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Enhanced Tribological Performance of Canola Oil-Based Nano-Cutting Fluids with Hexagonal Boron Nitride (h-BN) Nanoparticle Additives under the Minimum Quantity Lubrication (MQL) Method

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ABSTRACT

The modern manufacturing industry faces the challenge of improving product quality while reducing the environmental impact of using mineral oil-based cutting fluid. Minimum Quantity Lubrication (MQL) has emerged as an eco-friendly alternative. However, its thermal and tribological efficiency under intensive cutting conditions remains suboptimal. This study introduces canola oil-based nano-cutting fluids with hexagonal boron nitride (h-BN) nanoparticle additives to enhance thermal and tribological performance in MQL-assisted machining. Three formulations with varying concentrations of h-BN nanoparticles (0.1, 0.15 and 0.2 wt%) were synthesized and experimentally evaluated in the CNC milling of AISI 1045 using the MQL method. The experimental evaluation included testing thermophysical properties, such as density, dynamic viscosity, thermal conductivity, rheological properties, and tribological performance through measurements of cutting temperature, tool wear, and surface roughness. The results showed that adding h-BN nanoparticles increased density and viscosity, with the optimum thermal conductivity value reached at a fraction of 0.15 wt%. Tribologically, the nano-cutting fluid containing 0.15 wt% h-BN achieved the best performance, recording the lowest cutting temperature (35.43 °C), the least tool wear (0.120 mm²), and the smoothest surface finish (0.86 µm). These improvements are attributed to the synergistic effects of tribo-film formation and the enhanced thermal conductivity provided by the h-BN nanoparticles, outperforming dry cutting, Dromus, and pure canola oil. This study confirms the synergistic effect of biodegradable canola oil and h-BN in enhancing eco-sustainable precision machining, contributing to green manufacturing aligned with Sustainable Development Goal (SDG) 12.

Keywords:
MQL, Canola Oil, h-BN, Nano-Cutting Fluid

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1. Introduction

Modern manufacturing industries face critical challenges while balancing product quality improvement and eco-sustainability. The demand for quality improvement of high-precision products and extended component lifespan drives the optimization of precision machining processes such as Computer Numerical Controlled (CNC). Achieving this goal requires proper control of CNC machining parameters, including feed rate, depth of cut, cutting speed, and the efficiency of the cooling and lubrication system [1–3]. Cutting fluid contributes to cooling and lubrication, thereby lowering cutting forces, moving chips away from the cutting area, maintaining thermal stability, and extending tool life [4]. Conversely, about 85% of the total more than 2 million m^3 of cutting fluid used worldwide is mineral oil-based, with low biodegradability, which contributes significantly to environmental pollution through non-biodegradable hazardous waste [5,6]. Another impact shows that about 80% of machining operator infections occur due to direct contact with excessive cutting fluid [7,8]. The complexity of these challenges exposes the conflict between the need for high-quality production and the commitment to eco-sustainability. Thus, achieving the Sustainable Development Goals (SDGs), especially goal 12 on sustainable consumption and production, remains challenging for the modern manufacturing industry.

Minimum Quantity Lubrication (MQL) provides an alternative approach in improving cutting performance while offering a more sustainable approach by lowering the consumption of cutting fluids, which can reduce ecological impact [9,10]. Despite offering a viable solution for improved machining efficiency and reduced environmental footprint, the MQL method often fails to deliver adequate cooling and lubrication under heavy cutting conditions, particularly when mineral oil-based cutting fluids are utilized [11]. Due to the prominent limitations and environmental impact of mineral oil-based cutting fluids, extensive research initiatives have been directed towards exploring vegetable oils as alternative base fluids, due to their excellent biodegradability and promising capabilities in improving machining performance [12,13].

The study by Katna et al. [14] conducted a comprehensive investigation into the cutting performance of vegetable oil-based cutting fluids, concluding that such fluids hold significant potential as sustainable alternatives to their mineral oil-based counterparts. In a related investigation, Tiwari et al. [15] demonstrated that applying coconut oil as a cutting fluid utilizing the MQL method resulted in markedly improved cutting performance compared to mineral oil, as evidenced by lower surface roughness and reduced cutting temperature. These findings underscore the viability of further exploring diverse vegetable oils that may exhibit comparable or even superior tribological characteristics and biodegradability relative to mineral oils. Furthermore, Araujo et al. [16] performed an in-depth comparative analysis of various vegetable oils, including cottonseed, babassu nut, canola, sunflower, corn, and soybean oils, within the MQL milling process of AISI 1045 steel. Their results revealed that cottonseed and canola oil notably outperformed other oils in terms of cooling efficiency and tool life extension. Therefore, this study chose canola oil as the basic fluid for its favourable lubrication properties and its ability to form a protective lubricating film [17]. Despite its promising potential as an eco-friendly cutting fluid, canola oil exhibits low thermal stability under high-temperature conditions, constraining its application in heavy cutting operations [8]. To address this limitation, the present study integrates high thermal conductivity nanoparticles into canola oil to enhance its thermal and tribological performance within the MQL method [18].

The addition of nanoparticles to canola oil increases its viscosity and thermal conductivity. It also allows the nanoparticles to reach the cutting zone under high pressure, establish a protective lubricating layer, and induce a rolling effect [18,19]. The study by Wang et al. [20] investigated the effect of adding h-BN nanoparticles at 1, 2 and 5 wt% into castor oil on changes in friction coefficient, viscosity, and wear mechanism. The h-BN nanoparticles were selected in the study to improve the performance of a cutting fluid due to their thermal conductivity values, chemical stability, and performance advantages for tribological properties [21]. Wang et al. [20] also highlighted that the performance of nano-cutting fluids was determined not only by the presence of nanoparticles, but also by their concentration. A concentration that is too low can reduce tribological effects. At the same time, a concentration that is too high can cause particle agglomeration, and an excessive increase in viscosity can also reduce cutting performance [20]. Despite the increasing interest in eco-friendly cutting fluids and nano-additive technologies, prior studies have predominantly focused on either the independent use of vegetable oils or the application of nanoparticles-enhanced fluids in isolation. To date, limited attention has been paid to the synergistic effects of integrating canola oil, a biodegradable lubricant with excellent lubricity, with h-BN nanoparticles, particularly within the MQL method for CNC milling operations. This study aims to bridge this gap by investigating the unexplored synergy between biodegradable canola oil and thermally conductive h-BN nanoparticles in CNC milling operations using the MQL method. Furthermore, the influence of varying concentrations of h-BN on the thermophysical–tribological interplay of nano-cutting fluids under dynamic machining conditions remains underexplored.

Therefore, this study proposes a novel nano-cutting fluids formulation consisting of canola oil infused with h-BN nanoparticles at 0.1, 0.15 and 0.2 wt%, and systematically evaluates its performance in CNC milling utilizing the MQL method. The evaluation focuses on thermophysical behaviour (density, viscosity, and thermal conductivity), rheological properties, and tribological effectiveness (cutting temperature, tool wear, and surface roughness). The objective is to determine the optimal formulation that achieves enhanced tribological performance while supporting sustainable machining practices. By establishing a direct correlation between nanoparticle concentration and fluid performance, this study contributes to both academic knowledge and practical implementation of green nano-cutting fluids in precision manufacturing.

While this study promotes sustainability through the development of vegetable oil-based nano-cutting fluids utilizing the MQL method, it is important to acknowledge that the use of nanoparticle additives may also pose potential risks related to occupational exposure, aerosol generation, and waste disposal [22]. Although these concerns are beyond the primary scope of this study, future research is encouraged to address such safety considerations to ensure that the continued advancement of nano-cutting fluids remains aligned with sustainable machining practices and the objectives of SDG 12 on responsible consumption and production.

2. Methodology

2.1 Materials for Nano-Cutting Fluids

Canola oil obtained commercially under the Tropicana Slim brand and containing 100% pure refined canola oil without added synthetic compounds, preservatives, or emulsifiers was employed as the base fluid for nano-cutting fluid formulation in this study. In this formulation, the base fluid was enhanced with h-BN nanoparticles at varying concentrations of 0.1, 0.15 and 0.2 wt%. The physical properties of both the base fluid and nanoparticle additives are presented in Tables 1 and 2.

Table 1
Properties of canola oil [23–25]

Physical properties	Value
Density (kg/m^3)	933.25
Dynamic viscosity at 40 °C (mPa.s)	38.25
Dynamic viscosity at 100 °C (mPa.s)	16.25
Thermal conductivity (W/m.K)	0.160
Smoke point (°C)	220–230
Flash point (°C)	275–290
Acid value (mg KOH/g)	0.48
Refraction index (n D^{40})	Max 0.3

Table 2
Properties of h-BN nanoparticles [26,27]

Properties	Value
Color	White
Density (kg/m^3)	2200–2290
Specific surface area (m^2/g)	35.8–43.6

2.2 Characterization Techniques Applied to h-BN Nanoparticles

Figure 1 presents the stage of h-BN nanoparticles characterization. The characterization of h-BN nanoparticles was conducted to confirm their suitability as an additive for nano-cutting fluids formulation. The surface morphology and particle shape were analyzed using Scanning Electron Microscopy (SEM) [28]. To identify the crystal structure and estimate crystallite size, X-Ray Diffraction (XRD) analysis was conducted [25]. Additionally, the functional groups included in the h-BN nanoparticles were identified using Fourier Transform Infrared (FTIR) [28,29]. This multi-technique characterization ensures the structural integrity and purity of the h-BN particles, mitigating the risk of contamination during nano-cutting fluid preparation [29].

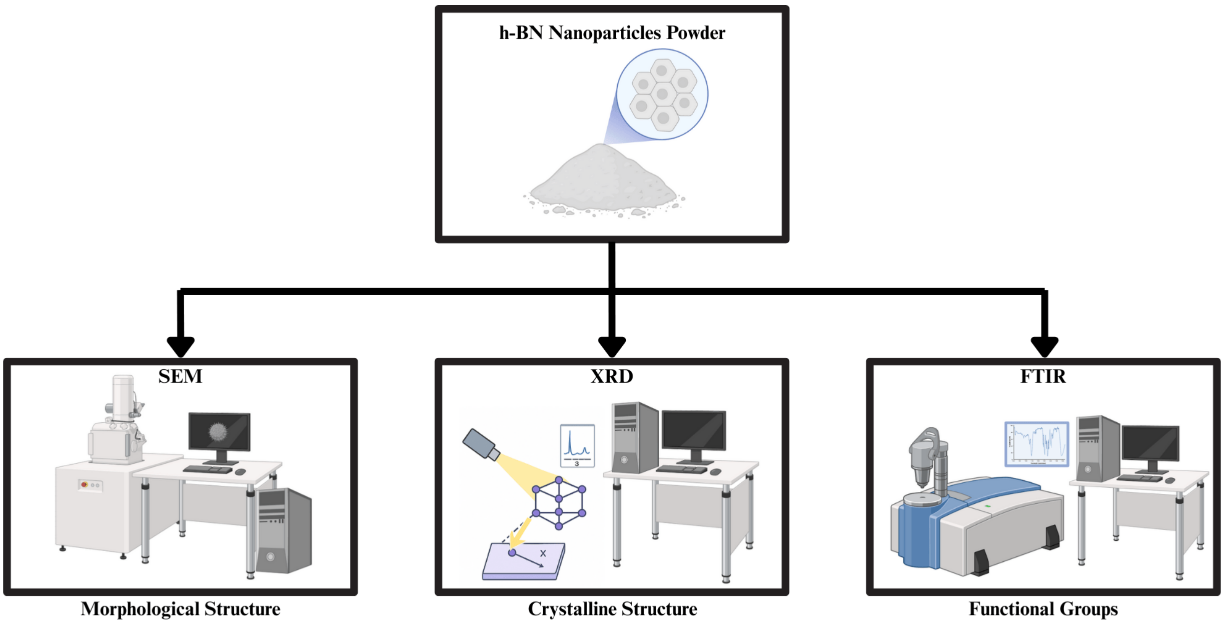

Fig. 1. Characterization of h-BN nanoparticles

2.3 Preparation of Nano-Cutting Fluids

The two-step synthesis method was selected due to its operational simplicity and proven effectiveness in achieving stable nanoparticle dispersion in base fluids [27,30]. The nano-cutting fluids preparation involved several stages to ensure the stable and homogeneous dispersion of h-BN nanoparticles within canola oil, as depicted in Figure 2. The nano-cutting fluids were prepared by dispersing h-BN nanoparticles into canola oil at 0.1, 0.15 and 0.2 wt%. The mixture was initially stirred at 1250 rpm and 15 °C to achieve preliminary homogenization. It was followed by 30 minutes of ultrasonication using an ultrasonic homogenizer to break down agglomerates and ensure stable dispersion [31–33]. After achieving homogeneity, the nano-cutting fluids were stored in a sealed container to prevent contamination and maintain their properties before testing in the MQL method during the milling process.

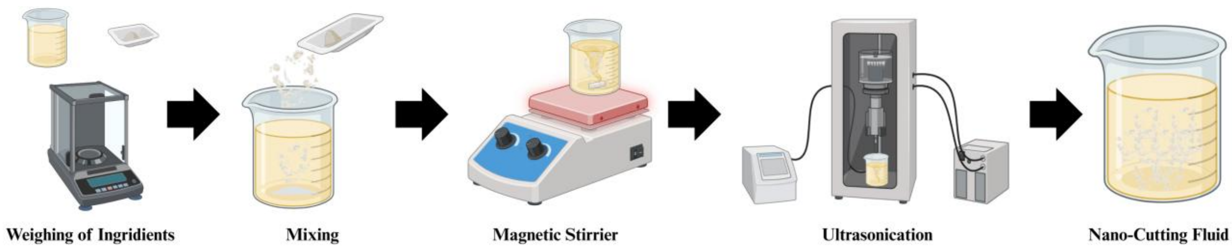

Fig. 2. Stages of sample preparation nano-cutting fluid using a two-step method

2.4 CNC Milling Setup

The effectiveness of nano-cutting fluids was systematically assessed through the MQL method. To provide a thorough evaluation, the nano-cutting fluids performance was evaluated by comparing it to dry cutting, Dromus, and pure canola oil. Dromus is a commercially available synthetic, water-based cutting fluid widely applied in industrial machining operations. In this study, it was employed as a baseline lubricant due to its stable emulsion characteristics, reliable thermal behaviour, and consistent lubricating performance under wet cutting conditions, making it a suitable reference point for evaluating alternative cutting fluids. Its established industrial use supports its relevance as a practical benchmark for assessing the relative performance of the developed nano-cutting fluid. Figure 3 illustrates the MQL method setup used in the CNC milling process, highlighting all relevant components and materials involved.

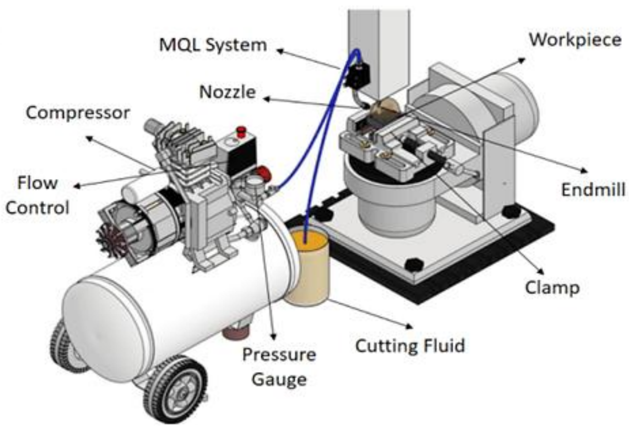

Fig. 3. Schematic of the setup in CNC milling using the MQL method [25]

AISI 1045 medium carbon steel was selected as the test specimen in the nano-cutting fluids test. This material is widely used in the manufacturing industry and possesses good machinability, high mechanical strength, good plasticity and toughness, and abundant availability [25,34]. The mechanical properties of AISI 1045 are shown in Table 3. Figure 4 illustrates the dimensions of the AISI 1045 specimens used in this study.

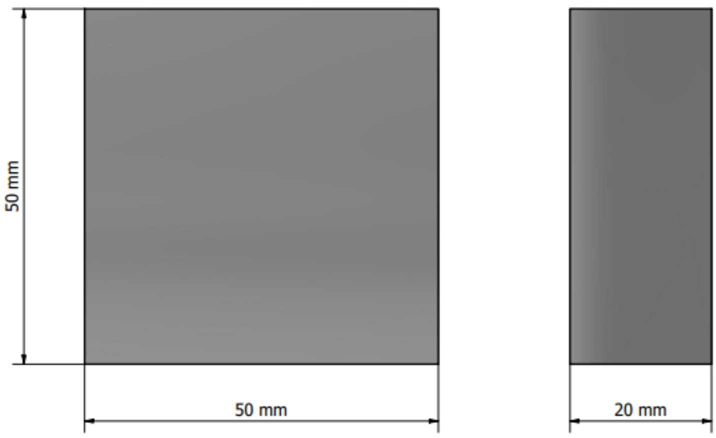

Fig. 4. Dimension of AISI 1045 specimen

High-speed steel (HSS) was selected as the cutting tool material due to its well-established combination of strength, toughness, and wear resistance, as well as its ability to retain hardness at elevated temperatures generated during machining [35]. An HSS endmill was used in this study, with its geometric specifications detailed in Table 4.

Table 3
Mechanical properties of AISI 1045 [25]

Mechanical properties	Value
Machinability (%)	55
Shear modulus (GPa)	80
Yield strength (MPa)	343
Ultimate tensile strength (MPa)	569
Modulus of elasticity (GPa)	205
Elongation (%)	20

Table 4
Specification of endmill HSS

Diameter	Value
Cutter diameter (mm)	8
Shank diameter (mm)	8
Cutting edge length (mm)	20
Overall cutting length (mm)	60
Number of flutes	4
Cutter diameter (mm)	8

2.5 Machining Parameters

CNC milling experiments were conducted under standardized cutting conditions utilizing the MQL method to ensure consistency and comparability across all lubrication scenarios, including dry cutting, Dromus, pure canola oil, and nano-cutting fluids. The milling parameters applied in this study are presented in Table 5, detailing the operational settings, including milling type, tool specifications, cutting conditions, and MQL configuration. The selection of MQL parameters, such as nozzle distance, nozzle angle, and pressure, was informed by established configurations reported in prior studies on vegetable oil-based cutting fluids and nanoparticle-enhanced formulations, ensuring both experimental reliability and relevance to sustainable machining practices.

Table 5
Milling parameters [25,36,37]

Milling parameter	Parameter setting
Machining operation	Face milling
Feed rate (mm/min)	0.12
Depth of cut (mm)	1.5
Spindle speed (rpm)	0.12
Cutting speed (m/min)	110
Cutting conditions	MQL
MQL nozzle distance (mm)	20
MQL nozzle angle (^{o})	45
MQL pressure (Bar)	4

2.6 Experimental Design and Test Conditions

The experimental design comprised multiple lubrication conditions to systematically evaluate the tribological performance of CNC milling under the MQL method. This setup enabled accurate comparisons among dry cutting, Dromus, pure canola oil, and nano-cutting fluids with varying h-BN concentrations. Details of the test conditions are provided in Table 6.

Table 6
Experimental design

Exp. no	Cutting fluid	Nanoparticles concentration (wt%)	Cutting condition
1.	Dry cutting	-	Dry
2.	Dromus	0	Dromus MQL
3.	Pure canola	0	Pure canola MQL
4.	Pure canola + h-BN	0.1	Nano-cutting fluid MQL
5.	Pure canola + h-BN	0.15	Nano-cutting fluid MQL
6.	Pure canola + h-BN	0.2	Nano-cutting fluid MQL

3. Results
3.1 Analysis of h-BN Nanoparticles Characteristics
3.1.1 Morphological analysis

The morphological structures observed were surface morphology and grain shape. The SEM results of h-BN nanoparticles form a lamellar structure with non-uniform size between particles, a similar phenomenon also occurred in previous studies [38]. The h-BN nanoparticles also experience agglomeration, which can be seen in Figure 5. Agglomeration between particles occurs due to Van Der Waals forces [27]. Agglomeration of h-BN nanoparticles can affect the dispersion of particles in canola oil. The preparation process involves magnetic stirring and ultrasonication techniques, which actively minimize nanoparticle agglomeration and promote homogeneous dispersion throughout the canola oil medium [25]. Uniform h-BN nanoparticles in canola oil aim to confirm the effectiveness of the nano-cutting fluids to create rolling effects during the machining process [21].

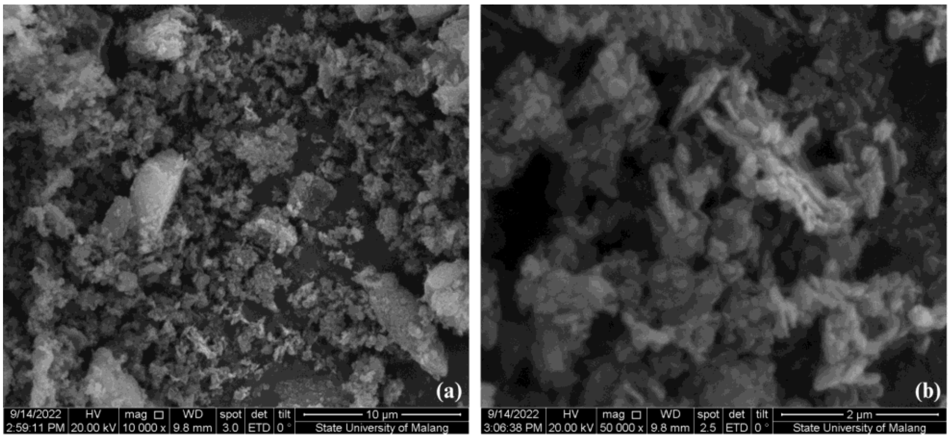

Fig. 5. h-BN nanoparticles morphology in (a) 10,000X and (b) 50,000X magnifications

3.1.2 Crystallographic structure

XRD was conducted to identify the crystal structure and estimate the average crystallite size of the h-BN nanoparticles. Based on Figure 6, the highest intensity peak at diffractogram 4579.36 has an angle position 2θ = 26.65° with Miller index value 002. Diffractograms with lower reflections were also observed and occurred at 2θ angles of 41.65°, 43.82°, 50.13°, 55.05°, and 75.94° with Miller index values of 100, 101, 102, 004, and 110, respectively. The XRD results may indicate h-BN nanoparticles in a high degree of purity in their crystalline structure [39–41]. Furthermore, based on the highest intensity peak by the Scherrer equation, the average crystallite size is estimated to be approximately 15.2 nm [41].

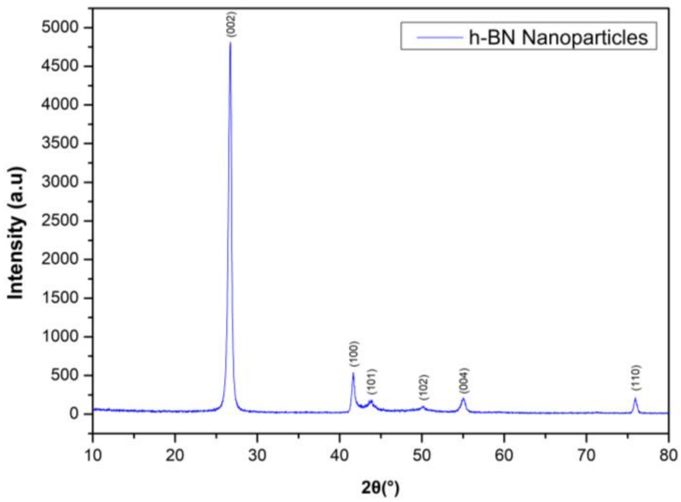

Fig. 6. XRD graph of h-BN nanoparticles

3.1.3 Functional group identification

The functional groups in the h-BN nanoparticles were determined using FTIR. The absorption peaks observed at 1276.88 cm^{-1} and 817.82 cm^{-1} correspond to B-N stretching and bending vibrations, respectively [42,43]. An additional peak at 2796.78 cm^{-1} is associated with O-H and N-H stretching, likely resulting from interactions with ambient moisture during the fabrication process [26]. The observed FTIR spectra provide conclusive evidence of the functional groups typical of h-BN, confirming the nanoparticle chemical identity.

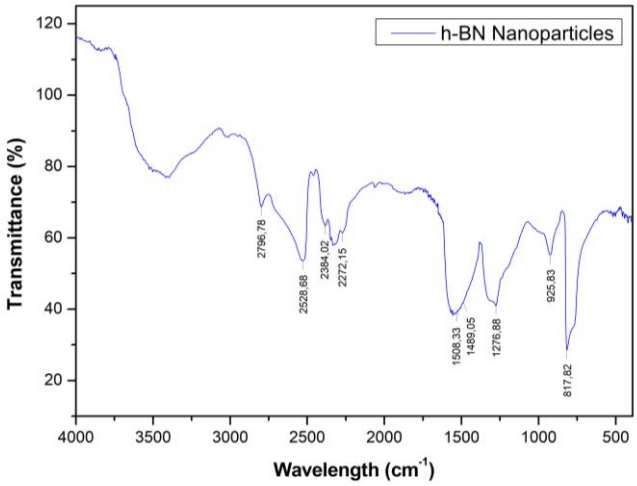

Fig. 7. FTIR graph of h-BN nanoparticles

3.2 Thermophysical Properties of Nano-Cutting Fluids
3.2.1 Density

As shown in Figure 8, the density of the nano-cutting fluids increased proportionally with the h-BN nanoparticles concentration, ranging from 933.25 kg/m^3 at pure canola oil to 939.42 kg/m^3 at 0.2 wt% h-BN nanoparticles. This increase is attributed to the higher intrinsic density of h-BN compared to the base fluid, resulting in a larger overall mass in a constant fluid volume. Elevated fluid density may enhance hydrostatic pressure and contribute to improved lubricant penetration into the cutting zone [44]. The density test results indicate that the increase in nanoparticle concentration is directly proportional to the increase in the density of the cutting fluid sample [45]. Adding h-BN nanoparticles to canola oil produces a nano-cutting fluid with a higher density than pure canola oil because the higher density of h-BN nanoparticles influences it. The rise in density improves hydrostatic pressure within the cutting zone, thereby enhancing the flow of nano-cutting fluids and upgrading the efficiency of the cutting process [25].

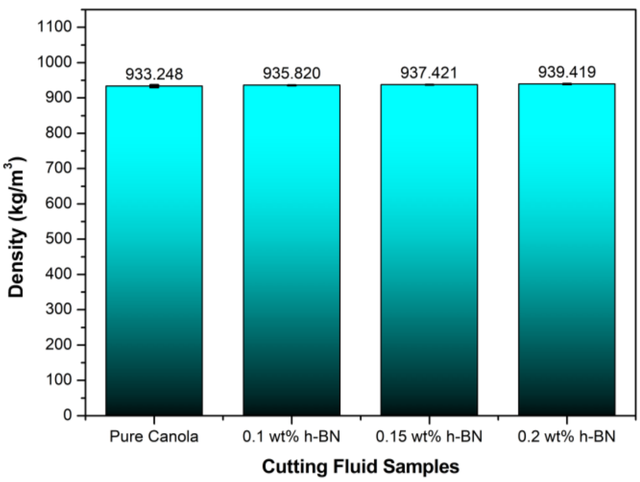

Fig. 8. Density of nano-cutting fluids sample

3.2.2 Viscosity

According to the dynamic viscosity test results presented in Figure 9, the nano-cutting fluids have increased in dynamic viscosity value as the concentration of h-BN nanoparticles increased at each temperature. The increase in viscosity is due to the higher concentration of h-BN nanoparticles in the cutting fluid sample [46]. The increased temperature during the testing process decreases the dynamic viscosity value due to the weakening of the Van der Waals force with the increase in temperature [47]. According to previous studies, viscosity can influenced by several factors, such as shear rate, nanoparticle concentration, size, shape, and temperature [47]. The relationship between dynamic viscosity, temperature variation, and the increase in h-BN nanoparticle concentration indicates the dispersion stability in canola oil. Nonetheless, at higher concentrations, the risk of nanoparticles agglomeration may increase due to intensified interparticle attractions, particularly van der Waals forces, which could interfere with homogeneous dispersion [5]. This agglomeration leads to the formation of nanoparticle clusters that limit fluid mobility, disrupt the lubrication film, and potentially increase friction during the cutting process [27,48].

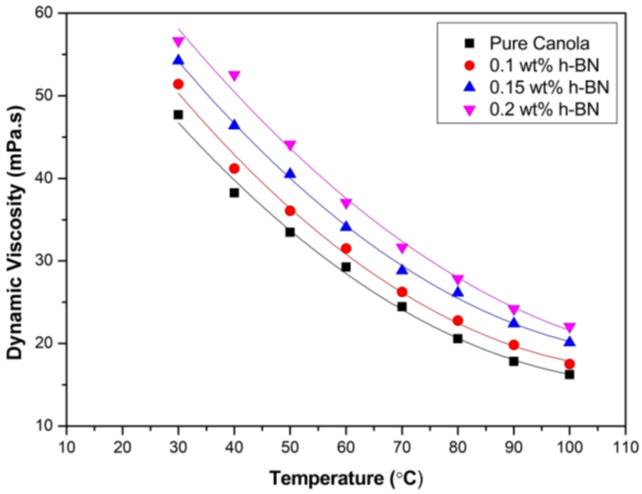

Fig. 9. Dynamic viscosity of nano-cutting fluids sample

3.2.3 Thermal conductivity

According to the thermal conductivity test results presented in Figure 10, the highest thermal conductivity value was observed in the nano-cutting fluids + 0.15 wt% h-BN sample at 0.169 W/m.K. The lowest thermal conductivity value observed in the canola oil sample without h-BN nanoparticles was 0.160 W/m.K. Overall, no significant variation in thermal conductivity was observed, indicating that the slight increase in h-BN nanoparticles concentration contributed minimally to heat transfer enhancement. Ideally, thermal conductivity increases as the concentration of h-BN nanoparticles in canola oil increases [49]. However, the thermal conductivity of the 0.2 wt% h-BN sample decreased, as excessive nanoparticle loading can diminish the Brownian motion effect of h-BN nanoparticles in the base fluid [25]. Furthermore, thermal conductivity is affected by factors such as preparation techniques [50]. Therefore, both the concentration of h-BN nanoparticles and the preparation technique in canola oil should be carefully considered, as they affect thermal conductivity outcomes.

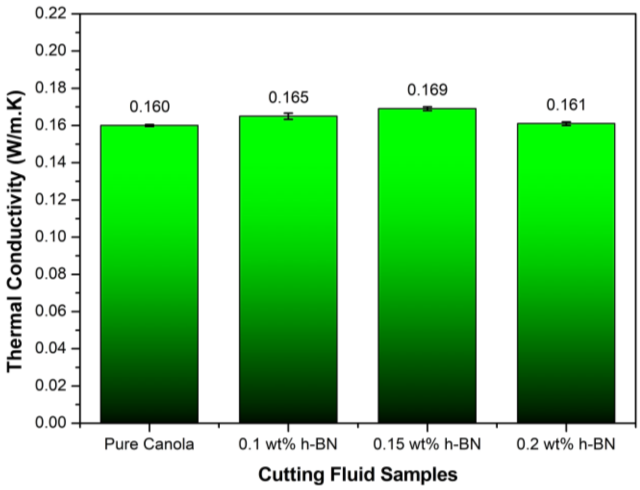

Fig. 10. Thermal conductivity of nano-cutting fluids sample

3.3 Rheological Properties of Nano-Cutting Fluids

The relationship between the shear rate and shear stress of the nano-cutting fluids was measured to assess the rheological characteristics. Equation 1 was employed to calculate the shear rate value. Figure 11 shows the results of the correlation between shear rate and shear stress in the nano-cutting fluids evaluated at 40°C and 100°C.

$$\gamma = \frac{2\,\omega\,R_{c^2}\,R_{b^2}}{x^2\,(R_{c^2}\,R_{b^2})} \tag{1}$$

Description:
γ = Shear Rate (/s)
ω = Shaft Angular Velocity (rad/sec)
R_c = Radius of the Vessel (cm)
R_b = Spindle Shaft Radius (cm)
x = Shear Rate Radius (cm)

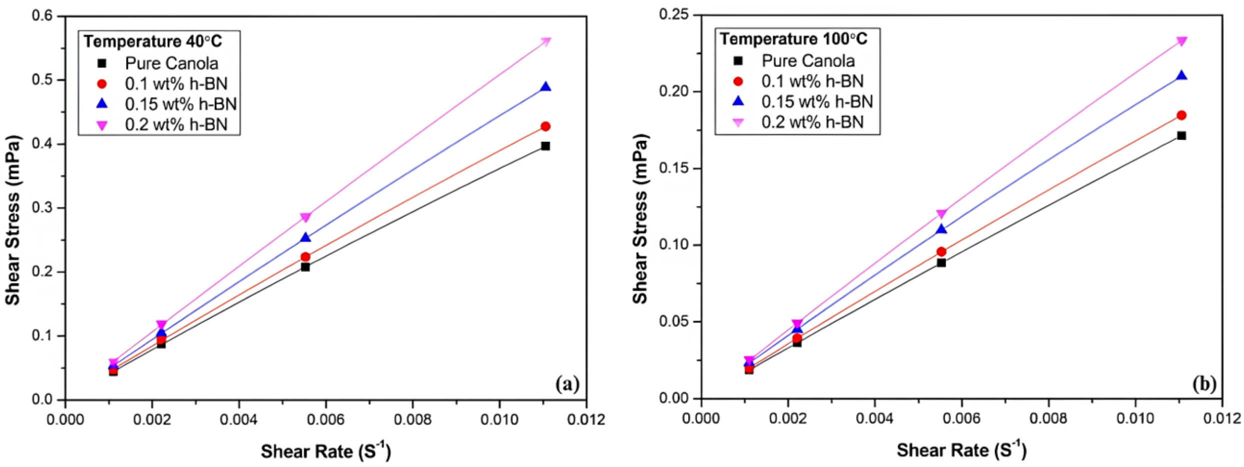

Fig. 11. Rheological properties of the nano-cutting fluids at (a) 40°C and (b) 100°C

According to the rheological test results presented in Figure 11, the cutting fluid sample with 0.2 wt% h-BN nanoparticles exhibited the highest shear stress values at both 40 °C and 100 °C. However, the results also show a decrease in shear stress at elevated temperatures, which is attributed to the weakening of Van der Waals forces [47]. Additionally, the rheological analysis reveals a direct linear correlation between shear stress and shear rate in the nano-cutting fluids. As the shear stress increases, there is a corresponding rise in the shear rate, indicating a proportional relationship between the two variables. The linear relationship can mean that all cutting fluid samples have Newtonian fluid flow behavior [44,45]. Newtonian flow behavior is crucial, especially in convection heat transfer [25]. The Newtonian flow behavior of all cutting fluids shows that the viscosity does not change significantly with shear rate variation, so the cutting fluid can consistently maintain its flow characteristics during the cutting process [46,47].

3.4 Tribological Performance of Nano-Cutting Fluids
3.4.1 Cutting temperature

In this study, the heat dissipation capability of the cutting fluid samples applied via the MQL method is assessed by measuring the cutting temperature in the cutting zone. Elevated temperatures in the cutting zone can accelerate tool wear and reduce surface quality during machining [51]. Therefore, monitoring the temperature during the cutting process is essential to assess how effectively each cutting fluid maintains thermal stability. The measurement scheme is shown in Figure 12. The cutting temperature results are shown in Figure 13.

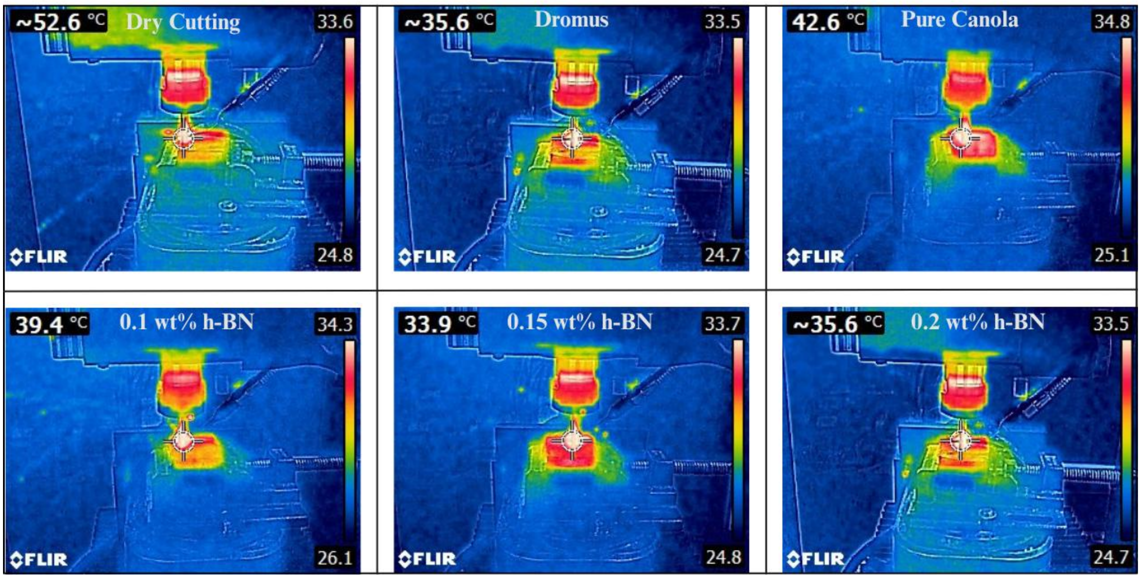

Fig. 12. Schematic of cutting temperature measurement

As shown in Figure 15, dry cutting conditions produced the highest temperature of 56.88 °C. The use of Dromus resulted in a cutting temperature value of 37.08 °C. Pure canola oil showed a temperature of 42.77 °C. The addition of h-BN nanoparticles to canola oil yielded varying temperature results, with the 0.15 wt% h-BN formulation recording the lowest temperature of 35.43 °C, followed by 0.2 wt% at 36.73 °C and 0.1 wt% at 39.22 °C.

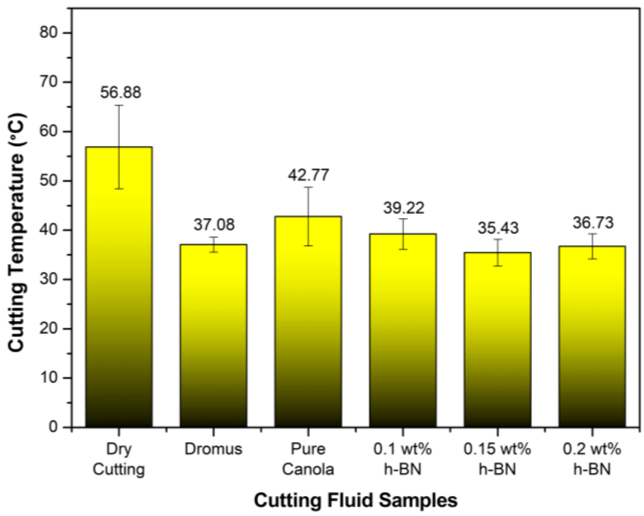

Fig. 13. Cutting temperature measurement

These results indicate that the 0.15 wt% h-BN formulation provided the most efficient cooling, which aligns with its highest measured thermal conductivity among all the samples tested, as shown in Figure 10. High thermal conductivity accelerates heat dissipation, minimizing the thermal stress that can degrade the tools and workpiece [33]. High viscosity also promotes a more uniform distribution of the cutting fluid under MQL conditions, contributing to the formation of an effective thermal protective layer. However, this effect must be complemented by a sufficiently high thermal conductivity to enhance heat dissipation [33]. Furthermore, the dispersed nanoparticles form a thin film at the cutting interface, acting as rolling elements that reduce friction and contribute to smoother machining [52].

3.4.2 Tool wear

Tool wear is one of the key factors impacting tool life, workpiece surface quality, and overall production cost-effectiveness [25,53]. Along with cutting time and mechanical load, the tool surface undergoes degradation due to high temperatures, friction, and direct contact with the workpiece. Excessive wear contributes to poor dimensional accuracy and accelerated tool failure [54–56]. The tool wear measurement scheme is illustrated in Figure 14.

Based on the test results shown in Figure 15, dry cutting conditions produced the highest wear rate of 0.222 mm^2. The use of Dromus produced a wear value of 0.163 mm^2. Meanwhile, pure canola oil showed a wear of 0.132 mm^2, lower than Dromus. The addition of h-BN nanoparticles to canola oil led to varying wear outcomes, with no drastic deviations observed. Nano-cutting fluids with a 0.15 wt% h-BN recorded the lowest wear of 0.120 mm^2, followed by 0.2 wt% h-BN at 0.124 mm^2, and 0.1 wt% h-BN at 0.127 mm^2.

The improved wear performance observed in nano-cutting fluids is primarily attributed to the tribological enhancement mechanisms induced by h-BN nanoparticles. Under the MQL method, these nanoparticles facilitate the formation of a tribofilm that minimizes metal-to-metal contact and abrasive interactions, thereby reducing wear [7,51,57,58]. In addition to tribological mechanisms, thermal conductivity also plays a vital role. The nano-cutting fluid with 0.15 wt% h-BN exhibited the highest thermal conductivity, enabling more efficient heat dissipation and reducing the cutting zone temperature. This effective heat dissipation under the MQL method helps delay tool degradation and extend tool life [22]. These findings underscore the potential of h-BN-enhanced canola-based nano-cutting fluids applied via MQL to improve tool life while advancing sustainable machining practices.

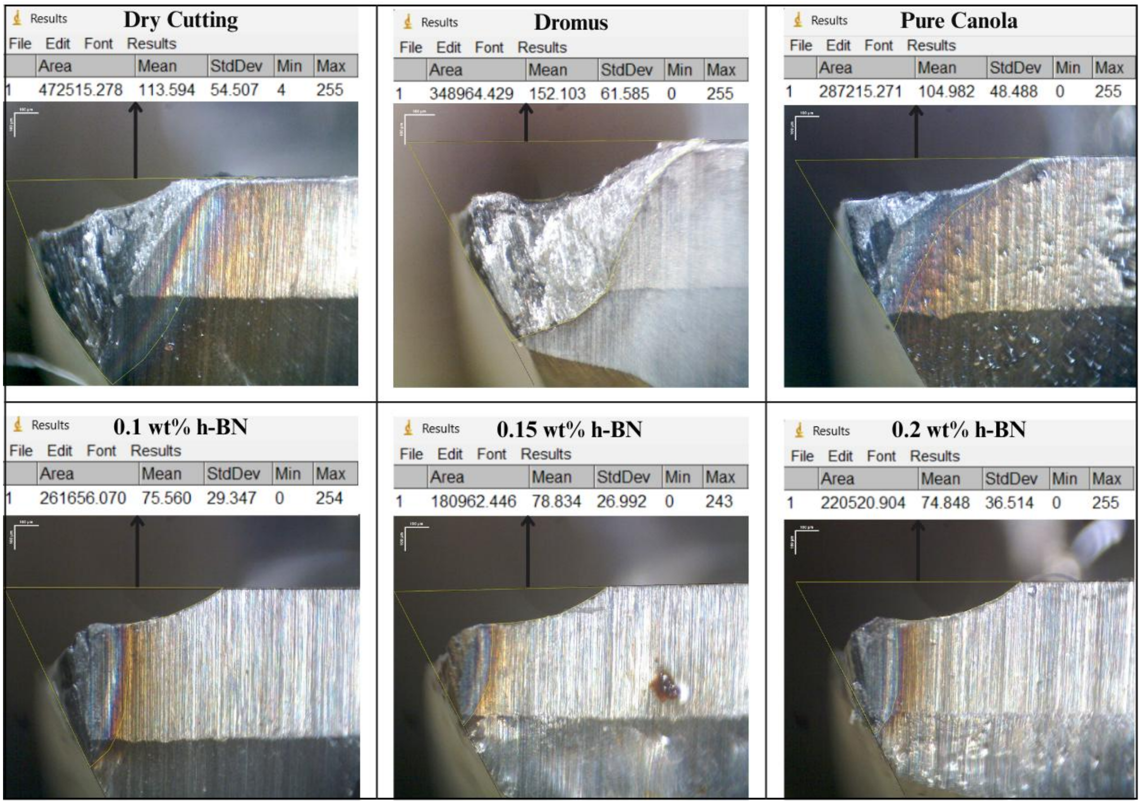

Fig. 14. Schematic of endmill tool wear measurement

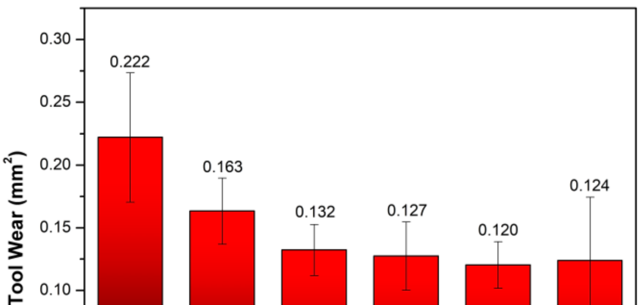

Fig. 15. Endmill tool wear measurement

3.4.3 Surface roughness

Surface roughness serves as a key indicator for evaluating the quality of machined components, particularly in precision-oriented industries where superior surface finish is critical. It is primarily governed by cutting temperature and tool wear, both of which are influenced by the performance of the applied cutting fluid [22,59]. The results obtained during the cutting process are illustrated in Figure 16. According to the test results, dry cutting produced the highest surface roughness of 2.18 µm. Dromus and pure canola oil obtained lower surface roughness values than dry cutting, at 1.88 µm and 1.44 µm, respectively. The application of canola oil-based nano-cutting fluids with h-BN nanoparticles led to the improved surface roughness, with the 0.15 wt% h-BN concentration recorded the lowest roughness of 0.86 µm, followed by 0.1 wt% h-BN at 1.11 µm, and 0.2 wt% h-BN at 1.14 µm.

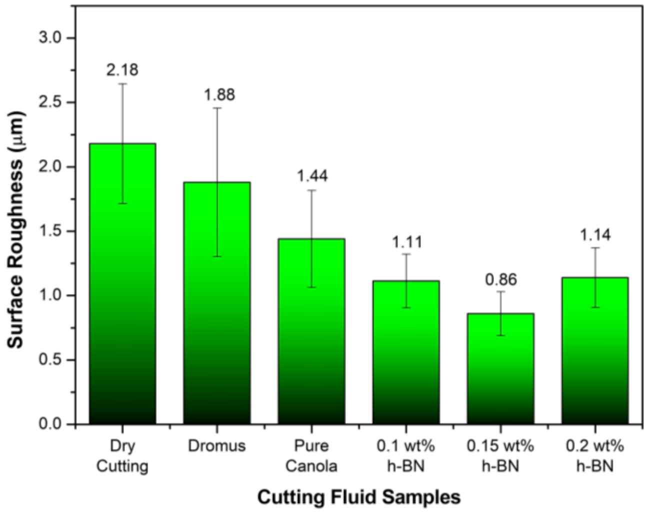

Fig. 16. Surface roughness measurement

These surface roughness results are inseparable from the complex relationship between tool wear, cutting temperature, and the thermophysical properties of the cutting fluid [60]. This mitigates excessive temperature rise that may lead to thermal deformation of the workpiece surface and degradation of surface quality. The higher thermal conductivity of the sample with 0.15 wt% h-BN accelerates the heat release from the cutting zone, thus preventing excessive temperature rise that can cause thermal deformation of the workpiece surface [33]. The tribological contribution of h-BN nanoparticles, through continuous tribofilm formation and the rolling effect, plays a vital role in reducing friction and minimizing micro-damage on the workpiece surface [51,58]. Additionally, an ideal viscosity aids in forming a stable lubricating film, maintaining separation between contact surfaces, and regulating friction during machining, which slows down tool wear and subsequently enhances surface finish [13].

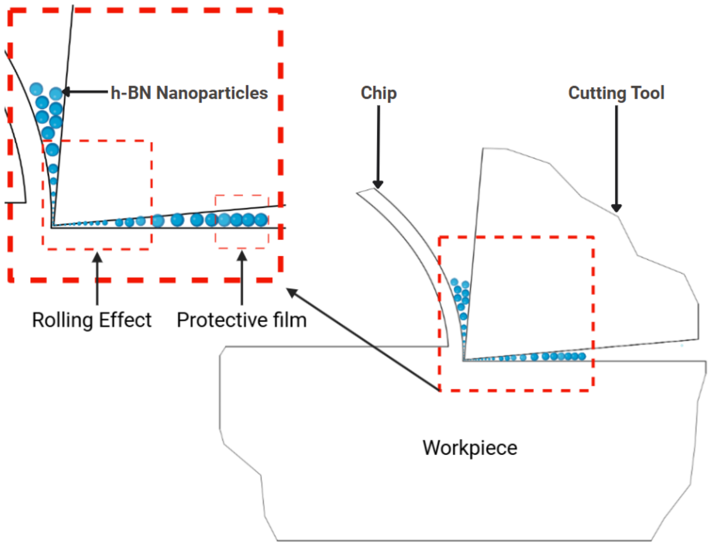

Fig. 17. Tribological mechanisms induced by h-BN nanoparticles

The synergistic tribological effect of h-BN is evident through both rolling and protective film mechanisms. The nanoparticles form a microscopic protective film between the tool and workpiece surfaces, acting as an additional lubrication medium that minimizes direct friction and prevents surface damage [7,51,57]. Conversely, in the 0.2 wt% h-BN nano-cutting fluid, excessive nanoparticle concentration may lead to agglomeration, triggering interparticle friction and localized stress concentrations that compromise the stability of the lubricant film [49]. These findings are further supported by the elevated roughness observed in dry cutting, where the absence of lubrication mechanisms exacerbates surface degradation [5]. An illustration of the rolling effect and protective film mechanism induced by the presence of nanoparticles is shown in Figure 17. The implementation of this lubrication mechanism contributes to the attainment of improved surface quality. These results demonstrate the superior potential of h-BN-enhanced nano-cutting fluids applied via the MQL method to significantly improve surface finish, thereby contributing to higher-quality and more sustainable machining practices.

4. Conclusions

The h-BN nanoparticles exhibited a lamellar morphology with an irregular size distribution, with an average crystallite thickness of approximately 15.2 nm. FTIR analysis confirmed the presence of B–N functional groups at 1276.88 cm^{-1} and 817.82 cm^{-1}, corresponding to stretching and bending vibrations, respectively. The thermophysical properties evaluated, such as density, thermal conductivity, and dynamic viscosity, showed that the nano-cutting fluids containing 0.2 wt% h-BN exhibited the highest density and viscosity, whereas the formulation with 0.15 wt% h-BN achieved superior thermal conductivity. The addition of excess h-BN nanoparticles, particularly in concentrations higher than 0.2 wt%, resulted in a decrease in thermal conductivity due to the disruption of Brownian motion. Moreover, viscosity increased with higher h-BN content but decreased with rising temperature. Rheological tests confirmed that all samples exhibited Newtonian flow behaviour, with viscosity increasing proportionally to the concentration of nanoparticles added.

The tribological performance results demonstrated that the nano-cutting fluids with 0.15 wt% h-BN outperformed other formulations, yielding the lowest cutting temperature of 35.90 °C, tool wear of 0.120 mm^2, and surface roughness of 0.86 µm. These findings highlight that the nano-cutting fluids containing 0.15 wt% h-BN provide the most effective tribological performance, enhancing machining efficiency and product quality by reducing wear and improving surface finish. This outcome underscores the ability of nanoparticle additives to significantly improve cutting fluid performance in precision machining.

While these advancements contribute to enhanced machining quality, the use of canola oil as the base fluid also promotes a more environmentally sustainable solution. This approach not only optimizes cutting performance but also aligns with the growing demand for eco-friendly alternatives in manufacturing processes. Given the increasing demand for high-precision, large-scale component production, these nano-cutting fluids offer high potential for application in automotive components, where extensive machining operations result in substantial consumption of cutting fluids. The ability to reduce fluid consumption while maintaining performance further supports SDG 12 concerning responsible consumption and production.

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