effect. It results from the interplay between matrix material and particle size, whereby particulates size increases the concentration of stress in nanoparticle-reinforced MMCs and decreases reinforcement matrix interaction. The impacts of the three particulate size, sliding distance, and sliding speed as well as their interactions were assessed using ANOVA. If the graphs exhibit parallelism between the interaction lines, it is presumed that there is no interaction between the parameters. On the other hand, it suggests that the parameters are interacting if the graphs are not parallel to one another. Figs. 8 and 9 clearly show the interaction graphs of the parameters considered on wear loss and COF values. The impact of interaction for all three variable parameters particulate size, sliding speed, and sliding distance is illustrated graphically for improved visualization. Fig. 8 shows the interaction charts between the factors of the wear process. The wear loss shows better interaction plots because of a discernible effect of parameter interaction. Particulate size, sliding speed, and sliding distance are the interaction graphs for the components affecting COF in Fig. 9. Each process parameter's significance can be established by looking at the slope of the lines in these plots. There is a substantial interaction between all the components, which causes variations in COF levels. Basic assumptions and the model's applicability were examined through the analysis of residuals generated to assess the model fit quality. Non-normality was found using a normal probability plot; if the model fits the data well, the residuals should be less structured. A graph of the residual vs. order plot was used to observe the time evolution of residuals. The residual vs. fits graph was created by displaying the response on the abscissa and the residuals on the ordinate. The residuals' histogram graph can be used to determine whether the data are skewed. Figs. 10 and 11 display the wear loss and COF value residual graphs, respectively. Residual graphs show that the model is accepted. Errors have been distributed normally, as shown by the straight lines that represent the residuals on the normal probability plots in Figs. 10 and 11. This demonstrates that the residuals are generally dispersed and have a goodness-of-fit. Since there are no outliers in the data, no departures from normalcy are evident, and the points are evenly spaced from the straight line, the equality of variance test has not been violated. The non-linear relationship is typically depicted by a random pattern on the residual vs. fitted values graph. The fact that the residuals are equally distributed on both sides of the zero line further supports the notion that the residual density was approximately equal. There is no obvious pattern in the residuals on either side of the zero line in the residual vs. order graph, which shows the beneficial effects of collecting data order. According to the current study's histogram with standardized residual, there are no outliers and the skewness is lower. The findings clearly suggest that the results obtained are accurate and precise, as residuals were found from the minimum to maximum range [21].

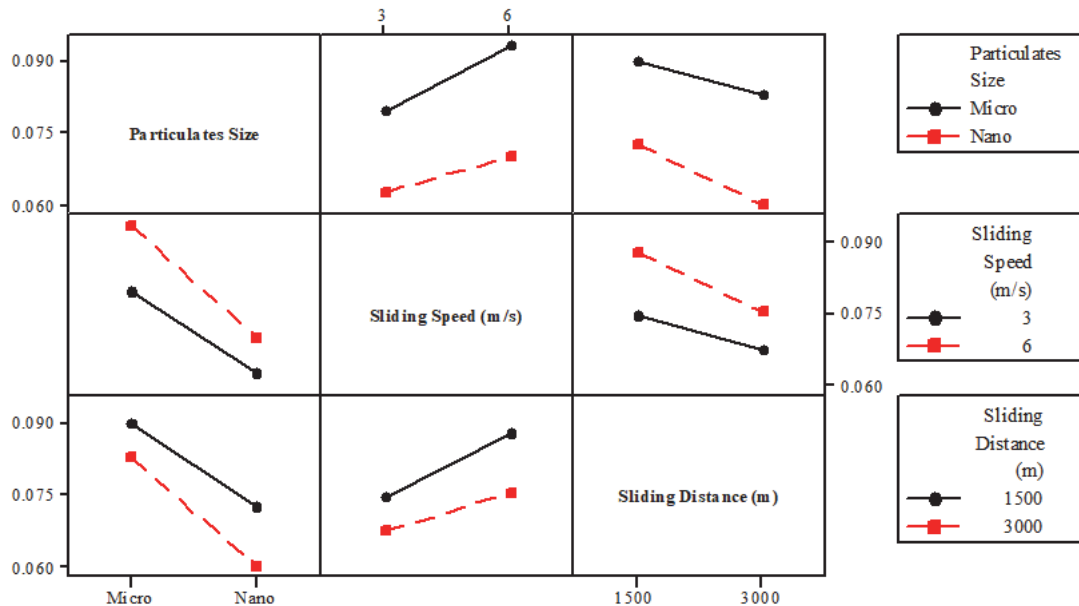


Figure 8: Interactions plot of Wear loss.

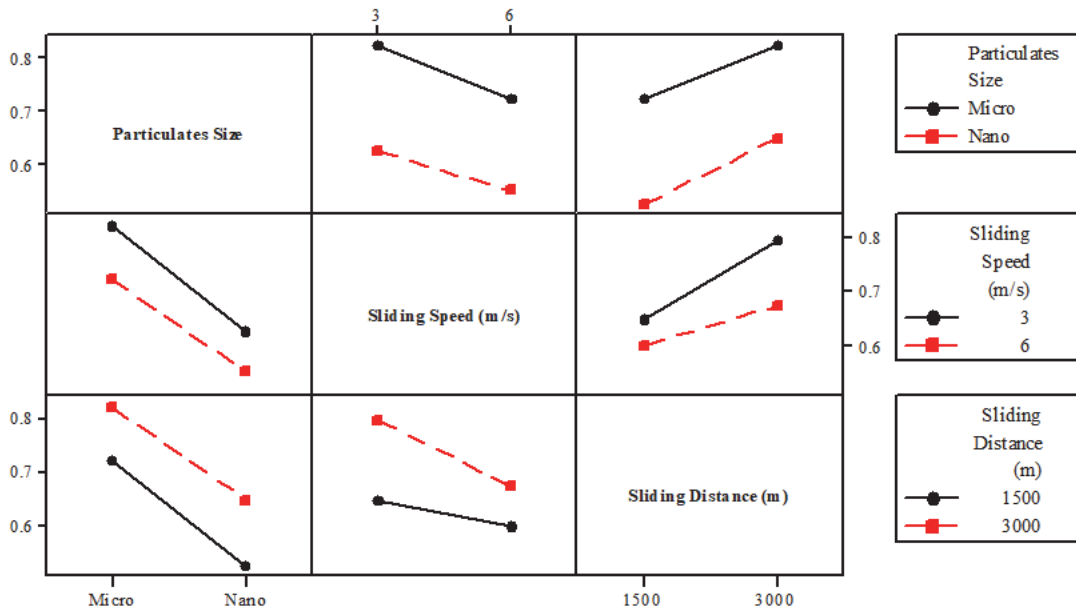


Figure 9: Interactions plot of COF.

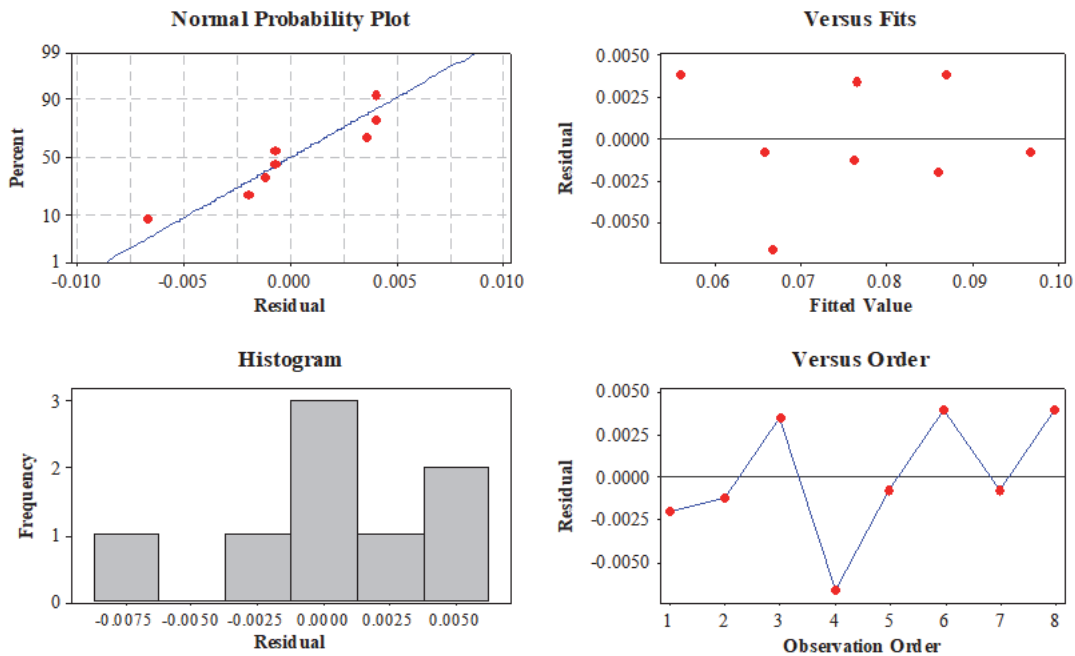


Figure 10: Residual plots of Wear loss (gms).

Confirmation Experiments

A confirmation test concluded the experiment design procedure. Confirmation experiments were conducted for the optimal parametric parameters suggested by the Taguchi method and genetic algorithm. The Main Effects Plot for Means was used to determine the ideal parameter choices. As can be seen, this was within acceptable bounds. Investigating the impact of process parameters on overall performance metrics while treating each response as a single system response indicator has been attempted. The first set of process parameters was chosen to be the combination for which the quality characteristics produced the highest value. The method is unique and has been found to be most closely aligned with the anticipated ideal processing circumstances for individual responses, as well as fitting well with the actual experimentation. This experimental data collection serves as a reference database for technological advancements in industrial applications, as does the chosen method for determining the best processing conditions. The ideal-level values and confirmation test response are shown in Tab. 7. The wear test results showed a maximum of 3.33 percent error and 9.09 percent error in



the COF of the produced composites, according to the confirmation experiments. This within the permitted range (acceptable limit), as can be seen.

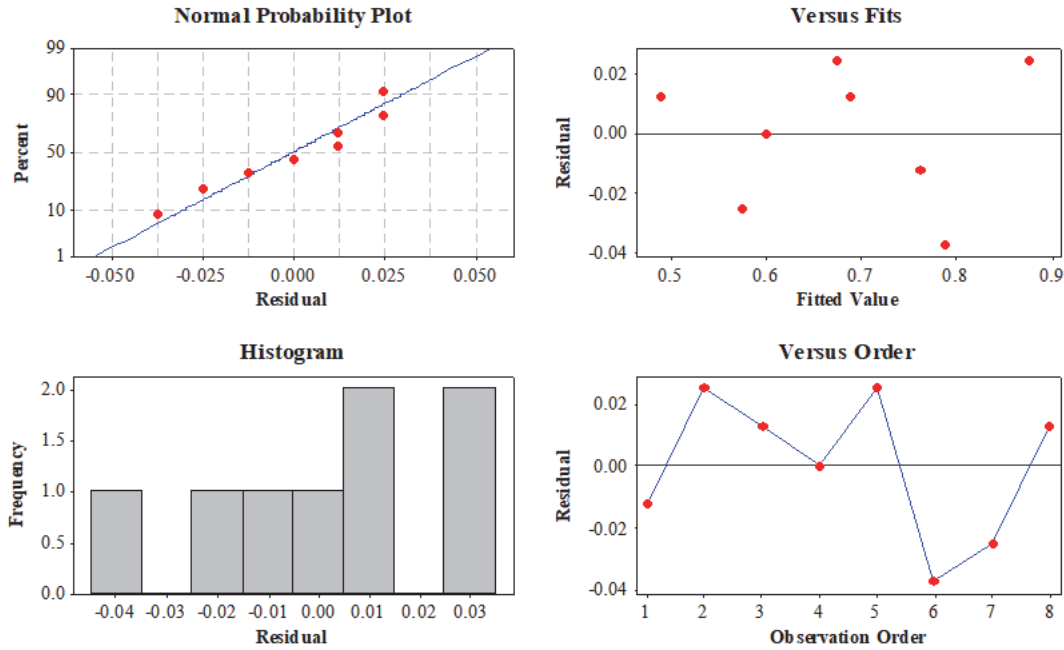


Figure 11: Residual plots of COF (μ).

Exp. Sources	Particulates Size	Process Parameters		OA Exp. Outcomes	Confirmatory Exp. Outcomes	Error (%)
		Sliding Speed (m/s)	Sliding Distance (m)			
Wear Loss (g)	Nano	3	3000	0.060	0.062	3.33
COF (μ)	Nano	6	1500	0.50	0.55	9.09

Table 7: Ideal-level values and response of confirmation tests.

Surface Roughness (R_a)

A polishing machine with different emery sheets is used to polish the micro and nano reinforced MMCs, and velvet cloth is used to finish the process. The SURFTEST SJ-210 (Mitutoyo Make) was used to measure the surface roughness. When measuring roughness, R_a values are taken into account. Fig. 12 displays the surface roughness results of polished samples of the created MMCs. The distribution, size, and hardness of the reinforced particles determine the composite materials' surface roughness. When compared to micro-sized particles, the nano-sized particles in the matrix tend to reduce the roughness. The smoother surface is the result of the nanoparticles filling up the spaces and imperfections between the matrix. It can be seen from Fig. 12 that the surface roughness is larger for micro-particle reinforcements. As the percentage of micro-sized B_4C reinforcements grows from 1 to 2.5 weight percent, the surface roughness also increases. On the other hand, the surface roughness of the nanoscale B_4C reinforced MMCs is consistent and smoother. Because nanoparticles are tougher and smaller, they can withstand deformation during polishing, resulting in a smoother surface roughness and a lower R_a value.

The pin-on-disc machine was used to test the wear of the polished samples. The results of wear tests on developed MMCs are displayed in Fig. 12. The surface experiences frictional contact, which results in adhesion, micro ploughing, material loss, and an abrasion-type surface roughness effect. Larger particles cause uneven dispersion, which weakens the matrix's interfacial bonding and produces hard patches. As abrasive protrusions, these hard patches increase the likelihood of material loss and raise surface roughness over time. During post-wear in micro composites, the particles that are being dragged out are forming pits and tiny craters that greatly raise the R_a values. However, in nano composites decreased R_a values were noted during post-wear. In order to minimize material removal and micro ploughing, the nano reinforcements provide finer microstructures and a stronger link with the matrix. The consistent load-bearing components help to keep

wear tracks in nano composites smoother and prevent severe wear. Because of the substantial wear debris and increased surface damages, it can be assumed that micro reinforced MMCs exhibit a significant increase in Ra value. However, even after wear, nano-reinforced MMCs frequently maintain smoother surfaces, particularly at reduced sliding distances and speeds [22].

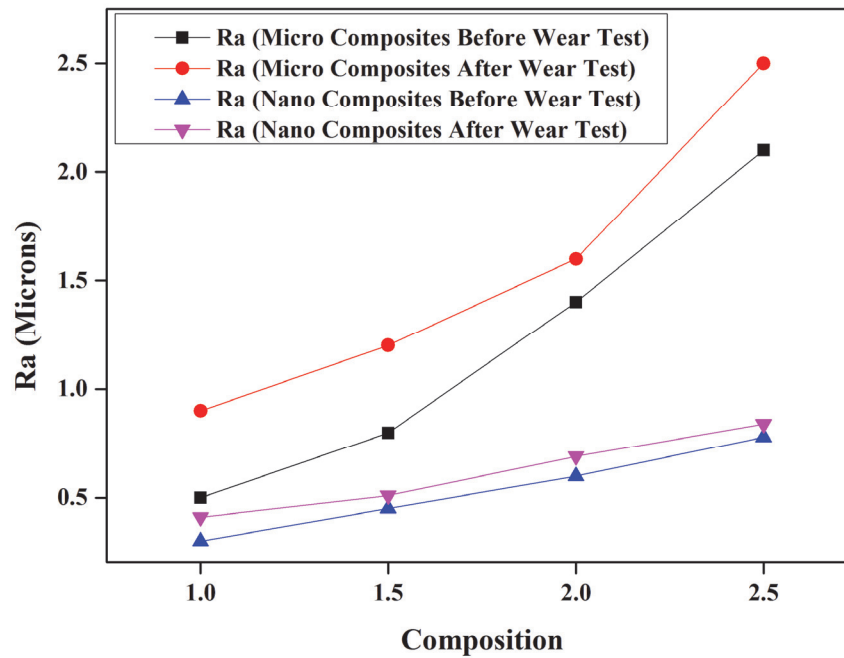


Figure 12: Surface roughness of the developed samples before and after the wear test.

Wornout surface

The composites' wear surface as a function of reinforcing particle size is shown in Fig. 13. From the Fig. 13, it clearly shows the wear mechanism of micro and nano composites. It indicates the nano sized particles reinforced MMCs shows the smoother surface with minimum surface damages when compared to the micro composites. It is due to the uniform dispersion of nano particles improves the grain structure, stiffness and strength of the developed MMCs. The composites' wear tracks reveal the existence of common wear characteristics such delamination, ploughing grooves, and wear scars. Due to high strain levels created during the wear test, the composites containing micro sized B_4C particles exhibit shallow ploughing grooves as well as some delamination cracks (Fig. 13a). These cracks emerge at the surface of the sample in contact with the counter disc. There is a smooth wear surface with minor delamination close to the wear track as a result of the reinforcement's further reduction in particle size (nano particles) (Fig. 13b). Lastly, a smooth wear surface with a finer wear scar is displayed by the composite that contains nanoscale reinforcing particles [5]. Fig. 13 displays the surface integrity of worn-out samples of the generated MMCs. The severe wear of MMCs is visible in the SEM micrograph. It develops because of the increased contact stresses and high temperature, which have a major impact on the surface. During wear, mechanical and thermal stress will result in improved bonding and surface integrity. It comprises surface roughness continuity and preservation of reinforcing particles. It is resistant to surface delamination and material pullouts. Micro-sized particle-reinforced MMCs exhibit significant particle dislocation at high speeds. It results from a high concentration of stress at their interfaces and a weaker interfacial bond. The matrix cracks or even the particles break as a result of the concentrated stress around the micro sized particles. It is possible to draw the conclusion that poor integration at high wear rates results in irregular wear tracks, increased material loss, and the formation of high surface roughness on micro-sized particulate reinforced composites. Similarly, nano-sized reinforcement's exhibit finely dispersed particles, which improves stress distribution and lowers localized deformations. By aiding in grain refinement, the nanoparticles improve the nano composites' wear resistance and matrix hardness. The SEM images (Fig. 13) demonstrate the stable tribo oxides at high temperatures, which strengthen interfacial connections, prevent particle pullouts in the nano composites, and shield the surface from additional damage. The development of a protective tribo-layer that preserves the integrity of the surface with fewer particle separations and smoother wear tracks. In nano composites, it results in reduced Ra values, improved wear resistance, and reduced material losses [23].

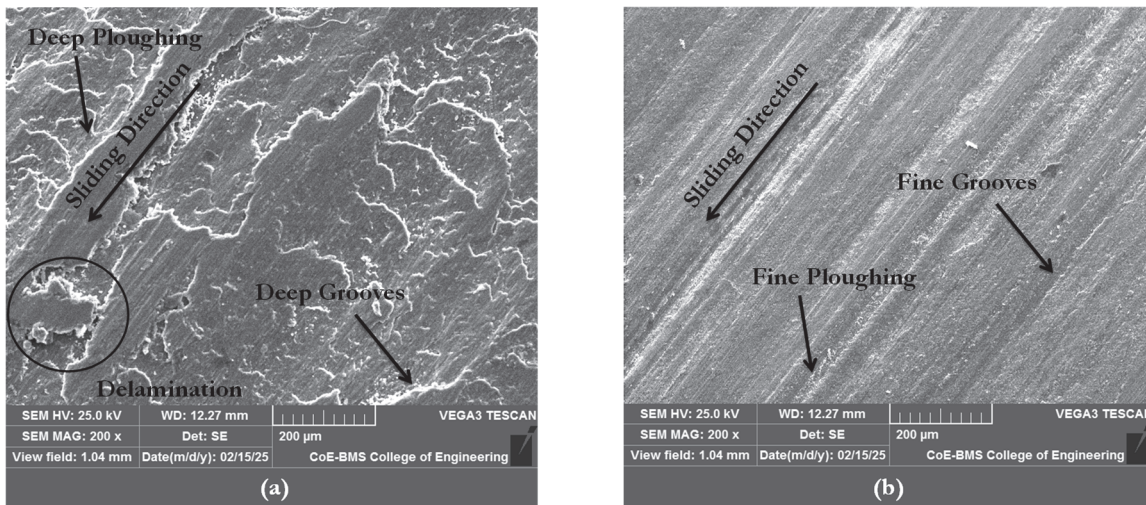


Figure 13: SEM micrograph of wear specimens of (a) micro and (b) nano composites.

The mechanical and tribological performance of nano and micro-reinforced MMCs is significantly influenced by surface integration and high surface energy. Micro composites' surface integrity demonstrates a robust interface, enables efficient stress transfer from the soft metal matrix to the tougher reinforcement particles, and enhances their mechanical strength and resistance to wear in nano composites; higher surface energy encourages improved wetting and bonding with the matrix. However, the reinforcement in nano composites works as a barrier to crack formation, increasing the fracture toughness and preventing cracks propagation. In other words, stable performance at high temperatures is the result of interfacial bonding between the matrix and particles. Micro composites, on the other hand, exhibit the undesired intermetallic face development between the particles and matrix. Under higher speed and distance circumstances, it causes severe damage and particle pullouts. On the other hand, particle agglomerations lower the intermetallic faces, produce weak patches and clusters, and increase surface energy [6]. It can be concluded that, micro and nano particles significantly influence the wear surface. The variations of particles size (micro and nano) significantly influence the wear surface. Micro particles improve the abrasion resistance of MMCs by providing a hard wear resistance surface. Also, a micro particle acts as an abrasive and causing wear on the counter face through scratching and gouging. However, nano particles lead to a smoother wear surface and fine wear scars. It is due to the nano particles facilitate better load transfer between the particles and matrix. Hence, nano particles reinforced MMCs show a smoother surface wear and form a tribo film on the wear surface. Also, nano particles activate anti-wear mechanisms by forming a protective layer (tribo film) on the wear surface. Hence it reduces the wear with minimum surface damage and reducing a stress concentration.

CONCLUSIONS

Based on the results, the experimental examinations of the effects of B_4C -particle size on mechanical and tribology properties are concluded here:

- The microstructural study demonstrates that the increase in B_4C particle content has resulted in a decrease in the average dendritic length. Additionally, it is clear that Micro B_4C refines dendrites more effectively than Nano B_4C .
- A stronger composite with less porosity can result from the more efficient filling of the gaps by smaller particles, or nanoparticles.
- The hardness and tensile strength of nanoscale B_4C particle-reinforced composites were higher than those of micro-scale composites. It has been noted that nano composites are stronger than micro composites. The strength of the developed nano composites increased by 12.90% in tensile strength and 16.06% in hardness.
- Because larger particles are more likely to crack, the broken surface indicates that the composites reinforced with larger particles exhibit many cracks. With dimples implanted on the reinforcement, the composite reinforced with smaller particles exhibits nearly a ductile fracture.



- The particle size is the most highly significant characteristic out of all the others, according to the ANOVA analysis for wear behavior. The wear test results showed a maximum of 3.33 % error and 9.09 % error in the COF of the produced composites, according to the confirmation experiments. This falls within the permitted range (acceptable limit) as it can be seen.
- The composite with nanoscale reinforcing particles exhibits a smooth wear surface with a finer wear scar when viewed from the wornout surface.

REFERENCES

- [1] Ravikumar, M., Rudra, N., Vinod, B.R., Chethana, K.Y. and Rammohan, Y.S. (2023). Study on nanosized Al₂O₃ and Al₂O₃-SiC on mechanical, wear and fracture surface of Al7075 composites for soil anchoring applications, *Materials Physics and Mechanics*, 51, pp. 1-18. DOI: https://doi.org/10.18149/MPM.51x2023_x.
- [2] Gangadharappa, M., Geetha, H.R, Manjunath, N.K, Umesh, G.L. and Shivakumar, M.M. (2024). Study on n-TiB₂ particulates reinforced Al7075 nano composite for soil nail applications: mechanical, wear, and fracture characterizations, *Materials Physics and Mechanics*, 52 (6), pp. 101-113. DOI: https://doi.org/10.18149/MPM.5262024_9.
- [3] Prakash, T.B., Gangadharappa, M., Somashekar, S. and Ravikumar, M. (2024). Impact of nanoparticles (B₄C-Al₂O₃) on mechanical, wear, fracture behavior and machining properties of formwork grade Al7075 Composites, *Frattura ed Integrità Strutturale*, 69, pp. 210-226.
- [4] Ravikumar, M., Reddappa, H.N., Suresh, R. and Sreenivasareddy, M. (2021). Experimental studies of different quenching media on mechanical and wear behavior of Al7075/SiC/Al₂O₃ hybrid composites, *Frattura ed Integrità Strutturale*, 55, pp. 20-31.
- [5] Chaubey, A. K., Gokuldoss, P. K., Wang, Z., Scudino, S., Mukhopadhyay, N. K., and Eckert, J. (2016), Effect of Particle Size on Microstructure and Mechanical Properties of Al-Based Composite Reinforced with 10 Vol. % Mechanically Alloyed Mg-7.4%Al Particles, *Technologies*, 4 (37), pp. 1-8. DOI: <https://doi.org/10.3390/technologies4040037>.
- [6] Ravikumar, M., Reddappa, H.N., Suresh, R., Babu, E.R. and Nagaraja, C.R. (2021). Study on Micro - Nano Sized Al₂O₃ Particles on Mechanical, Wear and Fracture Behavior of Al7075 Metal Matrix Composites, *Frattura ed Integrità Strutturale*, 58, 166-178.
- [7] Ravikumar, M., Reddappa, H.N., Suresh, R., Ram Mohan, Y. S., Nagaraja, C. R., and Babu, E. R. (2021). Investigations on tensile fractography and wear characteristics of Al7075-Al₂O₃-SiC hybrid metal matrix composites routed through liquid metallurgical techniques, *Frattura ed Integrità Strutturale*, 56, pp. 160-170.
- [8] Sajjadi, S. A., Ezatpour, H., and Beygi, H. (2011). Microstructure and mechanical properties of Al-Al₂O₃ micro and nano composites fabricated by stir casting, *Mater. Sci. Engg.*, A528, pp. 8765-8771.
- [9] Karbalaei Akbari, M., Baharvandi, H. B., Shirvanimoghaddamkbari, K. (2015). Tensile and fracture behavior of nano/micro TiB₂ particle reinforced casting A356 aluminum alloy composites. *Mater. Design*, 66, pp. 150-161.
- [10] Muley, A. V., Aravindan, S. and Singh, I. P. (2015). Nano and hybrid aluminum based metal matrix composites: an overview, *Manufacturing Rev.*, 2 (15), pp. 1-13. DOI: <https://doi.org/10.1051/mfreview/2015018>.
- [11] Dobrzanski, L. A., Włodarczyk-Fligier, A. and Adamiak, M. (2006). The structure and properties of PM composite materials based on EN AW-2124 aluminum alloy reinforced with the BN or Al₂O₃ ceramic particles, *J. Mater. Process. Technol.*, 175, pp. 186-191.
- [12] Ravinder, K., Kanishka, J., Shubham, S., Vineet, K., Changhe, L., Eldin, E. M. T., Rajkumar, S. and Krolczyk, G. (2022). Effect of particle size and weight fraction of SiC on the mechanical, tribological, morphological, and structural properties of Al-5.6Zn-2.2Mg-1.3Cu composites using RSM: fabrication, characterization, and modelling, *Heliyon*, 8, pp. 1-10.
- [13] Reihani, S. (2006). Processing of squeeze cast Al6061-30 Vol. % SiC composites and their characterization, *Mater., Des.*, 27, pp. 216-222.
- [14] Sharma, S. (2021). Investigation on mechanical, tribological and microstructural properties of Al-Mg-Si-T6/SiC/muscovite-hybrid metal-matrix composites for high strength applications, *J. Mater. Res. Technol.*, 12, 1564-1581.
- [15] Chak, V. and Chattopadhyay, H. (2021). Synthesis of graphene aluminium matrix nanocomposites: mechanical and tribological properties, *Mater. Sci. Technol.*, 37 (5), pp. 467-477.



- [16] Kumai, S., King, J. E. and Knott, J. F. (1990). Short and long fatigue crack growth in a SiC reinforced aluminium alloy, *Fatigue Fract. Eng. Mater. Struct.*, 13, pp. 511-524.
- [17] Odabas, D. (2018), Effects of Load and Speed on Wear Rate of Abrasive Wear for 2014 Al Alloy, *IOP Conference Series: Materials Science and Engineering*, 295, DOI: <https://doi.org/10.1088/1757-899X/295/1/012008>.
- [18] Idusuyi, N. and Olayinka, J. I. (2019). Dry sliding wear characteristics of aluminium metal matrix composites: a brief overview, *Journal of Materials Research Technology*, 8 (3), pp. 3338-3346.
- [19] Samal, P., Mandava, R. K. and Vundavilli, P. R. (2020). Dry sliding wear behavior of Al 6082 metal matrix composites reinforced with red mud particles, *SN Applied Science*, 2 (313), pp. 1-11.
DOI: <https://doi.org/10.1007/s42452-020-2136-2>.
- [20] Subramanian, K., Murugesan, S., Mohan, D. G. and Tomkow, J. (2021). Study on Dry Sliding Wear and Friction Behaviour of Al7068/Si₃N₄/BN Hybrid Composites, *Materials*, 14, pp. 1-14.
DOI: <https://doi.org/10.3390/ma14216560>.
- [21] Satyanarayana, T., Rao, P.S. and Gopi Krishna, M. (2019). Influence of wear parameters on friction performance of A356 aluminum graphite/granite particles reinforced metal matrix hybrid composites. *Heliyon*, 5, pp. 1-8.
- [22] Igwe, N. and Ozoegwu, C. (2024). Analyzing empirically and optimizing surface roughness and tool wear during turning aluminum matrix/rice husk ash (RHA) composite. *The International Journal of Advanced Manufacturing Technology*, 134, pp. 1563-1580.
- [23] Macek, W., Branco, R., de Jesus, J., Costa, J. D., Zhu, S.P., Masoudi Nejad, R. and Gryguć, A. (2024). Strain energy density and entire fracture surface parameters relationship for LCF life prediction of additively manufactured 18Ni300 steel. *International Journal of Damage Mechanics*, 33. DOI: <https://doi.org/10.1177/10567895241245879>.