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Enhanced Tribological Performance of Nano-Cutting Fluids with Soybean Oil and Hybrid h-BN/MWCNT Additive Nanoparticles Utilizing the Minimum Quantity Lubrication Method

This study explores the use of soybean oil-based nanolubricants that incorporate hexagonal boron nitride (h-BN), multi-walled carbon nanotubes (MWCNTs), and their hybrid at a concentration of 0.15 wt% for minimum quantity lubrication (MQL) in the computer numerical control (CNC) milling of AISI 1045 steel. Nano-cutting fluids were prepared via a two-step process, involving stirring followed by ultrasonication, and were characterized for density, viscosity, thermal conductivity, and rheology. Machining responses comprised tool wear length, cutting temperature, surface roughness, chip morphology, and chip colors. All samples exhibited Newtonian behavior at 40 °C and 100 °C. The hybrid h-BN/MWCNT formulation delivered the best overall performance, achieving the lowest tool wear length (~0.067 mm), reduced cutting temperatures, and the smoothest surfaces relative to dry cutting and single-additive fluids. The improvements are attributed to a synergistic mechanism in which h-BN platelets form a boundary-lubrication tribofilm, while MWCNT act as nano-bearings and a thermally conductive network that stabilizes the cutting zone. Simple sedimentation observations indicated higher dispersion stability for MWCNT-containing nano-cutting fluids than for h-BN alone. These results suggest that hybrid nano-additives in plant-oil-based cutting fluids may offer practical benefits for MQL-assisted machining or, particularly by helping reduce tool wear, improve thermal management, and support more sustainable machining.

Keywords: *Nano-cutting fluids; Cutting Fluids; CNC Machining, Tool Wear; Tribology; Surface Roughness.*

1. INTRODUCTION

Machining is a manufacturing process that employs a cutting tool to eliminate material from a workpiece [1]. It is one of the most adaptable and effective mechanical processes, enabling the removal of extra material in the form of chips to provide the required dimensions, geo–metry, and surface polish [2]. To improve the operational efficiency of rotating machinery, lubricants are extensively utilized in sectors such as power generation, transportation, and contemporary equipment, serving to reduce friction and wear among mechanical components [3].

Lubricants are typically liquid substances applied bet–ween two solid surfaces to reduce friction and establish a thin layer at the contact surfaces [4]. The function of this very thin layer, commonly referred to as a lubricating film, plays a crucial role in controlling wear and reducing friction between the contacting surfaces [5,6]. Lubricants commonly available on the market are made from processed petroleum or mineral oil, coal, or natural gas [7]. The application of lubricating oils derived from crude petroleum poses detrimental impacts on both environ–mental and health aspects [8]. Prolonged exposure to petroleum-based crude oil lubricants, whether through dermal contact or inhalation, can lead to respiratory inf–lammation and localized skin reactions, with potential carcinogenic effects [9]. The non-biodegradability of mi–neral oil and the rising worldwide demand have redi–rected research efforts from non-renewable to renewable sources [10]. Lubricant oil manufacturers are redirecting their focus towards the utilization of biodegradable, renewable energy sources for lubricant oil manufacturing [11]. The demand for bio-based lubricants has surged in recent years, driven by heightened environmental cons–ciousness among the public, government, and businessess [12].

Biolubricants represent a category of lubricants characterized by their ready biodegradability and non-toxic nature, both to human health and the environment [13]. Biolubricantsare a superior alternative to petro–leum-based oils, given that vegetable oils provide nu–merous environmental advantages related to renewa–

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bility, biodegradability, toxicity, and outstanding per–formance across a range of applications [14]. Biolub–ricants can be derived from synthetic esters obtained from minerals or vegetable oils [15]. Vegetable oils are biodegradable, non-toxic, possess excellent lubricating characteristics, and are inexpensive to produce[16]. Vegetable oils commonly as raw materials for biolub–ricants can be made from palm oil, cardoon oil, canola oil, sunflower oil, coconut oil, cottonseed oil, and soy–bean oil [4]. The availability and affordability of soy–bean oil are also key factors motivating the study [10].

Soybean oil represents 28% of global vegetable oil production and is the second most widely used vege–table oil in the world after palm oil, with consumption reaching 44 million metric tons [17]. Soybean oil serves as a viable lubricant in various machining processes. Compared to mineral oil, soybean oil has many advan–tages, including being renewable, naturally biodegra–dable, non-toxic, with good lubricating properties [12]. Soybean oil exhibits a commendable stability in vis–cosity alongside a notably low rate of evaporation loss. In addition, soybean oil is much cheaper. These charac–teristics are beneficial for achieving good lubrication results [18].

The commercialization of soybean oil as a biolub–ricant in the lubricant market is still very limited [12]. Soybean oil is currently not widely used as a lubricant due to several challenges and issues with its perfor–mance [9]. While vegetable oils exhibit favorable lubricating properties, their inadequate oxidative stabi–lity and suboptimal cold temperature characteristics, such as elevated pour points, require improvement [18]. The incorporation of lubricant additives represents a viable approach to enhancing and modifying the tribo–logical and rheological properties of lubricants. Nano additives have garnered significant interest across mul–tiple energy-related domains owing to their remarkable shape, size, tribological characteristics, and environ–mental implications [3]. Vegetable oil-based lubricants become as nanolubricants after the addition of nano–particles. The performance of vegetable oils may be enhanced through the incorporation of nanoparticles, including molybdenum disulfide (MoS_2) and multi-walled carbon nanotubes (MWCNTs) [18].

Nanomaterials have been widely investigated as lubricant additives because of their distinctive physi–cochemical characteristics, which can improve friction reduction, wear resistance, and heat transfer in lubri–cating systems. In biolubricants, nanomaterials are par–ticularly attractive because they can enhance tribolo–gical performance while maintaining the environmental advantages of plant-based oils. Previous studies have shown that lubrication improvement depends strongly on the type, structure, and dispersion behavior of the additive used [19,20]. For example, Ziyamukhamedova et al. [21] reported that h-BN nanoparticles reduced wear in soybean oil more effectively than in olive oil and palm oil. Cui et al. [18] also demonstrated that soybean oil containing MoS_2 and MWCNT additives exhibited imp–roved tribological performance. In machining appli–cations, several hybrid nano-cutting fluids have been reported to outperform mono-additive systems. Sharma et al. [22] found that an Al-MoS2 hybrid provided better performance than dry cutting, base fluid, and Al_2O_3 mono-nano-cutting fluid conditions during turning of AISI 304. Khan et al. [23] observed signi–ficant imp–rovements when using an Al-GNp hybrid compared with pure MQL and Al_2O_3 nano-cutting fluid in turning AISI 52100. Thakur et al. [24] similarly showed that an Al-CuO hybrid outperformed dry, wet, cryogenic, pure MQL, and mono-nanoparticle cooling strategies. Yildirim et al. [25] further reported that an Al_2O_3/MoS_2 hybrid nano-cutting fluid reduced surface roughness by 41.54% compared with dry cutting and base-fluid MQL, while Kumar and Gautam [26] showed that nano-additive-en–hanced soybean oil biolubricants could improve tribo–logical performance and surface finish.

Despite these advances, several limitations remain in the current literature. Most previous studies have focu–sed either on mono-additive systems, hybrid combi–nations other than h-BN/MWCNT, or base fluids other than soybean oil. In many cases, machining perfor–mance is emphasized without systematically relating it to the underlying thermophysical and rheological behavior of the fluid. As a result, the synergistic role of h-BN/MWCNT hybrid nanoparticles in soybean-oil-based cutting fluids, particularly under MQL-assisted CNC machining conditions, is still not clearly understood. To address this gap, the present study investigates soybean-oil-based nano cutting fluids containing h-BN, MWCNT, and hybrid h-BN/MWCNT additives under MQL conditions. By correlating density, viscosity, ther–mal conductivity, sedimentation stability, and rheological behavior with tool wear, cutting temperature, surface roughness, and chips morphology, this study provides a more integrated understanding of how hybrid nanopar–ticles influence both fluid characteristics and machining performance. This approach is expected to support the development of more effective and environ–mentally friendly cutting fluids for sustainable manufacturing.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

The base fluid used in the formulation of nano-cutting fluids (NCFs) in this study was soybean oil. In the NCFs formulation, soybean oil was mixed with nano–particle additives, including h-BN, MWCNT, and h-BN/MWCNT hybrids, each with a concentration of 0.15 wt%. The properties of soybean oil are shown in Table 1, while the properties of h-BN and MWCNT nano–particles are shown in Tables 2 and 3, respectively.

The experimentutilized AISI 1045 steel as the mate–rial for the milling process, with a workpiece dimension of 50 mm x 50 mm x 20 mm (L x W x H). Tables 4 and 5 present the chemical composition and mechanical properties. The SOLID brandhigh-spee–dsteel (HSS) endmillhad a diameter of 8 mm andfeatures 4 flutes.

Table 1. Properties of Soybean Oil [27]

PropertiesofSoybean Oil	Value
Density [kg/m^3]	919
KinematicViscosityat 40°C [mm^2/s]	29.5
FlashPoint [ºC]	329
AcidValue [mg.KOH/g]	0.20
Refraction Index [nD^{40}]	Max 0.3

Table 2. Properties of h-BN

Specification	Description
Appearance	WhitePowder
Purity [%]	99
Model Number	SY-BN04
ParticleSize	~50 nm
CAS Number	10043 11-5

Table 3. Properties of MWCNT

Specification	Description
Brand	XFNano
Purity [%]	>95
Density [g/cm^3]	~0.19
Diameter [nm]	25-30

Table 4. Chemical Composition of AISI 1045 Steel

Element	Component[%]
C	0.045
Mn	0.69-0.83
Si	0.19-0.29
P	0.008-0.039
S	0.015-0.02
Fe	Balance

Table 5. Mechanical Properties of AISI 1045 Steel

MechanicalProperties	AISI 1045 Steel
Ultimate Tensile Strength [MPa]	569
Yield Strength [MPa]	343
Modulus of Elasticity [GPa]	205
Shear Modulus [GPa]	80
Elongation [%]	20
Machinability [%]	55

2.2 NCFs Sample Preparation

NCFs were prepared using a two-step strategy mixing and homogenization. The sample preparation process began with mixing h-BN, MWCNT, and hybrid h-BN/ MWCNT nanoparticle additives into soybean oil and stirring with a magnetic stirrer for 20 minutes at a rota–tion speed of 1250 rpm. The process was then followed by homogenization using an ultrasonic homogenizer for 30 minutes to obtain a sample with an excellent disper–sion level in the cutting fluid sample. The NCFs sample preparation and experimental design in this study are shown in Figure 1 and Table 6.

Table 6. Experimental Design

No.	Sampel	Nanoparticles concentration [wt%]	Lubricating condition	Sample codes
1.	Dry (Without cutting fluid)	-	-	Dry
2.	Dromus (Commercial Cutting Fluid)	-	MQL	Dromus
3.	Soybean Oil	-	MQL	Pure SO
4.	Soybean Oil + h-BN	0.15	MQL	SO + h-BN
5.	Soybean Oil + MWCNT	0.15	MQL	SO + MWCNT
6.	Soybean Oil + Hybrid h-BN/MWCNT	0.15	MQL	SO + h-BN/MW CNT

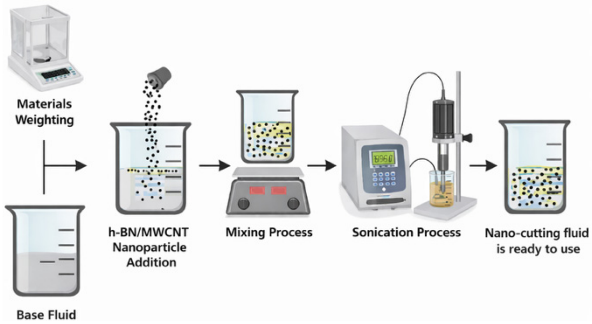


Figure 1. NCFs Sample Preparation Scheme

2.3 Experimental Setup for CNC Milling

This study utilized the CNC machining process to evalu–ate the performance of a soybean oil-based cut–ting fluid incorporating h-BN, MWCNT, and hybrid h-BN/MWCNT additive nanoparticles. This fluid was sprayed using the MQL method. Additionally, various components of the CNC machine utilized in the experi–ment were evaluated. The MQL preparation process involved a mist-shaped spraying nozzle, a compressor to apply pressure to the NCFs sample during machining, and a flow regulator to maintain consistent air pressure. The CNC machining scheme employing MQL is de–picted in Figure 2, along with the corresponding mac–hining parameters following previous studies [27- 29].

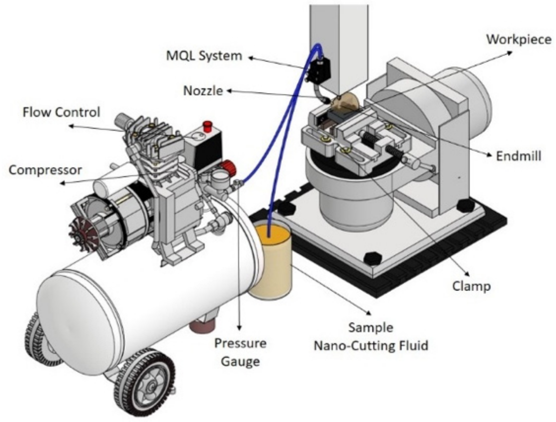


Figure 2. Schematic of Milling Experiment

2.4 Characterization Techniques

2.4.1 Characterization of Additive Nanoparticles

The morphology of additive nanoparticles was per–formed using scanning electron microscopy (SEM) with an FEI Inspect-S50, Japan. The phase identification and crystallite size of the additive nanoparticles were mea–sured using X-ray diffraction (XRD) with a PANalytical Expert Pro. The functional group of additive nano–particles was measured using Fourier transform infrared (FTIR) with a model IR Prestige 21 Shimadzu.

2.4.2 Thermophysical Test of NCFs Samples

Density testing of NCFs samples using analytical digital scales was conducted at room temperature. The mass value was obtained from the weight of the sample, while the volume was measured using a pycnometer. Thermal conductivity testing was performed to assess the heat transfer performance of the NCFs sample utilizing the KD2 Pro apparatus. Dynamic viscosity testing was con–ducted to determine the viscosity level or resistance value of the flow, facilitating the calculation of the rheological value of the NCFs sample using the NDJ-8S Viscometer at temperatures of 40°C and 100°C. Sedi–mentation testing was performed to assess the degree of separation between solid additive nanoparticles and soybean oil utilizing the gravity sedimentation method. The suspension lasted for 28 days.

2.4.3 Rheological Test of NCFs Samples

This investigation delves into the rheological charac–teristics to determine the flow behavior of NCFs, emp–hasizing the relationship between shear rate and shear stress. The assessment of shear rate and shear stress values necessitates the outcomes derived from the dynamic viscosity evaluation of the cutting fluid. The shear rate is determined using Equation 1, while the shear stress is calculated using Equation 2.

$$\gamma = \frac{2\omega R_c^2 R_b^2}{x^2\left(R_c^2 - R_b^2\right)} \qquad (1)$$

where γ is the shear rate (1/s); ω is the angular velocity (rad/sec); R_c is the container radius (cm); R_b is the rotor radius (cm); and x is the radius at which the shear rate is calculated (cm).

$$\tau = \mu \times \gamma \qquad (2)$$

where τ is shear stress (mPa.s); μ is dynamic viscosity (kg/m.s); and γ is shear rate (1/s).

2.4.4 Tribological Test of NCFs Samples

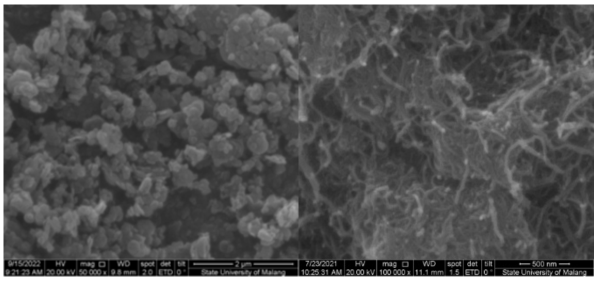
The wear of HSS endmill tools was analyzed using a Sinher Binocular optical microscope model XSZ-107 BN to assess the wear area at intervals corresponding to four HSS endmill flutes. The wear length was subse–quently measured using ImageJ software. The wear of the cutting tool was quantified on the edge side by asse–ssing the length of wear that develops in that area. Sur–face roughness testing was conducted to determine the roughness level of AISI 1045 workpieces produced by the CNC milling machining process. The cutting tempe–rature in this study was measured using a FLIR E8 Thermal Camera. Surface roughness testing was con–ducted on specimens machined with NCF samples. The morphology of chipswasanalyzed to examine the chip characteristics of machined AISI 1045 workpieces. The morphology of chipswasanalyzed using a scanning ele–ctron microscope, specifically the FEI Inspect-S50 from Japan. Chip color analysis was performed to identify the color produced during the workpiece cutting process. The formation of chips in machining can indicate exce–ssive heat during cutting and evaluate the performance of each NCFs sample.

3. RESULTS AND DISCUSSION

3.1 Characterization of Additive Nanoparticles

3.1.1 Morphology of Additive Nanoparticles

Figure 3 presents the results of scanning electron micro–scopy (SEM) characterization of h-BN nanomaterials at a magnification of 50,000×. Figure 3 illustrates that h-BN nanomaterials exhibit a spherical surface morp–hology and tend to aggregate [30]. The spherical morp–hology of h-BN may induce a rolling effect [31]. SEM testing results on MWCNT nanomaterials reveal the presence of cylindrical particles aggregated in clumps. Attractive van der Waals interactions lead to the aggre–gation of carbon nanotubes, resulting in clumps or bun–dles [32].

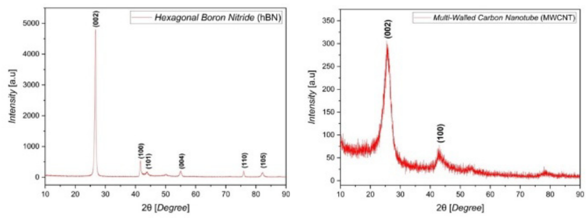


(a) (b)

Figure 3. SEM results (a) h-BN and (b) MWCNT

3.1.2 Phase of Additive Nanoparticles

Figure 4 presents the XRD spectrum of nanomaterials. The h-BN exhibits its highest peak intensity of 4723.83 at 2θ = 26.7241°. The crystal form was analyzed using the Match software, and the results showed that h-BN has a hexagonal form with boron 43.6% and nitrogen 56.4% as constituent elements. The crystallite size can be obtained from XRD testing using the Scherrer Equ–ation. For h-BN nanomaterials, this value was deter–mined at a position of 26.7241 with FWHM 0.1574, corresponding to a crystal diameter of 51.8763 nm. Based on the XRD spectrum, the MWCNT nanoma–terial has a hexagonal crystal structure pattern with peak data correlated at 26°. The Miller index (hkl) obtained from the diffraction analysis for each peak are (002) and (100), where carbon is present at the (002) peak [33].



(a) (b)

Figure 4. XRD results of (a) h-BN and (b) MWCNT

3.1.3 Functional Groups of Additive Nanoparticles

Based on Figure 5(a), the FTIR spectrum of h-BN shows peaks at 3394, 2797, 2526, 2382, 1557, 1300, 923, 817, and 426. The peaks in the h-BN nanomaterial spectrum were obtained from the B-O-H, -NH2, B-H, B=O, N-B, N-B-O, B-N, and O-B-O functional groups. Based on Figure 5(b), which shows the FTIR spectrum of MWCNT, valleys were identified atwavelengths of

3427, 2851, 1725, 1533, 1065, and 941. Furthermore, each valley was analyzed, and the functional groups identified in MWCNT nanomaterials were O-H, C-H, C=O, C=C, C-O, and C-C.

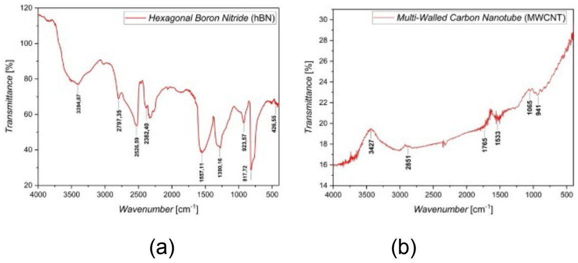


Figure 5. FTIR results of (a) h-BN and (b) MWCNT

Table 7. Functional Group of h-BN

Wavenumber [cm^{-1}]	Bond	References
3394.07	B-O-H	[34]
2797.35	-NH_2	[30]
2526.59	B-H stretching	[30]
2382.40	B-H stretching	[30]
1557.11	B=O stretching	[30]
1300.16	N-B	[34]
923.57	N-B-O	[35]
817.72	B-N	[35]
426.55	O-B-O	[36]

Table 8. Functional Group of MWCNT

Wavenumber [cm^{-1}]	Bond	References
3427	O-H stretching	[37]
2851	C-H stretching	[38]
1725	C=O stretching	[30]
1533	C=C stretching	[30]
1065	C-O stretching	[39]
941	C-C stretching	[38]

3.2 Thermophysical Properties of NCFs Samples

3.2.1 Density of NCFs Samples

Figure 6 shows that NCFs samples with added nano–particle additives have a higher density value than pure SO due to the addition of nanoparticles [30]. The inc–rease in density affects the cutting performance and the hydrostatic pressure generated by the fluid. The higher the fluid density value, the higher the hydrostatic pres–sure generated. Hydrostatic pressure plays a vital role in strengthening fluid flow in the cutting zone, thereby accelerating the machining process.

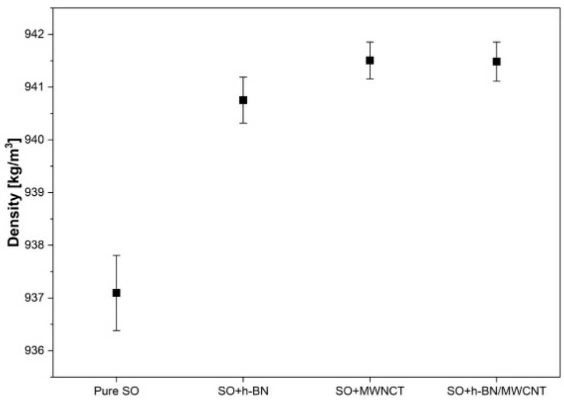


Figure 6. Density of NCFs Samples (mean ± SD, n = 3)

3.2.2 Dynamic Viscosity of NCFs Samples

Based on Figure 7, lubricating oil containing nano–particle additives experiences a decrease in viscosity. The viscosity value decreases with the addition of h-BN and MWCNT nanoparticles, which may be influenced bythe thixotropic effect [40]. This thixotropic pheno–menon is likely caused by the nanoparticle additives dispersed in the base fluid acting like ball bearings in the fluid, allowing smoother molecular movement and reducing internal friction between lubricant molecules [21]. In addition, factors such as nanoparticle surface interactions that can alter the microstructure of the lub–ricant affect the cohesive forces between oil molecules [18], allowing for more effortless molecular movement and leading to reduced flow resistance and decreased lubricant viscosity [41].

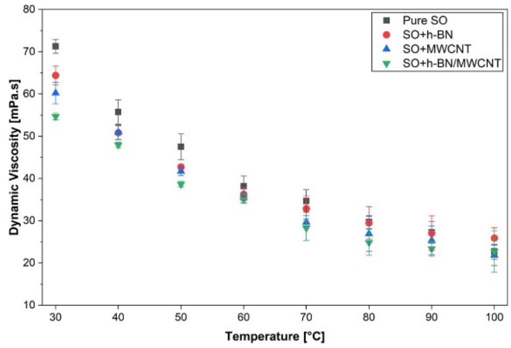


Figure 7. Dynamic Viscosity of NCFs Samples (mean ± SD, n = 3)

3.2.3 Thermal Conductivity of NCFs Samples

Figure 8 shows that the addition of nanoparticle addi–tives can increase the thermal conductivity of NCFs samples, and the increase varies for each additive. Na–noparticles enhance the thermal conductivity of biolub–ricants by acting as a high-conductivity "thermal bridge" that couples the fluid matrix and reduces inter–facial (solid–liquid) thermal resistance at nanoparticle–lubricant boundaries [42].

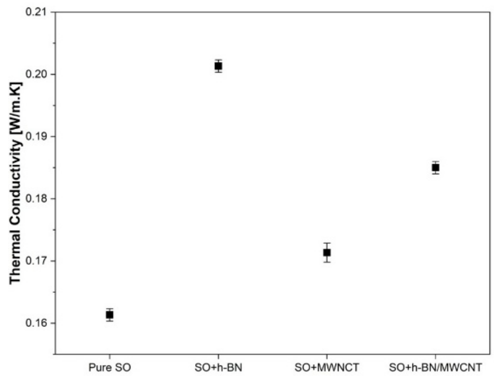


Figure 8. Thermal Conductivity of NCFs Samples (mean ± SD, n = 3)

Their high aspect ratio and large specific surface area facilitate the formation of continuous, phonon-mediated heat-transfer pathways, thereby improving energy trans–port through the suspension. The magnitude of this enhancement depends on geometry, notably particle size and layer thickness, which govern pathway connectivity and coupling with the surrounding fluid [43]. The incorporation of nanoparticles into a base fluid induces Brownian motion, characterized by the random motion of suspended particles due to continuous collisions with surrounding fluid molecules. This dynamic interaction enhances energy exchange within the medium, thereby improving heat transfer efficiency[44]. When intro–duced at an optimal concentration, nanoparticles can significantly increase the thermal conductivity of the base fluid [45].

3.2.4 Sedimentation of NCFs Samples

Based on Figure 9, a visual comparison from day 0 to day 28 of the sedimentation test, the sedimentation that occurred in SO+h-BN was faster than that of the other two nanolubricants. These results are consistent to the findings of [46], which concluded that the stability of nanolubricants is closely related to the size of the nanoparticles. Larger nanoparticle size can increase van der Waals attractive forces. These attractive forces are the reason for agglomeration between nano materials, which causes sedimentation problems [47]. The size of h-BN nanoparticles is larger than that of MWCNT na–noparticles, 50 nm and 25-30 nm, respectively. The SO+MWCNT sample was more stable and took longer to settle. The SO+MWCNT sample had a structure that allows it to form strong networks and bonds within the nanolubricant, resulting in increased overall stability [47].

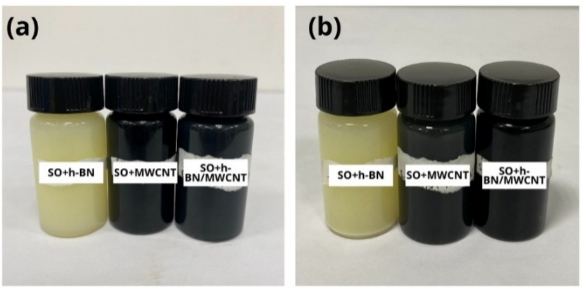
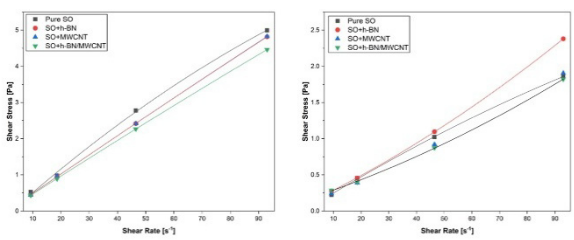


Figure 9. Sedimentation of NCFs at (a) 0-Day and (b) 28-Days

3.3 Rheology Properties of NCFs Samples

The results of the calculation of shear rate and shear stress values to determine the rheological properties of NCFs samples at temperatures of 40°C and 100°C in this study are shown in Figure 10. Based on the comparison of shear rate and shear stress values in soybean oil and NCF samples with different nanoparticle additives at 40°C and 100°C, the fluids exhibit Newtonian flow behavior.



(a) (b)

Figure 10. Rheological Properties of NCFs at Temperatures (a) 40°C and (b) 100°C

Newtonian fluids exhibit consistent performance in lubrication, particularly in NCFs applications where loads and speeds fluctuate. This consistency can main–tain surface separation, helping to prevent excessive friction and wear during the machining process [48].

3.4 Performance of NCFs Sample

3.4.1 Tool Wear

Figure 11 shows that the addition of nanoparticle addi–tives to pure SO can reduce tool wear, with the lowest tool wear occurring in SO+h-BN/MWCNT of 0.067 mm. The application of the MQL method in machining applications can reduce the mass of tool wear compared to using the dry condition method [49,50]. The addition of MWCNT to CNC Milling machining lubricants using the MQL method can extend the life and age of cutting tools because the tube structure of MWCNT functions as a rolling medium that can strengthen anti-friction properties [51]. On the other hand, h-BN has a two-dimensional layer structure similar to graphene and can support lubrication, while the addition of h-BN to lubricants can effectively reduce surface wear on steel [52]. In other words, the synergistic interaction of h-BN/MWCNT in forming a continuous tribofilm pro–duces a tribological mechanism that can reduce the rate of tool wear.

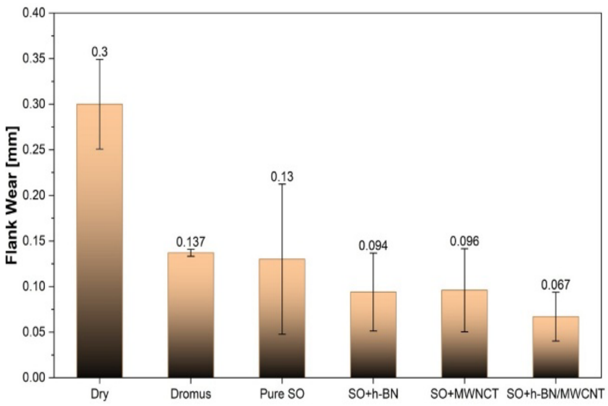


Figure 11. Tool wear test result after machining (mean ± SD, n = 3)

3.4.2 Cutting Temperature

Based on Figures 13 and 14, it is shown that the addi–tion of nanoparticles can lower the machining tempe–rature. This shows that nanoparticles play a substantial role in improving the thermal management of the cut–ting zone. The most abundant work of nanoparticles in oil, apart from increasing the thermal conductivity value in the base fluid, also serves as a protective medium on the surface of the object, counteracting the frictional force produced and generating energy to offset the fric–tional force [53]. The reduction in cutting temperature achieved by using NCFs based on vegetable oils and a mixture of nanoparticle additives is attributed to the combination of good thermal conductivity and oil pro–perties in the center of the machine handle, particularly at the contact surfaces of the cutting device, chips, and workpiece [54].

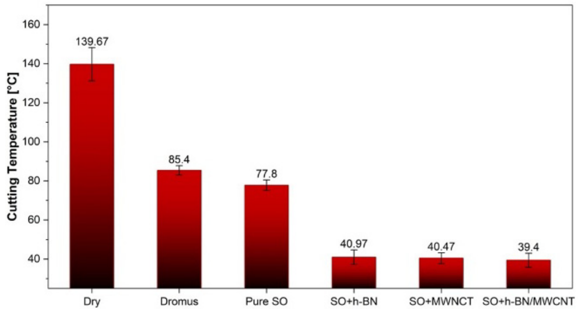


Figure 13. Cutting temperature test results (mean ± SD, n = 3)

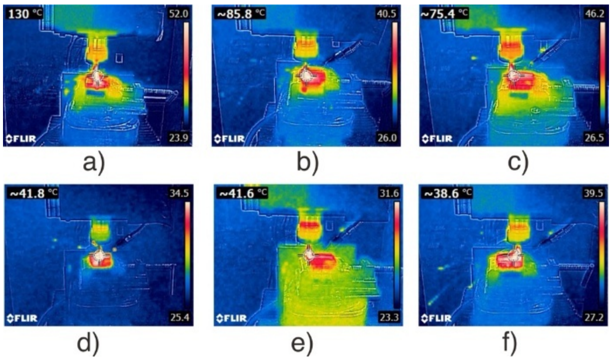


Figure 14. Temperature measurement during the machining process under the following conditions: (a) dry, (b) dro–mus, (c) pure SO, (d) SO+h-BN, (e) SO+MWCNT, and (f) SO+h-BN/MWCNT

3.4.3 Surface Roughness

Based on Figure 15, the lowest average surface rough–ness value was obtained for SO+h-BN/MWCNT due to a synergistic effect: h-BN platelets act as shear-slip solid lubricants that accelerate the formation of a pro–tective tribofilm and suppress adhesion [55], while MWCNT acts as a "nano-bearing" and a heat-conduc–tive network that lowers the cutting zone temperature. When dispersed in soybean oil, which has polar groups (supporting wetting/adsorption), both fill micro valleys (valley-filling), reduce plastic ploughing, and ultimately flatten the surface peak-valley profile so that the friction coefficient and temperature are reduced simultaneously, which is consistently associated with a decrease in rou–ghness in various MQL nano-cutting fluid studies [56].

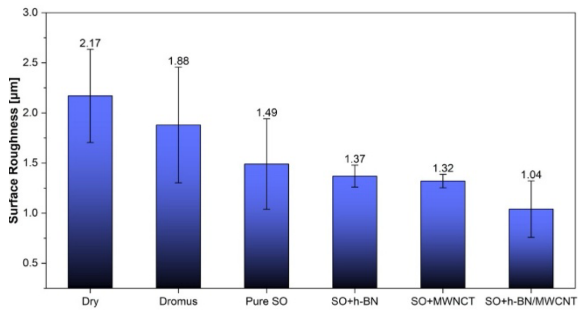


Figure 15. Surface Roughness of specimens after machi–ning (mean ± SD, n = 3)

Hybrid additive nanoparticles tend to outperform mono-nanoparticles in reducing R_a because they com–bine boundary lubrication, heat conduction, and micro-surface "polishing" functions [56-58], while CNT-based formulations have explicitly been shown to suppress cutting forces, temperatures, and R_a compared to con–ventional lubricants [59], findings on h-BN- nano-cut–ting fluid in machining also indicate reductions in temperature, tool wear, and roughness [60].

3.4.4 Morphology of Chips

Figure 16 shows that chip in dry conditions is coarse, randomly serrated, and irregular, typical of serrated chips resulting from adiabatic shear localization and the formation/release of built-up edges (BUE) at the tool-workpiece interface. This phenomenon is common in medium-carbon steel when stress–strain and local tem–perature increases trigger thermoplastic instability in the shear plane [61,62].

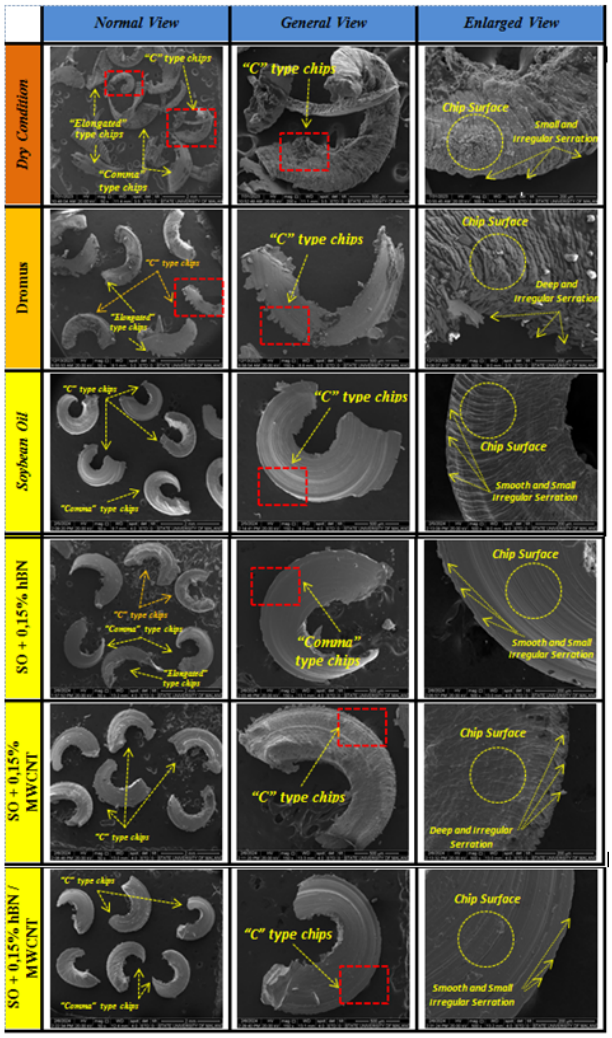


Figure 16. Morphology of Chips

The use of dromus improves heat transfer, but boundary lubrication remains limited compared to NCFs with MQL, so serration is still apparent even with larger pitches due to periodic thermal softening and cutting force fluctuations; this is consistent with the results that MQL/nano-cutting fluids are more effective at reducing temperature and force oscillations than conventional dry/wet conditions [63,64]. Conversely, SO+h-BN and especially SO+h-BN/MWCNT tend to produce smoot–her and more regular chips, as nanoparticles form a uni–form tribofilm on the rake face, reducing friction and delaying shear localization (reducing BUE/segmentation amplitude), resulting in more continuous and stable chip flow consistent with reports of HNMQL (h-BN/ MWCNT) and h-BN nano-cutting fluid that improve chip morphology, wear, and surface integrity [56], [65], [66]. The SO+MWCNT (mono) anomaly, which still displays coarse/irregular chips, can be explained by sub-optimal dispersion/concentration: MWCNT agglomera–tion increases viscosity and disrupts atomization/ trans–port in MQL, resulting in uneven tribological coating in the cutting zone [67,68]. Overall, the evolution of chip shape across these conditions reflects changes in cutting force, shear plane angle, and local temperature; when MQL-nano-cutting fluid suppresses force and tempe–rature (and their oscillations), a transition occurs from irregular serrated chips to more continuous and smooth chips [69].

4. CONCLUSION

Based on the results and discussion, the soybean-oil nanolubricant with hybrid h-BN/MWCNT additives (0.15 wt%) delivered the most superior and consistent performance in MQL-assisted CNC milling of AISI 1045. This was evidenced by the lowest tool wear (~0.067 mm), the lowest surface roughness, and a reduction in cutting temperature compared with the other conditions.These improvements were attributed to the synergistic mechanism between h-BN platelets, which promoted tribofilm formation and provided bou–ndary lubrication and anti-adhesion effects, and MWCNTs, which acted as nano-bearings and formed a thermally conductive network. Together, these mecha–nisms contributed to greater cutting process stability. In addition, all NCF samples exhibited Newtonian beha–vior at 40 °C and 100 °C, supporting stable surface se–paration under fluctuating load and speed throughout machining. These findings suggest that plant-oil-based NCFs containing h-BN/MWCNTs may serve as an en–vironmentally friendly lubricant alternative for MQL processes, particularly in applications where improved surface quality, longer tool life, and better thermal effi–ciency are desired. The study also provides useful insight for the formulation and selection of nano-cutting fluids by showing how thermophysical and rheological properties relate to machining performance. Future work should focus on optimizing dispersion and long-term stability (e.g., surfactant selection and particle size distribution), and strengthening statistical significance testing across samples to quantitatively validate performance differences.

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REFERENCES

[1] Nasution, A.R., Harahap, J.: Pengaruh variasi puta–ran spindel terhadap gaya potong pada proses pe–mesinan, Vocat. Educ. J., Vol. 2, No. 2, pp. 95-103, 2021.

[2] Sen, B., Mia, M., Uttam, G.M.K., Mandal, K., Prasad, S.: Eco-friendly cutting fluids in minimum quantity lubrication assisted machining: A review on the perception of sustainable manufacturing, Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 8, No. 1, pp. 249-280, 2021.

[3] Vardhaman, B.S.A., Amarnath, M., Ramkumar, J. Mondal, K.: Enhanced tribological performances of zinc oxide/MWCNTs hybrid nanomaterials as the effective lubricant additive in engine oil, Mater. Chem. Phys., Vol. 253, pp. 123447, 2020.

[4] Tesser, R., Russo, V., Turco, R., Vitiello, R., Di, M.: Bio-lubricants synthesis from the epoxidized oil promoted by clays: Kinetic modelling, Chem. Eng. Sci., Vol. 214, pp. 115445, 2024.

[5] Xiao, J., Wu, Y., Zhang, W., Chen, J. and Zhang, C.: Friction of metal-matrix self-lubricating com–posites: Relationships among lubricant content, lu–bricating film coverage, and friction coefficient, Friction, Vol. 8, No. 3, pp. 517-530, 2020.

[6] Nomède-Martyr, N., Vitulin, M., Joseph, H., Tho–mas, P.: Moringa oil with graphite and hexagonal boron nitride particles as additives for lubr–ication, Diam. Relat. Mater., Vol. 124, pp. 108930, 2022.

[7] Ocholi, O., Menkiti, M., Auta, M. Ezemagu, I.: Optimization of the operating parameters for the extractive synthesis of biolubricant from sesame seed oil via response surface methodology, Egypt. J. Pet., Vol. 27, No. 3, pp. 265-275, 2018.

[8] Nowak, P., Kucharska, K., Kamiński, M.: Ecolo–gical and health effects of lubricant oils emitted into the environment, Int. J. Environ. Res. Public Health, Vol. 16, No. 16, pp. 3002, 2019.

[9] Abdel-Hameed, H.S., El-Saeed, S.M., Ahmed, N.S., Nassar, A.M., El-Kafrawy, F., Hashem, A.I.: Chemi–cal transformation of jojoba oil and soybean oil and study of their uses as bio-lubricants, Ind. Crops Prod., Vol. 187, pp. 115256, 2022.

[10] Kharabati, S., Saedodin, S., Rostamian, S.H.: Ex–perimental investigation of thermal and rheological behavior of silica/soybean oil nano lubricant in low-temperature performance of internal combus–tion engine, Energy Sources Part A-Recovery Util. Environ. Eff., Vol. 47, No. 1, pp. 5493-5507, 2021.

[11] Owuna, F.J. et al.: Chemical modification of vege–table oils for the production of biolubricants using trimethylolpropane: A review, Egypt. J. Pet., Vol. 29, No. 1, pp. 75-82, 2020.

[12] Roberto, P., Flexa, C., Filho, R., Rocha, M., Loureiro, C., Jr, C.: Synthesis and tribological pro–perties of bio-based lubricants from soybean oil, Biomass Convers. Biorefin., Vol. 14, pp. 20509-20521, 2023.

[13] Cecilia, J., Plata, D.B., Saboya, R.M.A., De Luna, F.M.T., Cavalcante, C., Rodriguez-Castellon, E.: An overview of the biolubricant production pro–cess: Challenges and future perspectives, Processes, Vol. 8, No. 3, pp. 257, 2020.

[14] Abdollah, M.F.B., Amiruddin, H. and Jamallulil, A.D.: Experimental analysis of tribological perfor–mance of palm oil blended with hexagonal boron nitride nanoparticles as an environment-friendly

lubricant, Int. J. Adv. Manuf. Technol., Vol. 106, pp. 4183-4191, 2020.

[15] Durango-Giraldo, G., Zapata-Hernandez, C., Santa, J.F. and Buitrago-Sierra, R.: Palm oil as a biolub–ricant: Literature review of processing parameters and tribological performance, J. Ind. Eng. Chem., Vol. 107, pp. 31-44, 2022.

[16] Sabri, A.M., Talib, N., Sahab, A., Sani, A.: A study on tribological performances of hBN/WS2 and hBN /TiO2 hybrid vegetable based nanofluids for metal–working fluid, in: Proceeding of Engineering Rese–arch Day 2022, 13.07.2022, Melaka, pp. 248-249.

[17] Toda, T.A., Sawada, M.M., Rodrigues, C.E.C.: Ki–netics of soybean oil extraction using ethanol as solvent: Experimental data and modeling, Food Bioprod. Process., Vol. 98, pp. 1-10, 2015.

[18] Cui, X., Cao, P., Guo, J., Ming, P.: Use and performance of soybean oil based bio-lubricant in reducing specific cutting energy during biomimetic machining, J. Manuf. Process., Vol. 62, pp. 577-590, 2021.

[19] Kumar, M., Kıvak, T., Khanna, N.: A tribological performance of vegetable-based oil combined with GNPs and hBN nanoparticles on the friction-wear tests of titanium grade 2, Tribol. Int., Vol. 181, pp. 108314, 2023.

[20] Rahman, M., Islam, M., Roy, R., Younis, H., Alna–hyan, M., Younes, H.: Carbon nanomaterial-based lubricants: Review of recent developments, Lubri–cants, Vol. 10, No. 11, pp. 281, 2022.

[21] Ziyamukhamedova, U., Wasil, S., Kumar, S., Sehgal, R., Wani, M.F., Singh, C.S., Tursunov, N. and Gupta, H.S.: Investigating friction and antiwear characteristics of organic and synthetic oils using h-BN nanoparticle additives: A tribological study, Lubricants, Vol. 12, No. 1, pp. 27, 2024.

[22] Sharma, A.K., Singh, R.K., Dixit, A.R., Tiwari, A.K.: Novel uses of alumina-MoS2 hybrid nano–particle enriched cutting fluid in hard turning of AISI 304 steel, J. Manuf. Process., Vol. 30, pp. 467-482, 2017.

[23] Khan, A.M., Gupta, M.K., Hegab, H., Jamil, M., Mia, M., He, N., Song, Q., Liu, Z., Pruncu, C.I.: Energy-based cost integrated modelling and sus–tainability assessment of Al-GnP hybrid nanofluid assisted turning of AISI 52100 steel, J. Clean. Prod., Vol. 257, pp. 120502, 2020.

[24] Thakur, A., Manna, A., Samir, S.: Performance eva–luation of different environmental conditions on out–put characteristics during turning of EN-24 steel, Int. J. Precis. Eng. Manuf., Vol. 20, pp. 1839-1849, 2019.

[25] Yıldırım, Ç.V. et al.: A comparative study on the tribological behavior of mono and proportional hybrid nanofluids for susta–inable turning of AISI 420 hardened steel with cer–met tools, J. Manuf. Process., Vol. 73, pp. 695-714, 2022.

[26] Kumar, R., Gautam, R.K.: Tribological investi–gation of sunflower and soybean oil with metal oxide nanoadditives, Biomass Convers. Biorefin., Vol. 14, pp. 2389-2401, 2022.

[27] Puspitasari, P., Pramono, D.D., Habiby, M.N.A., Prabowo, Jaelani, A., Abdullah, M.I.H.C., Suyetno, A.: Experimental evaluation of biolubricant with additive nanoparticle calcium carbonate (CaCO3) from scallop shell waste as cutting fluids using mini–mum quantity lubrication (MQL) in CNC milling process, FME Transactions, Vol. 52, No. 2, pp. 319-334, 2024.

[28] Nurhidayat, M.A., Puspitasari, P., Nur, A.R., Abdiyar, M.A., Pramono, D.D.: Performance eva–luation of canola oil-based nano-cutting fluid with TiO2 nanoparticle additive in CNC milling process with minimum quantity lubrication (MQL) system, Tribol. Ind., Vol. 47, No. 3, pp. 443-452, 2025.

[29] Habiby, M.N.A., Puspitasari, P., Pramono, D.D., Suryanto, H., Fikri, A.A., Aminnudin, A., Ghazali, M.J.: Thermophysical, rheological, and tribological properties of corn oil with CaCO3 nanoparticle additive derived from scallop shell waste as nano–cutting fluid in CNC milling machining processes, J. Manuf. Process., Vol. 156, pp. 816-833, 2025.

[30] Katon, R., Puspitasari, P., Ayu, A., Ilman, M.: Identification of thermophysical and rheological properties of SAE 5W-30 with addition of hexa–gonal boron nitride, Transmisi, Vol. 19, No. 2, pp. 41-48, 2023.

[31] Kumar, M., Jayashree, G.: Role of size of hexa–gonal boron nitride particles on tribo-performance of nano and micro oils, Lubr. Sci., Vol. 30, No. 8, pp. 1-16, 2018.

[32] Pistone, A., Ferlazzo, A., Lanza, M., Milone, C., Iannazzo, D., Piperno, A., Piperopoulos, E., Gal–vagno, S.: Morphological modification of MWCNT functionalized with HNO3/H2SO4 mixtures, J. Nanosci. Nanotechnol., Vol. 12, No. 6, pp. 5054-5060, 2012.

[33] Purwanto, M.R., Puspitasari, P., Permanasari, A.A., Abdullah, M.I.H.C.: Investigation of thermo–physical and rheological properties of scallop shell powder/SAE 5W-30 nanolubricant, Transmisi, Vol. 19, No. 2, pp. 30-36, 2023.

[34] Cui, Z. et al.: Large scale thermal exfoliation and functionalization of boron nitride, Small, Vol. 10, No. 12, pp. 1-4, 2014.

[35] Hassan, J., Naz, S., Haider, A., Raza, A., Ul-Hamid, A., Qumar, U., Haider, J., Goumri-Said, S., Benali, M., Ikram, M.: h-BN nanosheets doped with transition metals for environmental remediation: A DFT approach and molecular docking analysis, Mater. Sci. Eng. B, Vol. 272, pp. 115365, 2021.

[36] Xu, Y. et al.: Femtosecond laser-assisted fabrication of fluorescent boron nitride quantum dots, in: IEEE International Conference on Mani–pulation, Manu–facturing and Measurement on the Nanoscale (3M-NANO), 04-08.08.2019, Zhenjiang, pp. 7-10, 2019.

[37] Abuilaiwi, F.A., Laoui, T., Al-Harthi, M., Atieh, M.A.: Modification and functionalization of multi–walled carbon nanotube (MWCNT) via Fischer esterification, Arab. J. Sci. Eng., Vol. 35, No. 1C, pp. 37-48, 2010.

[38] Solhy, A., Machado, B.F., Beausoleil, J., Kihn, Y., Pereira, M.F.R., Figueiredo, J.L., Faria, J.L. and Serp, P.: MWCNT activation and its influence on the catalytic performance of Pt/MWCNT catalysts for selective hydrogenation, Carbon, Vol. 46, No. 9, pp. 1194-1207, 2008.

[39] Zaman, A., Rashid, T.U., Khan, M.A., Rahman, M.M.: Preparation and characterization of multi–wall carbon nanotube (MWCNT) reinforced chito–san nanocomposites: Effect of gamma radiation, BioNanoScience, Vol. 5, pp. 31-38, 2015.

[40] Cristea, G.C., Radulescu, A., Georgescu, C., Radu–lescu, I. and Deleanu, L.: Influence of additive con–centration in soybean oil on rheological and tribo–logical behavior, INCAS Bull., Vol. 10, No. 4, pp. 35-43, 2018.

[41] Georgescu, C., Solea, L.C., Deleanu, L.: Additi–vation of vegetal oils for improving tribological characteristics, in: IOP Conf. Ser.: Mater. Sci. Eng., Vol. 514, Paper 012012, 2019.

[42] Wang, B. et al.: Thermal conductivity and mecha–nical properties enhancement of CF/PPBESK ther–moplastic composites by introducing graphene, Po–lym. Compos., Vol. 43, No. 5, pp. 2736-2745, 2022.

[43] Danial, W.H., Abdul Majid, Z.: Recent advances on the enhanced thermal conductivity of graphene nanoplatelets composites: A short review, Carbon Lett., Vol. 32, pp. 1411-1424, 2022.

[44] Oulahou, Y., Elguennouni, Y., Hssikou, M., Balit, J., Alaoui, M.: Numerical investigation of natural convection heat transfer using TiO2/Al2O3-water nanofluids, FME Transactions, Vol. 52, No. 1, pp. 157-172, 2024.

[45] Seyhan, M., Altan, C.L., Gurten, B., Bucak, S.: The effect of functionalized silver nanoparticles over the thermal conductivity of base fluids, AIP Adv., Vol. 7, No. 4, pp. 045101, 2017.

[46] Liang, T., Hou, J., Qu, M., Xi, J., Raj, I.: Appli–cation of nanomaterial for enhanced oil recovery, Petrol. Sci., Vol. 19, pp. 882-899, 2022.

[47] Ilyas, S.U., Pendyala, R., Narahari, M.: Stability and thermal analysis of MWCNT-thermal oil-based na–nofluids, Colloids Surf. A, Vol. 527, pp. 11-20, 2017.

[48] George, H.F., Qureshi, F.: Newton's law of viscosity, Newtonian and non-Newtonian fluids, in: Wang, Q.J. and Chung, Y.-W. (Eds.): Encyclopedia of Tribology, Springer US, Boston, pp. 2416-2420, 2013.

[49] Akhmal, V., Syah, R. and Ritonga, D.A.A.: Meka–nisme pembentukan chip proses pembubutan kering menggunakan pahat PVD dan CVD berlapis, Bul. Utama Tek., Vol. 18, No. 2, pp. 187-192, 2023.

[50] Gasni, D., Rahmadiawan, D., Irwansyah, R., Khalid, A.E.: Composite of carboxymethyl cellulose/MXene and Span 60 as additives to enhance tribological properties of bio-lubricants, Lubricants, Vol. 12, No. 3, pp. 78, 2024.

[51] Parambil, K.L., Kumar, D., M., S.M., Hirani, H.: Thermal and frictional performance evaluation of nano lubricant with multi wall carbon nano tubes (MWCNTs) as nano-additive, AIP Conf. Proc., Vol. 1953, pp. 100032, 2018.

[52] Wu, C., Hong, Y., Ni, J., Teal, P.D., Yao, L., Li, X.: Investigation of mixed hBN/Al2O3 nanopa–rticles as additives on grease performance in rolling bearing under limited lubricant supply, Colloids Surf. A, Vol. 659, pp. 130811, 2023.

[53] Peña-Parás, L., Maldonado-Cortés, D., Rodríguez-Villalobos, M., Romero-Cantú, A.G., Montemayor, O.E.: Enhancing tool life, and reducing power consumption and surface roughness in milling pro–cesses by nanolubricants and laser surface textu–ring, J. Clean. Prod., Vol. 253, pp. 119836, 2020.

[54] Hu, S., Li, C., Zhou, Z., Liu, B., Zhang, Y., Yang, M., Li, B., Gao, T., Liu, M., Cui, X., Wang, X., Xu, W., Dambatta, Y.S., Li, R., Sharma, S.: Nano–particle-enhanced coolants in machining: Mecha–nism, application, and prospects, Front. Mech. Eng., Vol. 18, No. 4, pp. 53, 2023.

[55] Yıldırım, Ç.V., Sarıkaya, M., Kıvak, T., Şirin, Ş.: The effect of addition of hBN nanoparticles to na–nofluid-MQL on tool wear patterns, tool life, roug–hness and temperature in turning of Ni-based Inco–nel 625, Tribol. Int., Vol. 134, pp. 443-456, 2019.

[56] Aydın, A., Sağdıç, Ö.F., Yücel, M., Yapan, Y.F., Kızılkaya, H.Z., Uysal, A.: Evaluation of mono and hybrid nanofluids in MQL milling of Ti-6Al-4V: Machining performance, surface integrity and sus–tainability, Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 13, pp. 413–434, 2025.

[57] Abellán-Nebot, J.V., Ameen, K.H., Khan, A.M. and Mondragón, R.: Application of hybrid nanofluids in MQL assisted machining operations: Exploring sy–nergies and establishing guidelines, Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 12, No. 2, pp. 657-689, 2025.

[58] Tóth, Á., Szabó, Á.I., Kuti, R.: Tribological pro–perties of nano-sized ZrO2 ceramic particles in au–tomotive lubricants, FME Transactions, Vol. 49, No. 1, pp. 36-43, 2021.

[59] Dennison, M.S., Jebabalan, S.K., Barik, D.: Appli–cability of nano-cutting fluids for enhanced cooling, low tool wear, and high tribological performance during machining: A review, Discov. Appl. Sci., Vol. 6, No. 12, pp. 663, 2024.

[60] Abdiyar, M.A., Puspitasari, P., Pramono, D.D., Nurhidayat, M.A., Nur, A.R., Razak, J.A., Rosli, M.A.M.: Enhanced tribological performance of ca–nola oil-based nano-cutting fluids with hexagonal boron nitride (h-BN) nanoparticle additives under the minimum quantity lubrication (MQL) method, MJCSM, Vol. 17, No. 1, pp. 1-20, 2025.

[61] Qibiao, Y., Zhanqiang, L., Bing, W.: Charac–terization of chip formation during machining 1045 steel, Int. J. Adv. Manuf. Technol., Vol. 63, pp. 881-886, 2012.

[62] Wang, Q., Zhao, Y., Zhang, C., Xu, H., Xu, B., Wei, Z., Kang, C., Li, D., Guo, J.: Prediction and formation mechanism of serrated chips in cutting of SA508-3 steel under enhanced cooling and lubrica–

tion environments, Tribol. Int., Vol. 200, pp. 110053, 2024.

[63] Salur, E., Kuntoğlu, M., Aslan, A., Pimenov, D.Y.: The effects of MQL and dry environments on tool wear, cutting temperature, and power consumption during end milling of AISI 1040 steel, Metals, Vol. 11, pp. 1674, 2021.

[64] Pang, S., Zhao, W., Qiu, T., Liu, W., Yan, P., Jiao, L., Wang, X.: Effect of cutting fluid on milled surface quality and tool life of aluminum alloy, Materials, Vol. 16, pp. 2198, 2023.

[65] Velmurugan, K.V., Mani, N.: Influence of hBN nanofluid MQL on machining characteristics in turning of Inconel 625, Mater. Today Proc., 2023.

[66] Makhesana, M.A., Patel, K.M., Bagga, P.J.: Eva–luation of surface roughness, tool wear and chip morphology during machining of nickel-based alloy under sustainable hybrid nanofluid-MQL strategy, Lubricants, Vol. 10, No. 11, pp. 315, 2022.

[67] Duan, Z., Wang, Z., Wang, S., Zhang, B., Bian, P., Li, Y., Liu, J., Song, J., Li, C., Liu, X.: Tool wear in enhanced minimum quantity lubrication assisted milling: From mechanism to application, Chin. J. Aeronaut., pp. 103597, 2025.

[68] Sallakhniknezhad, R., Ahmadian, H., Zhou, T., Weijia, G., Anantharajan, S.K., Sadoun, A.M., Abdelfattah, W.M. and Fathy, A.: Recent advances and applications of carbon nanotubes (CNTs) in machining processes: A review, J. Manuf. Mater. Process., Vol. 8, No. 6, pp. 282, 2024.

[69] Günay, M., Korkmaz, M.E.: Understanding the relationship between surface quality and chip mor–phology under sustainable cutting environments, Materials, Vol. 17, No. 8, pp. 1826, 2024.

NOMENCLATURE

R_c	Vessel radius (cm)
R_b	Shaft radius (*spindle*) (cm)
R_a	Surface roughness (μm)
x	Radius shear rate is being calculated(cm)
K	Constant (0.9)
d	Crystallite size (nm)

Greek symbols

γ	Shear rate (/s)
ω	Shaft angular speed (*spindle*) (rad/sec)
λ	X-Ray wavelength (1.5406 Å)
β	Fullwidth half maximum (2θ)
θ	Bragg's angle (^{o})

Acronyms and abbreviations

MWCNT	Multi-walled carbon nanotubes
h-BN	Hexagonal boron nitride
SiO_2	Silicon dioxide
MoS_2	Molybdenum disulfide
Al_2O_3	Aluminium oxide
GNp	Graphene nanoplatelets
CuO	Copper oxide
MQL	Minimum quantity lubrication
AISI	American iron and steel institute
NCFs	Nano-cutting fluids
CNC	Computer numerical Control
HSS	High-speedsteel
SEM	Scanning electron microscopy
XRD	X-ray diffraction
FTIR	Fourier transform infra-red
FWHM	Full width half maximum
hkl	Indeks Miller
BUE	Built-up edges

ПОБОЉШАНЕ ТРИБОЛОШКЕ ПЕРФОРМАНСЕ НАНО-ТЕЧНОСТИ ЗА РЕЗАЊЕ СА СОЈИНИМ УЉЕМ И ХИБРИДНИМ H-BN/MWCNT АДИТИВНИМ НАНОЧЕСТИЦАМА КОРИШЋЕЊЕМ МЕТОДЕ МИНИМАЛНЕ КОЛИЧИНЕ ПОДМАЗИВАЊА

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Ова студија истражује употребу нано-мазива на бази сојиног уља која укључују хексагонални боров нитрид (h-BN), вишезидне угљеничне наноцеви (MWCNT) и њихов хибрид у концентрацији од 0,15 тежинских% за минималну количину подмазивања (MQL) у глодању челика AISI 1045 помоћу рачу–нарске нумеричке контроле (CNC). Нано-течности за резање су припремљене двостепеним поступком, који укључује мешање праћено ултразвуком, и окарактерисане су густином, вискозитетом, топлот–ном проводљивошћу и реологијом. Одговори обраде обухватали су дужину хабања алата, температуру резања, храпавост површине, морфологију струго–тине и боје струготине. Сви узорци су показали Њутново понашање на 40 °C и 100 °C. Хибридна формулација h-BN/MWCNT пружила је најбоље укупне перформансе, постижући најмању дужину хабања алата (~0,067 мм), смањене температуре ре–зања и најглађе површине у односу на суво резање и флуиде са једним адитивом. Побољшања се припи–сују синергијском механизму у којем h-BN плочице формирају трибофилм за гранично подмазивање, док MWCNT делују као нано-лежајеви и термички проводљива мрежа која стабилизује зону резања. Једноставна посматрања седиментације указала су на већу стабилност дисперзије за нано-флуиде за резање које садрже MWCNT него за сам h-BN. Ови резултати сугеришу да хибридни нано-адитиви у флуидима за резање на бази биљног уља могу понудити практичне користи за обраду уз помоћ MQL-a или, посебно тако што помажу у смањењу хабања алата, побољшању управљања температуром и подршци одрживијим процесима обраде.