



Impact of nanoparticles ($B_4C-Al_2O_3$) on mechanical, wear, fracture behavior and machining properties of formwork grade Al7075 composites

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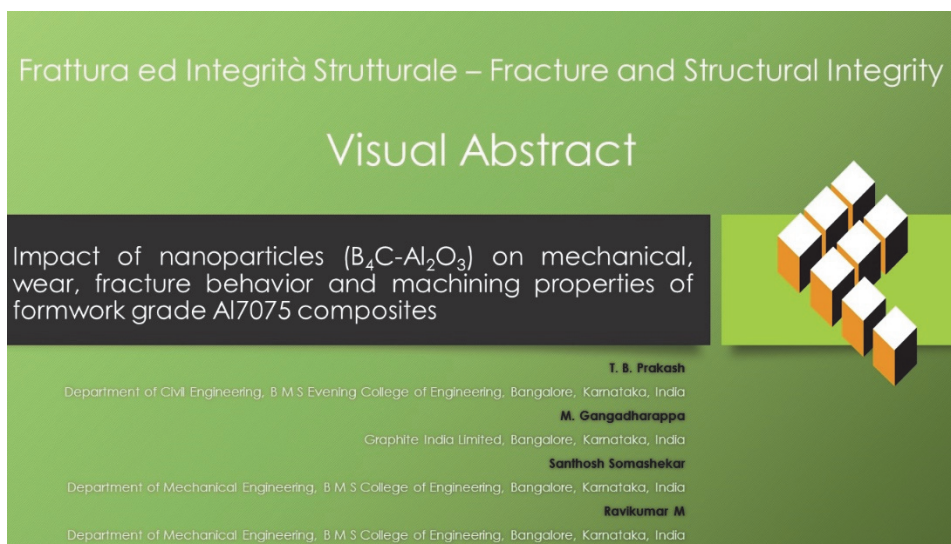
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Citation: Prakash, T. B., Gangadharappa, M., Somashekar, S., Ravikumar, M., Impact of nanoparticles ($B_4C-Al_2O_3$) on mechanical, wear, fracture behavior and machining properties of formwork grade Al7075 Composites, 69 (2024) 210-226.

Received: 12.04.2024

Accepted: 08.05.2024

Published: 27.05.2024

Issue: 07.2024

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KEYWORDS. Hybrid nano composite, Stircasting, Mechanical, Wear, Fracture surface, Machining force, Ra, Taguchi techniques.

INTRODUCTION

Many applications opt for aluminum (Al) composites over traditional materials due to a growing number of regulatory mandates. Aluminum, magnesium and titanium alloys form the base materials in metal composites, while Metal Matrix Composites (MMCs) employ fibers or particles such as Alumina (Al_2O_3), Graphite (Gr), Boron carbide (B_4C) and Silicon carbide (SiC) as reinforcing elements [1]. These enhanced composites, termed Advanced



Metal Matrix Composites (AMMCs), are often recognized for their cost-effectiveness. The composites provide notable gain in density compared to the base alloy while also enhancing strength, stiffness, and fatigue resistance. The aerospace and automotive sectors extensively utilize Al composites due to their outstanding strength and stiffness properties. However, due to the abrasive nature of the reinforcing particles, machining these aluminum composites can pose challenges. The inclusion of these reinforcing particles profoundly alters the mechanical properties and machinability of composite materials. When referring to “operational characteristics” in machining these materials, it encompasses subjective characteristics of a cutting tool, including factors such as material removal rate (MRR), tool durability, and surface quality. Although MMCs are manufactured to precise standards, additional machining may be necessary to achieve desired specifications. Machining attributes are significantly impacted by variables such as the nature of reinforcement (particles or whiskers), the proportion of reinforcements by weight, the even dispersion of reinforcement within the primary matrix, and the selection of reinforcing materials. These factors play a crucial role in determining the machinability of the composite materials. Owing to the hardness and brittle nature of the reinforced particles, the machining process for MMCs differs significantly from traditional metal machining techniques. Machining composite materials elicits a diverse response as the cutting tool interacts with both the base matrix and the reinforcing components. The principal challenge encountered in machining MMCs is the accelerated rate of tool wear, which can lead to inefficiencies and increased production costs. Unique considerations regarding tool geometry and wear resistance must be meticulously addressed when machining MMCs to ensure optimal performance and productivity in the manufacturing process [2]. The integration of reinforcement into composites to augment their mechanical properties mainly affects their machinability. Despite their inherent anisotropic characteristics, non-uniformity, and inclusion of abrasive particles, composites pose considerable challenges during processing. The machinability of MMCs is subjected to diverse factors, including the matrix type, type of reinforcements utilized, and specific machining conditions employed. Furthermore, the selection of cutting tools, as well as the composition and properties of the composite materials themselves, are pivotal in determining the material's machinability. Composites have limited application in industries due the intrinsic complexities linked with their machining. The existence of strong reinforcing materials like Alumina (Al_2O_3) and Boron carbide (B_4C) compounds requires excessive machining. While MMCs often achieve near-net shape, additional machining is frequently necessary to attain accurate measurements and surface texture. Evaluating variables such as work-piece material, machining, tools cutting fluids and machining parameters is crucial for assessing machining effectiveness and this is where machinability analysis plays a significant role. When assessing the quality of cutting tools, machinability typically encompasses factors such as Metal removal rate, tool longevity, surface texture, resultant force, and tool temperature. Machinability is a pivotal aspect of manufacturing, as it dictates the efficiency of industrial production. Understanding the machining properties of specific composites slated for processing is essential for process planning. With the increasing integration of automation in machining, achieving optimal results with modern technologies necessitates reliable machinability data. Even with traditional manufacturing methods, efforts to establish consistent statistical data for production purposes are imperative to accurately define criteria for various machining concepts and processes. The presence of robust ceramic reinforcements significantly impacts the ease of machining of MMCs. These resilient ceramic particles embedded within composite materials lead to heightened tool wear during machining operations. The dimensions and proportion of these reinforcements are crucial factors in the processing of MMCs. Moreover, the surface quality of machined components is significantly influenced by the dimensions and weight distribution of these particles. The presence of hard ceramic nano particles in the machining process might lead to fewer discernible gaps on the machined surfaces, potentially elucidating this phenomenon. Thus, this condition plays an imperative role in achieving the MMCs' higher Ra value. Furthermore, specimens with lower reinforcement content were found to have lower Ra values in comparison to composite samples with higher reinforcement content. This emphasizes how much the reinforcement ratio affects the quality of the surface finish in MMCs. Kannan [4] reports that their study found a relationship between higher weight percentage of particles and observable tool wear, which in turn influenced the Ra value of the composite samples. The main factor contributing to high tool wear was found to be the existence of hard ceramic particles. Surface roughness increased during wet cutting procedures due to the gradual separation and formation of micro gaps among the relatively unbound particles. Morsiya and Pandya [5] stated that, the stir casting is used to create hard ceramic particles reinforced MMCs. The reinforcement ratio by weight percentage was found to be critical factors affecting the properties of aluminium alloy. Krishnamurthy [6] used regression analysis models and the Design of Experiments (DOE) methodology to investigate the machinability properties of AMMCs reinforced with SiC. Their research demonstrated the importance of the weight percentage of reinforcement by showing that higher SiC weight percentages in AMMCs produced higher resultant forces as a result of higher composite hardness. According to a study by Shrinivasa [7], MMCs based on aluminum have gained popularity as engineering materials recently. However, in some MMCs made of aluminum, using a single reinforcement may occasionally cause the material's physical qualities to deteriorate. On the other hand, the concept of using two distinct types of reinforcements in the aluminum matrix is being investigated as a way to address the issue of

single reinforced composites. The novelty of present research work was to the study the material properties of formwork grade Al7075 reinforced by nano sized B₄C-Al₂O₃. In this present work, formwork grade alloy were developed by stircasting method. Material properties were studied and analyzed using Taguchi technique. In conclusion, the experimental results were correlated with the regression-analysis.

EXPERIMENTATIONS

Materials and method

The improvement of mechanical characteristics in MMCs depends significantly on a robust bond between the matrix and the reinforcements. Among the various methods, stir casting stands out as most as simplest and most cost-effective techniques for MMC fabrication, which has been effectively used by many researchers. Because of its cost-effectiveness, stir casting was chosen in this research for the manufacture of MMCs with particles. In this specific study, MMCs consisting of Al-7075 reinforced with nanoparticles such as Al₂O₃-B₄Cp were produced using stir casting techniques. Nanoparticles of B₄C and Al₂O₃, varying in size is from 30 to 50 nm, were integrated into the matrix as reinforcements. To ensure optimal casting conditions, safety measures were implemented by maintaining a stirring speed of 100 rpm, a stirring time of one minute, and a casting temperature of 750°C during sample production. In this process, heated hard ceramic nano-reinforcements were mixed with the molten melt, and degassing agents were added to reduce porosity. The resulting mixture was then poured into a cast iron mold box. After solidification, the samples were extracted from the mold box for further processing. After machining using CNC lathe according to ASTM specifications, the test samples as shown in Fig. 1, were subjected to a hardening process at 530°C for two hours, followed by rapid cooling using ice cubes. The samples were then subjected to age hardening for five hours at varying temperatures (100, 120, and 140°C) until reaching room temperature (27°C). For metallographic studies, diamond grit sheets of different sizes were employed to polish the composite specimens, ensuring a fine Ra. After polishing the samples, they were etched using Keller's reagent, a common etching agent, and left to air dry. Utilizing an optical microscope (Nikon E-200), the homogeneous dispersion of nanoparticles within the matrix was observed. The developed hybrid nano MMCs were subjected to microhardness testing in compliance with E92-ASTM guidelines. Specimens with dimensions of 25 mm in diameter and 20 mm in thickness were used to evaluate the hardness. A constant load of 5 kg was applied to a diamond indenter for thirty seconds. Tensile testing were performed using a 450 KN weight on a Universal Testing Machine (UTM) according to ASTM E8 requirements (gauge length: 50 mm and gauge diameter: 10 mm). A steel disc of grade EN32 was used in the wear test, which was carried out using the PIN-ON-DISC method under a continuous load of 30 N and a sliding speed of 2 m/s. CNC machining was used to create test samples that were 35 mm long and 8 mm wide. Weight loss was used to calculate wear loss for developed hybrid nano composites. To further investigate the machinability parameters of nano-Al₂O₃/B₄Cp reinforced composites, a CNC milling machine was utilized. The study used specific parameters, including a feed rate of 0.1 mm/min, a depth of cut of 0.2 mm/min, and a spindle speed of 1000 rpm. The CNC milling machine utilized in this study is the FANUC Series (OJ MADE MD), boasting the following attributes: a maximum workpiece size of 360 x 360 mm, a maximum bed size of 800 x 400 mm, and a top speed of 600 rpm. The machine operates along the X, Y, and Z cutting tool orientations. To measure and analyze the Ra value of the machined surface, a device with specifications including a tip radius of 5 μm (equivalent to 200 μinch), a Z-axis stroke measurement range of 350 μm, and a speed measurement range of 0.25 mm/sec to 0.5 mm/sec was used.

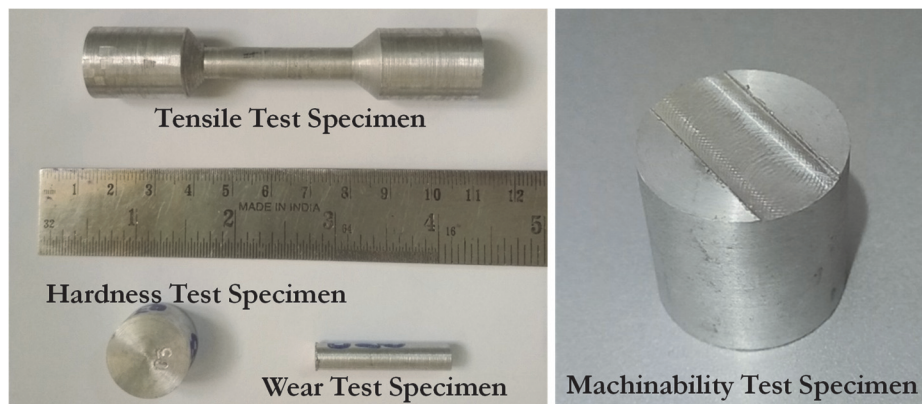


Figure 1: Specimens prepared by cast sample.

Design of experiments

The effect of reinforcements on Ra and cutting force of composites was evaluated using the DOE (Design of Experiments) approach. To optimize experimental trials and reduce the required number of tests the Taguchi technique with an L27 orthogonal array was employed. Tab. 1 shows the levels of each process variable. Specifically, the study focused on analyzing the volume fraction, heat treatment temperature, and process parameters of nano-sized Al₂O₃/B₄C particles. Initial pilot tests were carried out to determine each parameter's values. The aging temperature range was 100°C to 140°C. At 140°C, the ideal mechanical and physical characteristics were noted, with 4.5 % B₄C and 2 % Al₂O₃. It was observed that the properties of the composite decreased as the reinforcement level increased. Following this, the Taguchi optimization process was carried out, taking into account three levels of nano-sized B₄C reinforcement (1.5%, 3%, and 4.5%), three levels of nano-sized Al₂O₃ reinforcement (1%, 1.5%, and 2%), and three ageing temperature ranges (100°C, 120°C, and 140°C). The goal of this strategy was to determine the best possible combination of parameter to improve the composite performance.

Process parameters	Level A	Level B	Level C
n-B ₄ C (wt. %)	1	1.5	2
n-Al ₂ O ₃ (wt. %)	1.5	3	4.5
Heat-treatment (°C)	100	120	140

Table 1: Levels of process parameters.

OUTCOMES AND INTERPRETATION

Microstructure analysis

The microstructure of the produced composites, exhibiting this uniform dispersion, is illustrated in Figs. 2 (a and b). It is clear that the addition of hard ceramic nano particles is necessary for grain refinement of Al-7075 alloys. Thus, the formation of the produced hybrid composites can be related to the grain refinement process of the Al alloy triggered by the inclusion of nano-sized B₄C-Al₂O₃ particles. Enhancing the mechanical strength of hybrid nano composites requires the dispersion of hard particles in the base matrix. The microscopic analysis reveals that, the grain surrounding hard reinforcements attributes to the finer than the grain surrounding free matrix alloy reinforcements. Hard nanoparticles can thereby accelerate the nucleation of particles between the matrix and the reinforcement phase, causing the Al alloy to recrystallize. It's worth noting that the properties of a material can vary significantly with changes in composition and microstructure, which was a focus of this study, as indicated by references [8 and 9].

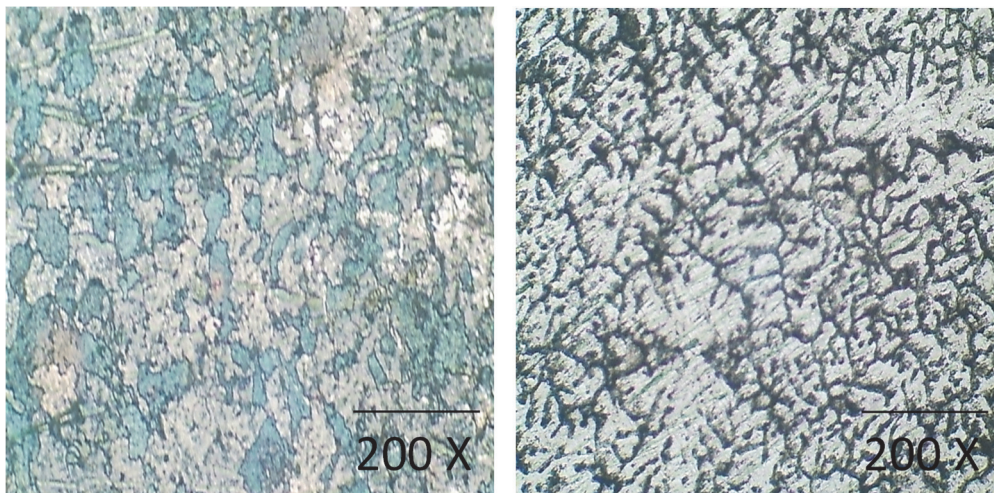


Figure 2: Optical Micrograph of (a) Al 7075 (b) Al 7075 reinforced with nano-Al₂O₃+ B₄Cp with uniform dispersal.

Hardness

Micro hardness tests were conducted on samples with compositions of Al7075 / nano sized $B_4C-Al_2O_3$ using a load of 5 kg. The impact of $B_4C-Al_2O_3$ nanoparticles on the hardness of the cast composite is as shown in Fig. 3. Because of the uniform dispersion of nano sized $B_4C-Al_2O_3$ particles in melt during stirring process, the developed nano composites with high weight percentage of $B_4C-Al_2O_3$ content have a higher hardness than the base matrix. Due to the pre-heating of nano-particles, it was observed that, the bonding between the reinforcements and matrix was excellent. Nano particles in the metal matrix composites will enhance the hardness. It improves the resistance to corrosion and oxidation. In addition it improves the grain structure leading to the better performance on the composite material. Dipankar Dey et al. reported similar results [10]. Hard nano particles have a high hardness, and their presence in the composite increased the hardness. A decrease in grain size may also be associated with an increase in hardness. It has been observed that the hardness of the composite increased as the ageing temperature increased up to $140^\circ C$, after which it dropped as the ageing temperature increased to $160^\circ C$. It is most likely caused by brittleness development and a decrease in the bonding strength between the nano particles at higher temperatures [8].

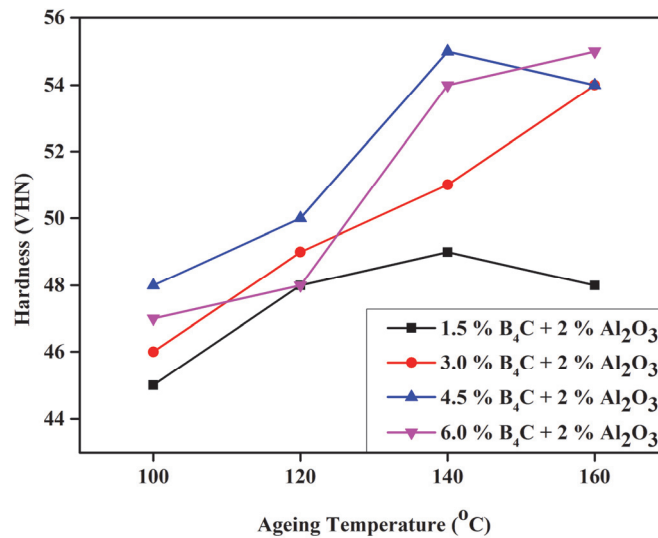


Figure 3: Hardness of developed hybrid nano composites.

Tensile strength

The ASTM E8 guidelines were followed in the tensile testing of the Al7075/n- B_4C/Al_2O_3 composite test samples, and the results were presented on a graph. Fig. 4 displays the tensile strength of a produced nano composite with different n- B_4C/Al_2O_3 weight percentages. It was observed that nano composites had increased strength; this could be attributed to the uniform dispersion of the particles. Nano particles significantly enhance the mechanical properties of MMCs. They will increase the tensile strength of the developed material, making it to more resistant to deformation. Additionally, nano particles will improve fatigue and creep resistance of the nano composites, it leads to the longer lifespan under high stress conditions. As the weight percentage of reinforcement grew, the majority of the load was placed on the reinforced particles, increasing their strength. Similar findings were reported by Dipankar Dey et al. [10], who found that the tensile strength of the created nano composite was much higher compared to that of the monolithic. This is due to the fact that hard, tiny particles aid in well-bonding with the matrix. Second, the strengthening process of the nano composite is affected by changes in the coefficient of thermal expansion. The inclusion of n- B_4C/Al_2O_3 particles to composites resulted in gain in strength but reduction in ductility, as they acted as micro-crack initiators throughout the deformation process. Particles of n- B_4C/Al_2O_3 are often more brittle and strong. During deformation, two types of micro-cracks are caused by the n- B_4C/Al_2O_3 particles. If there is a strong interface unit that exists between the n- B_4C/Al_2O_3 particles and the matrix material, then parameters such as dislocation density, strain, and stress all reach critical values at high concentration. Second, the nanoparticles will break before the matrix material sandwiched between them arises with nucleated microcracks if there is a poor interfacial bond that exists between the n- B_4C/Al_2O_3 particles and a matrix material. Therefore, strong interfaces increase the strength and flexibility of the generated nano composite, while weak interfaces lead to the initiation of microcracks at low external stress. As the n- B_4C/Al_2O_3 percentage rises, the produced nano composites decrease tensile strength and can be linked to a decrease in the slip distance dislocation. The effect of ageing temperature on tensile strength is also depicted in Fig. 4. Tensile strength of the n- B_4C/Al_2O_3 reinforced Al

composite was found to rise with increasing ageing temperature up to 140°C, and then to decrease with further increasing ageing temperature to 160°C. The reduction of the tensile strength between 140°C – 160°C of the aged composites were observed (Fig. 4) during the tensile strength test. It is due to the increasing the ageing temperatures lead to the thermal expansion, mismatches between the matrix and the reinforcements causes reduction in internal stresses, further reduce in the overall tensile strength on the developed nano composites. Also, higher temperature will accelerate the degradation of the matrix material, compromising its ability to effectively transfer loads and distribute the stress [8].

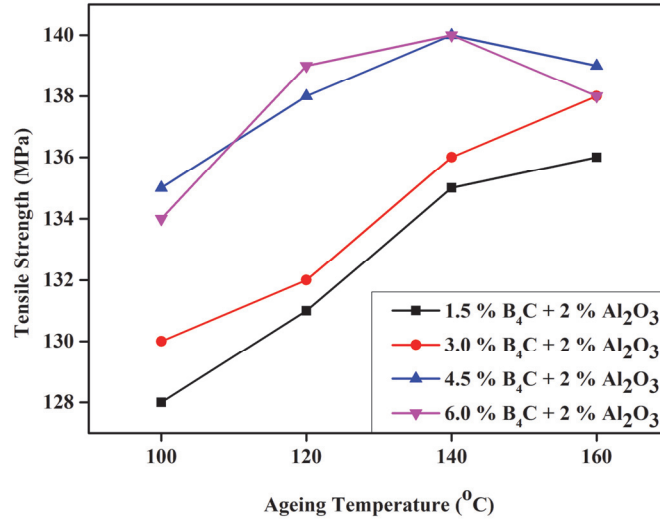
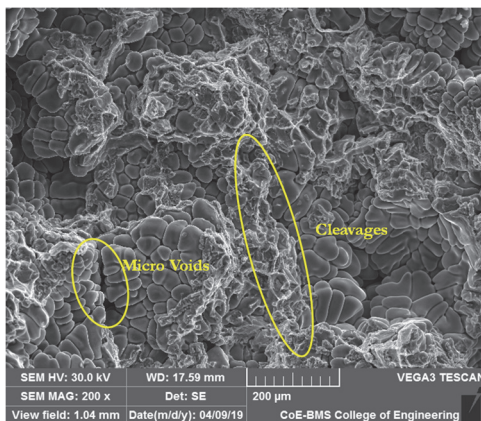
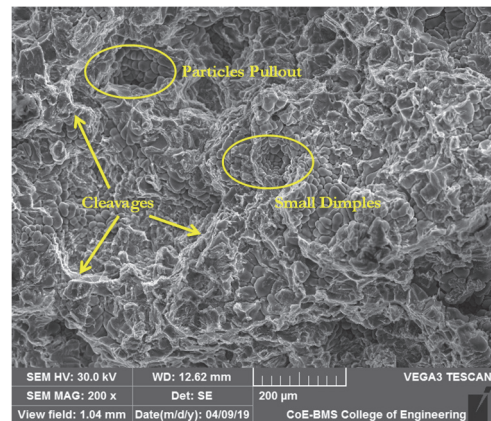


Figure 4: Tensile strength of developed hybrid nano composites.

Fig. 5 shows the cracked surfaces of Al7075 + n-B₄C/Al₂O₃ composites. Decohesion of the reinforcement from the matrix phases and grooves within the matrix phase are visible on the shattered surfaces of an n-B₄C/Al₂O₃ reinforced nano composite (Fig. 5(a-d)). The appearance of the dimples can be explained by the decohesion of reinforcement and the fusion as well as nucleation of cavities caused by the shear deformation caused by the strength and fragmentation of ceramic under the effect of focused stress. Nanosized B₄C/Al₂O₃ particles confirmed the presence of elongation and brittle fracture by comparing the shattered surface of the lower weight percentage of reinforcements to the circumstances of the higher weight percentage of reinforcements composite. The triaxial condition of stress in the proximity of hard particles is initiated by the presence of soft matrix, which leads to the formation of voids. It calls for properly connecting the matrix and reinforcements. The interaction of hard particles at the interface is indicated by the shattered surface of the tensile specimens. By strengthening the matrix's link and reducing ductility, the presence of hard particles of ceramic on the fractured surface and in micro voids further improves the mechanical characteristics. In the current study, the primary reason for the MMCs' reduced ductility was interface debonding. Furthermore, the primary factor causing the quick failure of MMCs is the presence of nano-sized B₄C/Al₂O₃ particle clusters, which likewise have no effect on the tensile strength of MMCs at increasing weight percentages of nano reinforcements [11, 12].



(a)



(b)

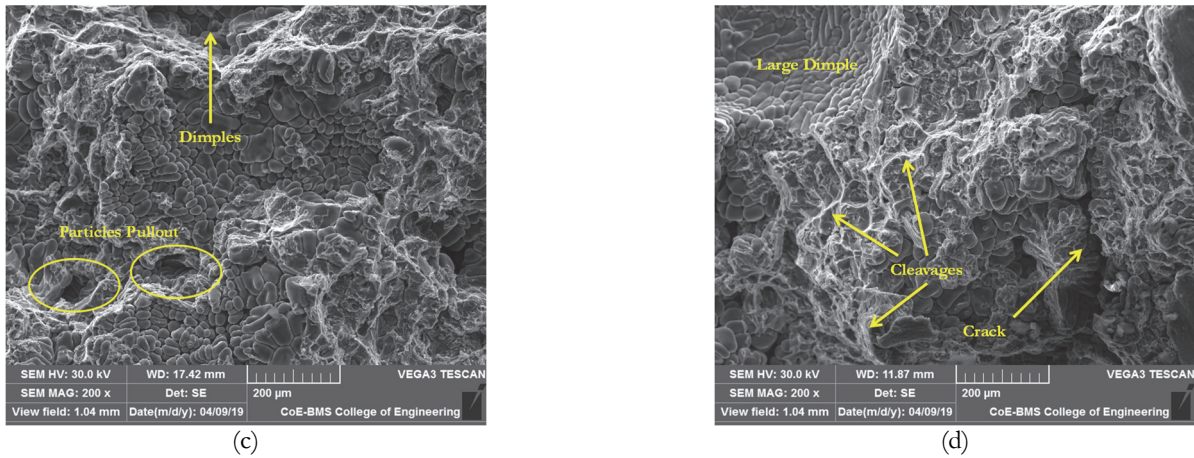


Figure 5: Fracture surface of tensile test specimens (a) Al7075 - 1.5% B₄C+2 Al₂O₃ (b) Al7075 - 3% B₄C+2% Al₂O₃ (c) Al7075 - 4.5% B₄C+2% Al₂O₃ (d) Al7075 - 6% B₄C+2% Al₂O₃.

Wear loss

Using pin-on-disk wear testing apparatus, the wear behavior of Al 7075-SiC-Al₂O₃ composites was investigated under a 3N load and at a sliding speed of 2 m/s against an EN32 steel disk. By using machining, composite specimens measuring 35 mm in length and 8 mm in diameter were created. The worn specimens' starting weight was determined to within 0.0001 grams. The effect of nano B₄C-Al₂O₃ and ageing temperature on wear loss of developed hybrid MMCs are shown in Fig. 6. It has been observed that when the weight percentage of hard ceramic particles increases, the wear resistance of the MMCs also increases [13, 14]. Nano particles in the metal matrix composites will greatly improve the wear resistance. It is due to the dispersing of nano particles within the MMCs, it improves the uniform structures that resistance the abrasion and wear. Normally, a nano particle acts as barriers to prevent the dislocation and reduce the wear rate. Comprehensively the addition of nano particles enhances the wear resistance. In the present research work, the wear is reduced when Al₂O₃ particles are firmly (intensely) bound to the Al matrix, shielding the composite surfaces from the counter face's destructive action. One of the crucial constraints is the interface between the reinforcement particles and the matrix. However, because of the interfacial interactions and low wettability, interfaces may be subtly weak. The wear resistance of MMCs is continuously increased by improved bonding between the matrix and reinforcing particles, which results in a rise in the weight percentage of reinforcements. Regarding Al composites, the hard ceramic nano reinforcements that protrude usually direct the depth of dispersal caused by the hard asperities of the hard steel disc. It is observed that samples that had heat treatment at 160°C showed more wear loss. The mechanical qualities of heat-treated samples revealed lower values at these temperatures, which increases wear loss. The decreased bonding strength between the particles, which raises the wear rate, and is most likely to be a reason for the lower strength in developed samples.

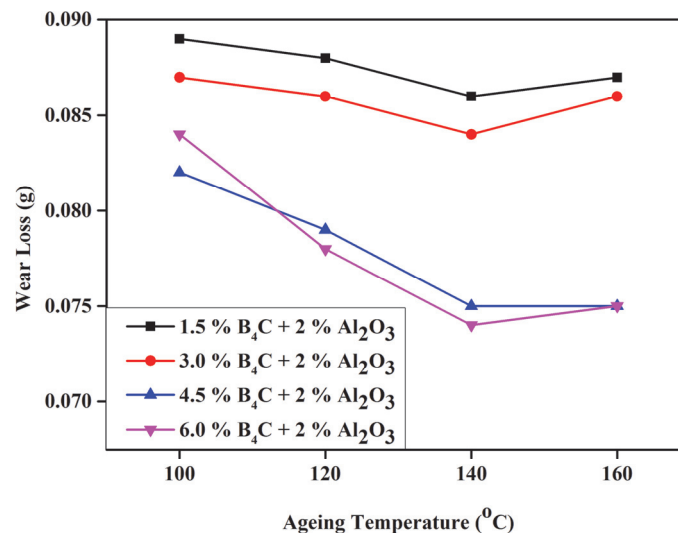


Figure 6: Wear loss of developed hybrid nano composites.

Fig. 7 (a - d) shows SEM images of the worn-out surfaces of developed nanocomposite specimens. Micro-pits, high material flow, and thin grooves were the hallmarks of the worn surfaces. It is observed that, the presence of narrow grooves in the dark layer of the SEM image. Micro pits, or tiny grooves, hide the worn-out surfaces of MMCs and indicate that the wear mechanism is delaminating and plowing. On the worn-out surface of nano MMCs, there is severe deformation and delamination, which indicates that delamination, is a wear characteristic. The strain placed on the nanoparticles of ceramic leads to surface wrapping and these strong ceramic nanoparticles often provided superior wear resistance by acting as a wrapping material on the sliding surfaces. The microstructure reveals that the worn-out surfaces of the nano composites have a significant number of narrow grooves. These constant, parallel grooves are therefore proof of micro plowing. On the worn-out surfaces of nano composites, which exhibit noticeable wear behavior in the nano MMCs, wide plowing is also visible. The creation of narrow grooves with dark layers is seen in the SEM study of the nanocomposites' worn surface. This suggests that wear resistance can be enhanced by raising the weight percentage of nanoparticles. While the constant sliding may operate as an abradant for a brief amount of wear, potentially the nanoparticles will debond from the matrix material and become trapped between the sliding surfaces.

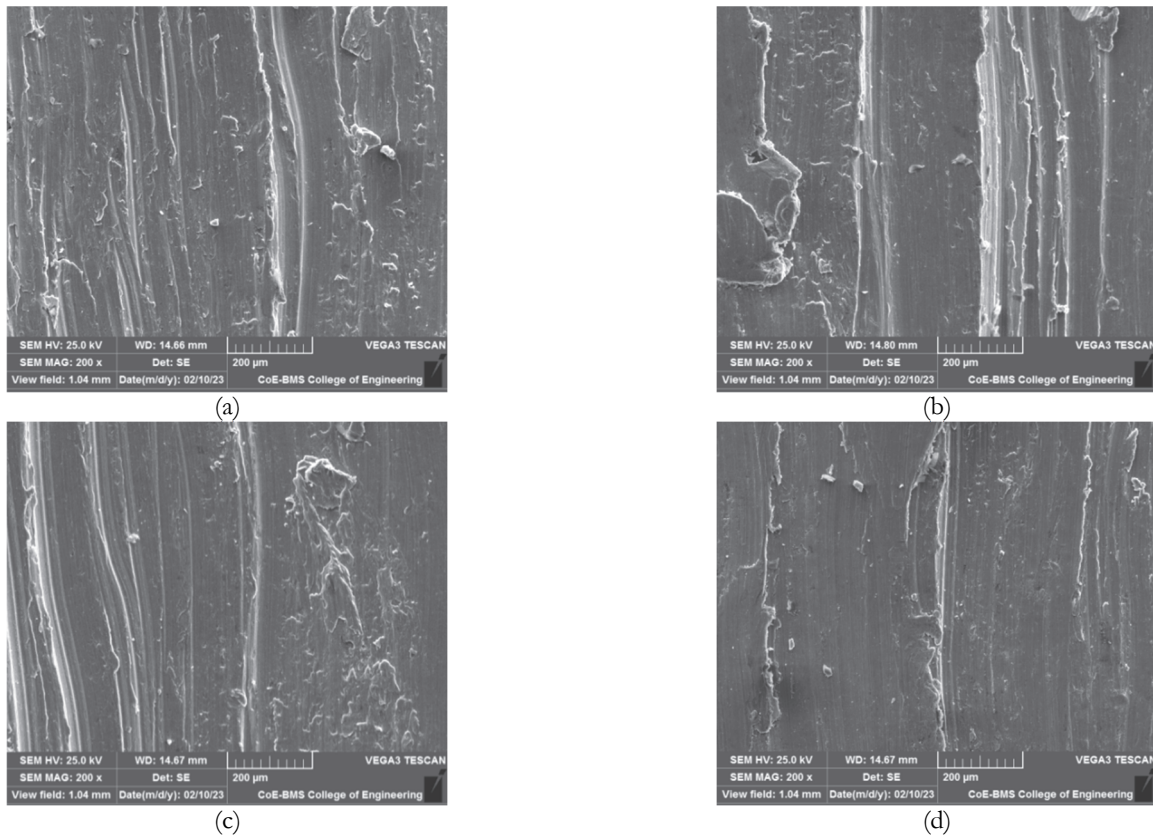


Figure 7: Wornout surface of wear test specimens (a) Al7075 - 1.5% B₄C+2% Al₂O₃ (b) Al7075 - 3% B₄C+2% Al₂O₃ (c) Al7075 - 4.5% B₄C+2% Al₂O₃ (d) Al7075 - 6% B₄C+2% Al₂O₃.

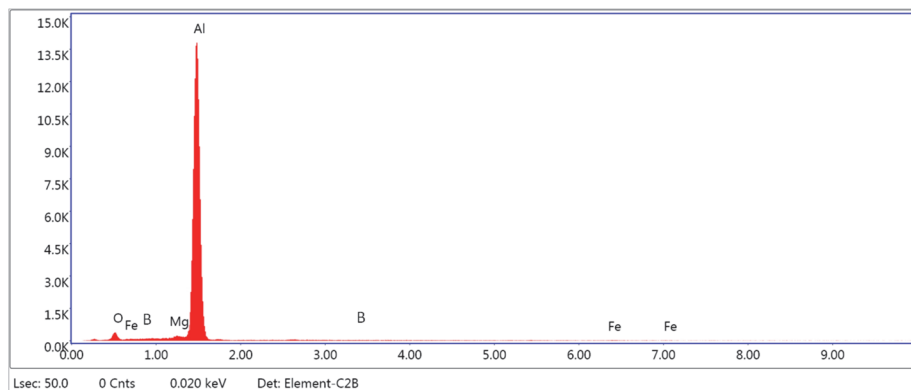


Figure 8: EDS spectrum of developed hybrid nano composites.



Fig. 8 displays the findings of an Energy Dispersive Spectroscopy (EDS) investigation conducted on an aluminum matrix containing nano $\text{Al}_2\text{O}_3+\text{B}_4\text{C}$ particles. The presence of primary constituent elements such as boron, oxygen, and aluminum peaks in the EDS analysis provides evidence for the incorporation of nano $\text{Al}_2\text{O}_3+\text{B}_4\text{C}$ particles into aluminum composites. The results indicate that the trace amount of oxygen detected by EDS might have originated from an oxide (Al_2O_3) likely introduced during the sample preparation process. This underscores the significance of sample preparation methods in composite materials analysis and emphasizes the need for careful interpretation of EDS results.

Sl. No.	n-B ₄ C (wt. %)	Al ₂ O ₃ (wt. %)	Ageing Temperature (°C)	Machining force (N)	Ra (µm)
1	1.5	1.0	100	4.35	1.05
2	1.5	1.0	120	5.68	1.25
3	1.5	1.0	140	8.56	1.29
4	1.5	1.5	100	10.25	1.26
5	1.5	1.5	120	7.56	1.32
6	1.5	1.5	140	4.53	1.35
7	1.5	2.0	100	10.44	2.56
8	1.5	2.0	120	8.95	1.89
9	1.5	2.0	140	8.35	1.80
10	3.0	1.0	100	7.22	2.01
11	3.0	1.0	120	9.66	2.10
12	3.0	1.0	140	6.50	1.95
13	3.0	1.5	100	13.35	3.55
14	3.0	1.5	120	11.35	2.35
15	3.0	1.5	140	10.98	2.30
16	3.0	2.0	100	15.60	3.56
17	3.0	2.0	120	11.20	2.66
18	3.0	2.0	140	10.25	2.54
19	4.5	1.0	100	15.30	2.78
20	4.5	1.0	120	14.91	2.88
21	4.5	1.0	140	10.09	3.09
22	4.5	1.5	100	16.30	3.12
23	4.5	1.5	120	13.25	3.19
24	4.5	1.5	140	15.46	2.78
25	4.5	2.0	100	15.95	4.02
26	4.5	2.0	120	16.35	3.35
27	4.5	2.0	140	17.35	3.40

Table 2: Experimental outcomes of machining force and Ra.

Cutting force and Ra

Machinability, often described as an "ease" with which a material can be machined, plays a crucial role in determining the efficiency of cutting operations. While machinability cannot be precisely quantified, parameters such as chip formation, machining pressures, surface finish, and power consumption are commonly utilized for evaluation. Extensive studies have been conducted on the machinability of nano- $\text{Al}_2\text{O}_3/\text{B}_4\text{C}$ reinforced Al7075. One essential output of these studies is the examination of machining force (Fm). During trials, values for Feed force (Ff), Cutting force (Fc), and Thrust force (Ft) measurements are collected. The mean machining force, often referred to as the mean force, is computed using the theoretical equation provided in Eqn. (1). This computation aids in understanding the overall force exerted during the machining process, providing valuable insights into the machinability characteristics of the material.



$$F_m = \sqrt{(F_t^2 + F_f^2 + F_c^2)} \tag{1}$$

Validating the ideal ranges of factors is the goal of optimization determination. For Al7075 composites the experimental results of cutting force and Ra values under various process settings are shown in Tab. 2, which also summarizes the results of each trial. The tabulated data provides a comprehensive record of the experimental observations made during the optimization process. This makes it easier to identify the process parameters that work best for achieving the desired surface roughness and machining force characteristics in Al 7075 composites.

To find the Ra and machining force value, regression equations were applied, taking into account ANOVA models. The predicted regression analysis method was used to evaluate the significance of these effects. ANOVA results were employed to elucidate the effects of Ra and machining force, providing insight into their respective impacts on the overall machining process. The ANOVA findings presented in Tab. 3 offer insights into the significance of machining force in the context of composites. Notably, nanosized B₄C emerges as the most influential factor, contributing the largest percentage (62.78%) among all process factors. This downplays the paramount importance of nanosized B₄C in determining machining force. In contrast, with individual parameter contributions of 14.78 % and 3.97 %, respectively, nanosized Al₂O₃ and ageing temperature were found to be the least significant. The overall error, attributed to various factors, stands at 18.44 %. The presence of hard nano reinforcing particles renders hybrid composite materials less machinable compared to traditional counterparts. As the weight proportions of nano-B₄C content increased during milling operations, there was a gradual rise in material cutting pressures. This observation highlights the dynamic relationship between material composition and machining behaviour [11]. The investigation's findings were used to determine the significance of the variables influencing Ra using ANOVA. Tab. 4 demonstrates that, of all the components, nano B₄C makes up the largest percentage (66.29%), highlighting its noteworthy impact on Ra. On the other hand, with individual contributions of 16.39% and 3.50%, respectively, nano B₄C and ageing temperature were found to have the least significance.

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F-value	P-value	Cont. %	Remarks
n-B ₄ C	1	244.131	244.131	244.131	78.2754	0.0000000	62.78	Significant
n-Al ₂ O ₃	1	57.495	57.495	57.495	18.4345	0.0002709	14.78	Significant
Ageing Temperature	1	15.475	15.475	15.475	4.9618	0.0359819	3.97	Significant
Error	23	71.734	71.734	3.119			18.44	
Total	26	388.836					100	

Table 3: ANOVA results of machining force.

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F-value	P-value	Cont. %	Remarks
n-B ₄ C	1	12.2348	12.2348	12.2348	110.417	0.0000000	66.29	Significant
n-Al ₂ O ₃	1	3.0258	3.0258	3.0258	27.308	0.0000267	16.39	Significant
Ageing Temperature	1	0.6460	0.6460	0.6460	5.830	0.0241096	3.50	Significant
Error	23	2.5485	2.5485	0.1108			13.80	
Total	26	18.4551					100	

Table 4: ANOVA results of Ra.

The findings from the Taguchi Method trial runs have been visually depicted through the creation of Main Effects Plots (MEP) for the Ra and machining force of the MMCs. These MEPs, illustrated in Figs. 9 and 10, illustrate the correlation between process parameters and the machining force and Ra values of MMCs. These graphical representations enhance the comprehension of the relationship between different parameters and Ra and machining force in MMCs. In Fig. 9, the

primary effect graph shows the machining force and the "smaller the better" criterion is the focus of the examination. The chart clearly shows the best settings for machining the hybrid nano MMCs developed in our study: level-1 of nano-B₄C, level-1 of nano- Al₂O₃, and level-3 of ageing temperature. The cutting force was found to increase in direct proportion to the weight proportions of nanoparticles. In contrast to homogenous materials, a fracture crack that originated over the silicon carbide particles and extended beneath the particles was revealed amid the process machining of ceramic-reinforced hybrid nano MMCs, as opposed to a single crack that occurred within the shear zone. The main cause of the increased Ra and, thus, higher machining forces is the particle's rotational characteristic. It was also observed that brittleness produced by an increase in ageing temperature resulted in a decrease in machining force. Fig. 10 shows a major effect graph that centers on Ra values with the goal of identifying the ideal machining parameters that lead to the best possible surface quality. The graph clearly shows that the most advantageous points in this study, which correlate with improved surface texture of composites, are: level-1 of nano-B₄C, level-1 of nano-Al₂O₃, and level-3 of ageing temperature [12]. It was shown that as the ageing temperature increased, Ra decreased. The observed phenomenon can be explained by the decrease in frictional stress on micro MMCs and the decreasing tendency towards the formation of Built-Up Edges (BUEs) with increasing ageing temperatures [13]. Predominantly, samples that have been heat-treated had smoother surfaces than samples that had not, which are in line with research findings from other studies [14]. Three variables were evaluated in the ANOVA analysis: heat-treatment temperature, B₄C, and nanosized Al₂O₃. Their interactions were also examined. There is no interaction between the parameters when looking at the plots and if the interaction lines are parallel to other parameter lines. In contrast, a plotting arrangement where the lines do cross one another indicates that the parameters are interacting [15]. Plots of the interactions taken into account for machining force and Ra values are shown in Fig. 11 and 12 in precise detail. Weight proportion of nano-sized B₄C-Al₂O₃, and the heat treatment temperature are the three variable parameters that are illustrated and improved by this graphical representation.

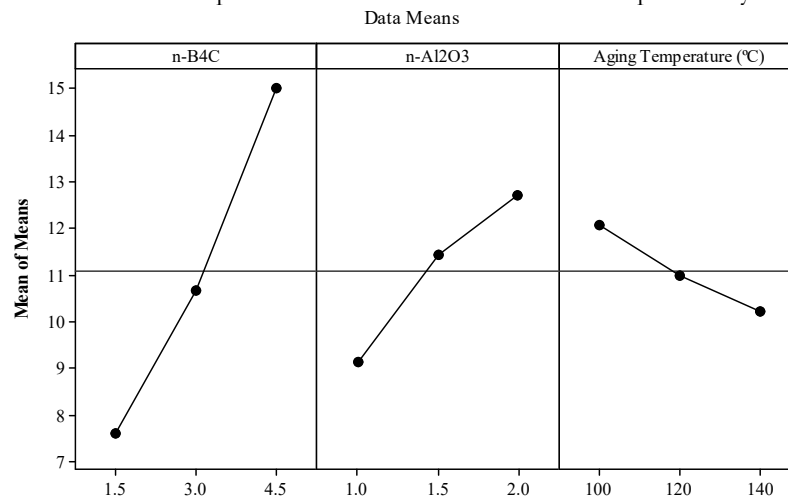


Figure 9: Main effect graph for machining force of nano composite.

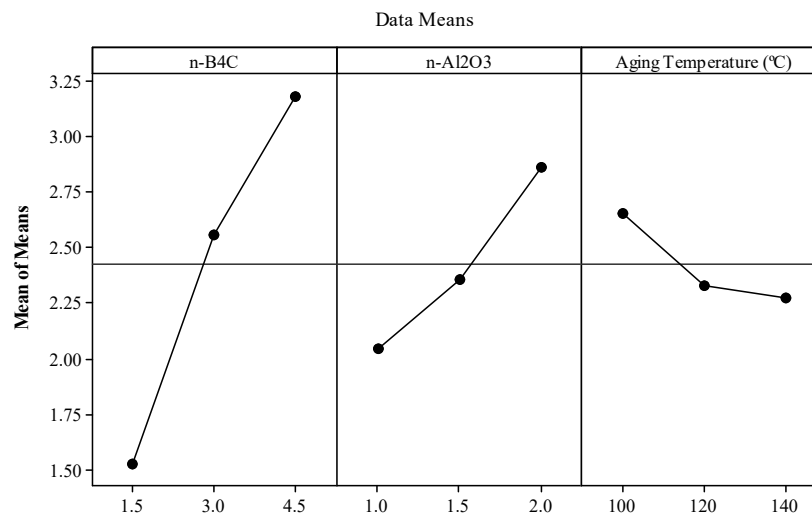


Figure 10: Main effect graph for Ra of nano composite.

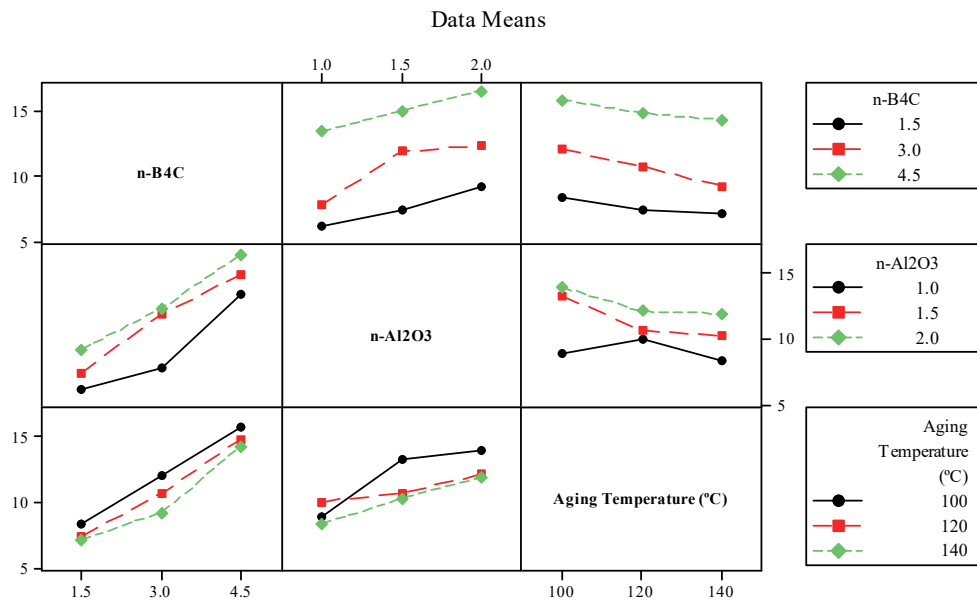


Figure 11: Interaction graph for machining force of nano composite.

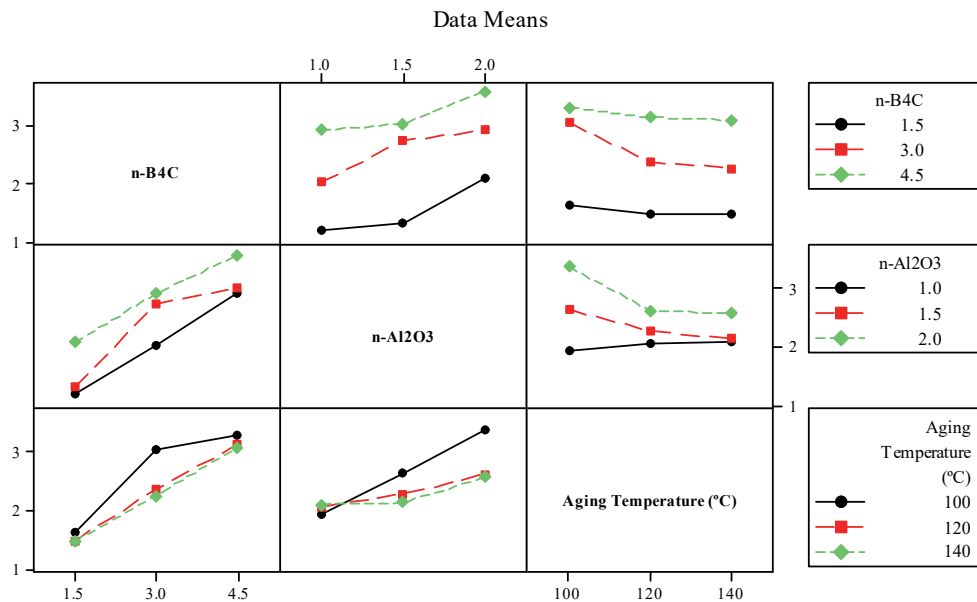


Figure 12: Interaction graph for Ra of nano composite.

Because of the existence of strong reinforcing particles, hybrid nano MMC machinability presents unique challenges compared to conventional materials. As the weight fraction of B₄C content increased, as the weight percentage of B₄C content increased, the material cutting pressures gradually increased during milling operations, consistent with the results of previous studies [16, 17]. Interaction plots illustrating the relationships between machinability process parameters are presented in Fig. 11. Notably, the machining force shows more prominent interaction plots due to the significant impact of parameter interactions. Fig. 12 illustrates interaction plots for Ra parameters, incorporating nanosized B₄C, Al₂O₃, and ageing temperature. These visual representations facilitate the evaluation of each process parameter's importance, with noticeable changes in Ra attributed to significant parameter interactions. Regression analysis has been utilized to predict the characteristics of hybrid MMCs, with regression equations employed to forecast Ra and machining force among the examined attributes [18]. Typically, these equations are structured as $Y = f(A, B, \text{ and } C)$, where Y represents the performance parameters, including Ra and machining force. The variables A, B, and C correspond to factors investigated in the current study, such as the ratio of nano- Al₂O₃/B₄C (wt. %) and heat treatment temperature (HT). Through regression analysis, these equations provide valuable insights into how variations in process parameters impact Ra and machining force in hybrid MMCs. The regression equations for machining force and Ra are as follows:



$$\text{Machining force} = 3.93759 + 2.45519 \text{ n-B}_4\text{C} + 3.57444 \text{ n-Al}_2\text{O}_3 - 0.0463611 \text{ Ageing Temperature } (^\circ\text{C}) \quad (2)$$

R-Sq = 81.55%

$$\text{Ra} = 0.68 + 0.54963 \text{ n-B}_4\text{C} + 0.82 \text{ n-Al}_2\text{O}_3 - 0.00947222 \text{ Ageing Temperature } (^\circ\text{C}) \quad (3)$$

R-Sq = 86.19%

To validate the reliability of the test trials, a series of experiments were conducted, and the disparities between the actual experimental results and the expected outcomes were graphically illustrated. In Figs. 13 and 14, the experimental data points are plotted against the predicted values for Ra and machining force across each level of variables. These graphical representations enable a visual comparison between the observed results and the anticipated values, aiding in the assessment of the accuracy and effectiveness of the experimental procedures. By scrutinizing these graphs, researchers can discern any discrepancies or deviations between the predicted and actual outcomes, thus ensuring the robustness and reliability of the experimental findings.

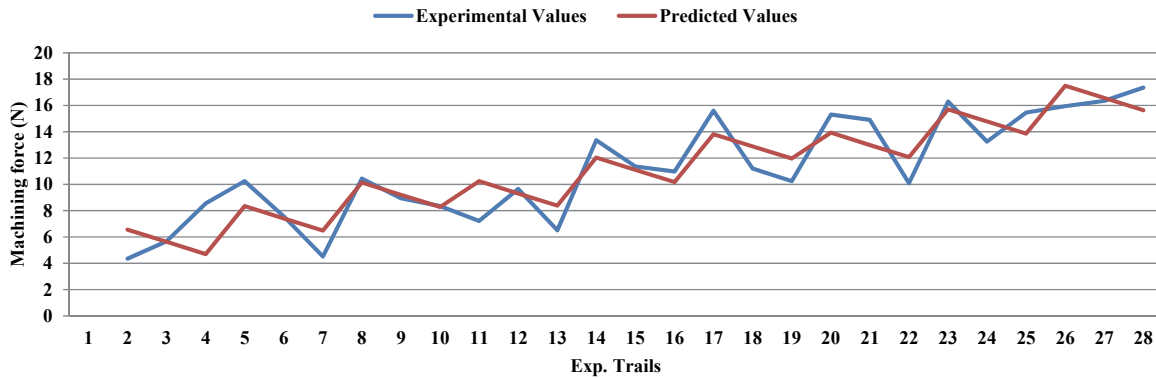


Figure 13: Plot of Experiment versus Predicted values for machining force comparison.

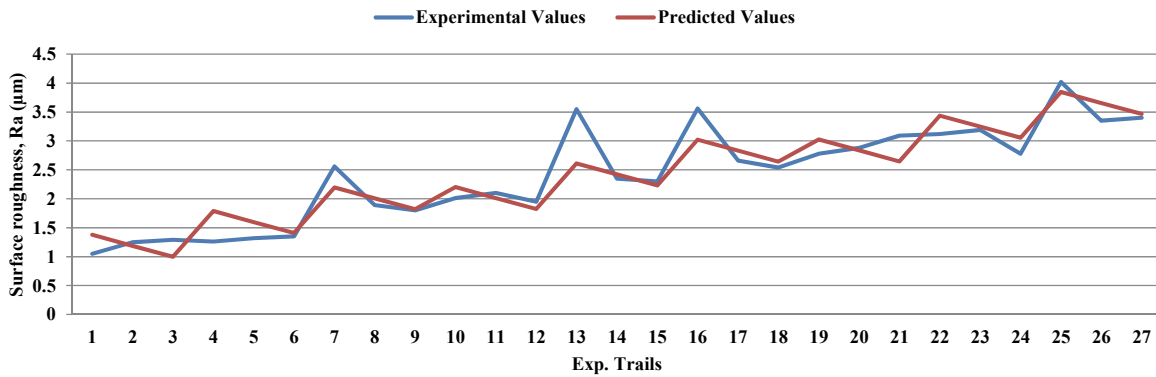


Figure 14: Plot of Experiment versus Predicted values for Ra comparison.

Tabs. 5 and 6 provide a clear response compiled from Ra and machining force outcomes. By ranking the delta of the means at 1, these tables provide a clear indication of the significance of different parameters. Specifically, the ranks assigned to the parameters in the response table highlight that nano-sized B₄C particles play a crucial role in machining force, while nano-sized Al₂O₃ particles significantly influence Ra. This ranking system allows the identification of the most pertinent characteristics in each aspect of the machining process, enabling researchers to prioritize their focus on factors that have the greatest impact on surface quality and machining efficiency.

Level	n-B ₄ C	n-Al ₂ O ₃	Ageing Temperature
1	7.630	9.141	12.084
2	10.679	11.448	10.990
3	14.996	12.716	10.230
Delta	7.366	3.574	1.854
Rank	1	2	3

Table 5: Response table for Mean - machining force.

Level	n-B ₄ C	n-Al ₂ O ₃	Ageing Temperature
1	1.530	2.044	2.657
2	2.558	2.358	2.332
3	3.179	2.864	2.278
Delta	1.649	0.820	0.379
Rank	1	2	3

Table 6: Response table for Mean - Ra.

Contour plots from the regression model are created and utilized to show the combined effect of the variables that were employed in the present study. Usually, these graphs are used to illustrate the relationship between the two parameters. By evaluating these graphs, the ideal values for each parameter can be predicted [19]. The wear loss contour graphs based on independent factors for each of the developed materials are shown in Figs. 15 and 16. It shows that, increasing of machining force with increase in addition of n-B₄C and n-Al₂O₃ in the MMCs. It is due to the addition of reinforcement's cause's brittleness and high hardness of the MMCs and it creates a higher machining force and Ra values during machining operations. Similarly ageing temperature verses nano particles indicates the lower ageing temperature with high wt. % of nano particles leads to increase the machining force and Ra values in the developed nano composites and also, it shows that, machining force and Ra values reduces at higher ageing temperature. The main reason is that, the ageing temperature (100°C - 140°C) leads to the grain refinement and uniform nano particles dispersion takes place in the matrix material. This causes reduction of machining force and Ra values during machining of developed nano MMCs.

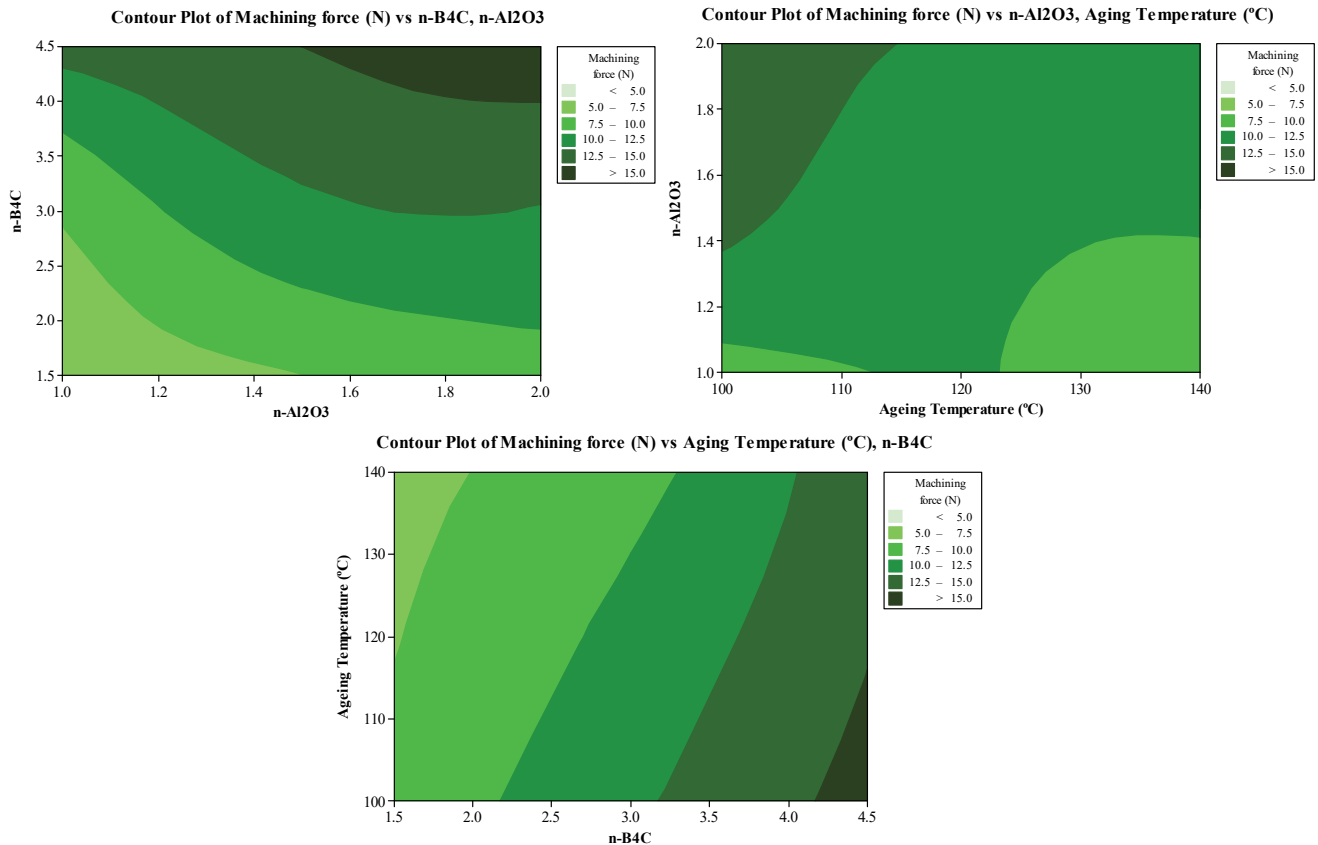


Figure 15: Contour Plot of Machining force.

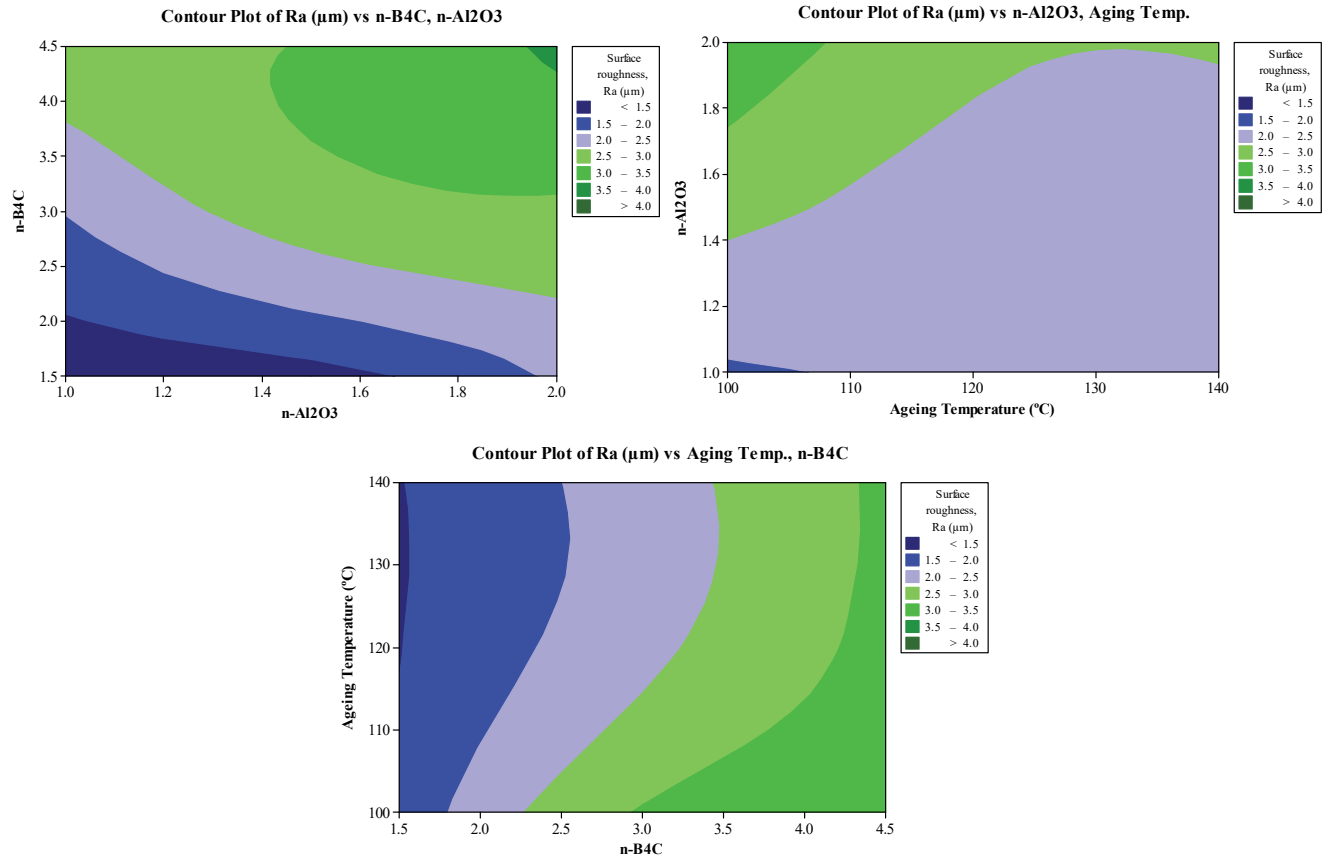


Figure 16: Contour Plot of Ra values.

The motivation behind the confirmation test primarily stems from the aim of optimizing the levels of process parameters [20]. This test serves to validate the optimal combinations of process factors and their corresponding values. Utilizing the ideal parameters determined through the Taguchi technique, composite samples were created and subsequently tested to evaluate machining force and Ra. The optimal process parameters and confirmatory results for Ra and machining force values, as obtained from the Taguchi analysis research, are summarized in detail in Tab. 7.

Process Parameters	Optimized Values For machining force and Ra	Machining force, Fm (N)			Ra (μm)		
		Experimental Values	Confirmatory outcomes	Error (%)	Experimental Values	Confirmatory outcomes	Error (%)
n-B ₄ C (wt. %)	1.5						
n-Al ₂ O ₃ (wt. %)	1	8.56	8.95	4.35	1.29	1.32	2.27
Ageing Temperature (°C)	140						

Table 7: Confirmatory results of machining force and Ra values.

This tabulated data (Tab. 7) provides a comprehensive overview of the ideal settings identified through the optimization process and their corresponding outcomes, serving as a valuable reference for future studies and practical applications in the field of composite material machining. From the outcomes of confirmatory trials, a maximum error of 4.35% was found in machining force of developed nano composite whereas, for the Ra it was 2.27% of error. It can be concluded that, this is within the acceptable limit.



CONCLUSIONS

The successful creation of Formwork Grade Al7075 reinforced with nanoscale B₄C-Al₂O₃ hybrid MMCs was achieved by the stir casting method in the study. The subsequent evaluation focused on the machining force and Ra values, yielding the following key findings:

- Ageing temperature and weight percentage of nano-sized reinforcements exhibited a nearly linear effect on both Ra and machining force.
- The addition of nanoparticles and heat treatment considerably improves the tensile strength, hardness, and wear resistance of hybrid composites by 3%, 17%, and 10%, respectively, for samples reinforced with 4.5% B₄C + 2% Al₂O₃.
- The Incorporation of nano-Al₂O₃/B₄C particles led to an increase in both the machining force and Ra of MMCs. This phenomenon stemmed from the interaction of hard nanoparticles with a softer matrix, resulting in increased friction during machining.
- With increasing ageing temperature, the cutting force (F_t, F_f, and F_c) decreased, while Ra values of composites demonstrated an increase with higher weight percentages of nano- Al₂O₃/B₄C and decreased with increasing ageing temperature.
- Utilizing Taguchi's method optimized the machining parameters, effectively reducing Ra and machining force.
- Optimal results in terms of minimizing machining force and Ra were achieved at 1.5% nano-B₄C, 1% nano-Al₂O₃, and an ageing temperature of 140°C.
- From the outcomes of confirmatory trials, a maximum of 4.35% error was found in machining force of developed nano composite whereas, for the Ra it was 2.27% error. It can be conclude that, this is within the acceptable limit.
- These findings provide valuable insights into the effects of varying process parameters on machining outcomes in Formwork Grade Al7075 nano composites, highlighting the importance of careful parameter selection and optimization for enhanced machining performance and surface quality.

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