Journal Homepage: https://dergipark.org.tr/tr/pub/isibted

Isı Bilimi ve Tekniği Dergisi

Archive: https://tibtd.org.tr/dergi

Experimental Investigation of Effects of Nano-Fluid Usage on Cooling in Machining

Kemal BİLEN [1, *], Hakan Zafer KIZILKAYA [1, 2], Abdulmecit GÜLDAŞ [3]

[1] Ankara Yıldırım Beyazıt University, Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, 06100, Ankara, Türkiye
[2] Turkish Aerospace Incorporation, Ankara, Türkiye
[3] Gazi University, Faculty of Technology, Department of Manufacturing Engineering, 06100, Ankara, Türkiye

A R T I C L E   I N F O

2026, vol. 46, no.1, pp. 79-89
©2026 TIBTD Online.
doi: 10.47480/isibted.1757702

Research Article
Received: 04 August 2025
Accepted: 04 April 2026

* *Corresponding Author*
e-mail: kemal.bilen@aybu.edu.tr

Keywords:
Boron mineral oil–water mixture
Nano-fluid
Thermo-physical property
Surface roughness
Machining

ORCID Numbers in author order:
0000-0003-1775-7977
0000-0002-7842-241X
0000-0002-1865-2272

A B S T R A C T

Application of nano-fluids in machining is becoming increasingly common due to their convenient thermo-physical properties. Previous studies indicate that adding Al_2O_3, MWCNT or TiO_2 nano-particles into base fluids improves properties like density, viscosity, and thermal conductivity. This experimental study investigates the impact of addition of these nano-particles at concentrations of 0.5%, 1%, and 1.5% into a boron mineral oil–water mixture. This research was carried out in three stages: Nano-fluid preparation, determination of thermo-physical properties, and machining experiments on Ti-6Al-4V alloy. Results showed that increasing nano-particle concentration led to a consistent rise in fluid density at 24.5 °C. However, similar trends were not observed for dynamic viscosity and thermal conductivity, which began to decline beyond 1% concentration and this situation was attributed to precipitation and sedimentation showing fluid instability. Furthermore, the use of nano-fluids significantly marked down temperature at the tool–workpiece interface. For instance, usage of 0.5% MWCNT reduced interface temperature by approximately 18%, in °C unit, and improved surface finish by around 25%. Besides, higher concentrations resulted in increased interface temperature and surface roughness due to particle deposition. The study concluded that nano-fluids only with optimal concentrations improve machining performance, as with excessive amounts degrade the performance –a finding supported by SEM images of the cutting inserts.

Talaşlı İmalatta Nano-Akışkan Kullanımının Soğutmaya Etkilerinin Deneysel Olarak Araştırılması

M A K A L E   B İ L G İ S İ

Anahtar Kelimeler:
Bor mineral yağı–su karışımı
Nano-akışkan
Termofiziksel özelik
Yüzey pürüzlülüğü
Talaşlı imalat

Ö Z E T

Nano-akışkanların talaşlı imalatta kullanımı, elverişli termofiziksel özelikleri nedeniyle giderek yaygınlaşmaktadır. Önceki çalışmalar; Al_2O_3, MWCNT veya TiO_2 nano-parçacıklarının, baz akışkanlara eklenmesinin; yoğunluk, viskozite ve ısıl iletkenlik gibi özelikleri iyileştirdiğini göstermektedir. Bu deneysel çalışma; bahse konu nano-parçacıkların %0.5, %1 ve %1.5 derişikliklerinde bor mineral yağı–su karışımına eklenmesinin etkisini araştırmaktadır. Bu araştırma, üç aşamada gerçekleştirilmiştir: Nano-akışkan hazırlama, termofiziksel özeliklerin belirlenmesi ve Ti-6Al-4V alaşımı üzerinde talaşlı imalat deneyleri. Sonuçlar; nano-parçacık konsantrasyonunun artmasının, 24.5 °C'da akışkan yoğunluğunda tutarlı bir artışa yol açtığını göstermiştir. Bununla birlikte, dinamik viskozite ve ısıl iletkenlikte benzer eğilimler gözlenmemiştir; bu değerler, %1'lik konsantrasyondan sonra düşmeye başlamış ve bu durum, akışkanın kararsızlığını gösteren çökelme ve tortulaşmaya bağlanmıştır. Ayrıca; nano-akışkanların kullanımı, kesici takım-iş parçası ara-yüzündeki sıcaklığı önemli ölçüde düşürmüştür. Örneğin; %0.5'lik bir MWCNT kullanımı, ara-yüzdeki sıcaklığı, °C biriminde yaklaşık %18 oranında azaltmış, yüzey kalitesini ise yaklaşık %25 oranında iyileştirmiştir. Buna karşılık; daha yüksek konsantrasyonlar, parçacık birikmesi nedeniyle ara-yüzdeki sıcaklığın ve yüzey pürüzlülüğünün artmasına neden olmuştur. Çalışma; yalnızca optimum derişikliğe sahip nano-akışkanların, talaşlı imalat performansını artırdığı, aşırı miktardakilerin ise performansı düşürdüğüyle sonuçlanmıştır –bu bulgu; kesici uçların, SEM görüntüleriyle de desteklenmektedir.

NOMENCLATURE

a_p	Depth of cut (mm)	p	Pressure (Pa)
ε	Emissivity (–)	q	Heat transfer rate (W)
f	Feed rate (mm/rev)	$\dot{Q}$	Volumetric flow rate (mL/h)
φ	Volume fraction of nano-particle (vol.%)	Ra	Surface roughness (μm)
Ø	Diameter (mm)	ρ	Density (g/cm^3)
k	Thermal conductivity (W/(m·K))	t	Time (s) *or* (min)
l	Nozzle distance from tool rake face (mm)	T	Temperature (°C) *or* (K)
μ	Dynamic viscosity (mPa·s) *or* (cP)	V_c	Cutting speed (m/min)

ABBREVIATIONS

Al_2O_3	Aluminum dioxide *or* dialuminum trioxide	HRC	Hardness Rockwell C-scale
BR	Base fluid ratio	LN_2	Liquefied nitrogen
BUE	Built-up edge	MoS_2	Molybdenum disulfide
CaF_2	Calcium fluoride	MQL	Minimum quantity lubrication
CNC	Computer numerical control	MWCNT	Multi-walled carbon nanotube
CNT	Carbon nanotube	MWCNTs	Multi-walled carbon nanotubes
CNTs	Carbon nanotubes	NC	Numerical control
CO_2	Carbon dioxide	NR	Nano-particle ratio
Cu	Copper	SEM	Scanning electron microscope
FPS	Fluid property sensor	SiO_2	Silicon dioxide
hBN	Hexagonal boron nitride	TiO_2	Titanium dioxide

INTRODUCTION

Cooling and lubrication play a crucial role in machining processes by reducing temperature at the tool–workpiece interface, minimizing friction, facilitating chip evacuation, preventing built-up edge (BUE) formation, lowering power consumption, and extending tool life. Since introducing of cooling strategies in the mid of the 19th century, they have evolved in parallel with increasing demands on machining performance, particularly for hard-to-machine materials (Groover, 2010). Recent studies emphasize the tribological aspects of machining, as friction, wear, and lubrication conditions directly influence tool wear, surface integrity, stress distribution, and overall process efficiency.

In aerospace manufacturing, materials such as aluminum alloys, steels, nickel-based superalloys, and titanium alloys require advanced cooling strategies due to their high strength, hardness, and poor machinability. Among these materials, Ti-6Al-4V is widely used because of its high strength-to-weight ratio and corrosion resistance although its machining is challenging due to severe tool–material interactions, especially at hardness levels exceeding 45 hardness Rockwell C-scale (HRC). Optimizing cutting parameters and minimizing thermal and mechanical loads in the cutting zone are therefore essential to control tool wear and improve productivity (Davim, 2011).

Cutting fluids are widely used to control friction-induced heat, improve surface finish, and extend tool life. Despite their effectiveness in lubrication and heat dissipation, conventional cutting fluids raise environmental and health concerns (Najiha et al., 2016). Consequently, alternative cooling and lubrication strategies have gained increasing attention. Conventional flood cooling systems typically rely on water-based emulsions, whereas minimum quantity lubrication (MQL) systems deliver a small amount of lubricant mixed with compressed air directly to the cutting zone, significantly reducing fluid consumption while maintaining effective cooling and lubrication (Shashidhara and Jayaram, 2010; Shokrani et al., 2012; Deshpande and Deshpande, 2019).

Cryogenic cooling techniques employing liquefied gases, such as liquefied nitrogen (LN_2) and carbon dioxide (CO_2), provide a highly effective means of heat removal by enabling extremely low cutting temperatures in machining processes. These methods are particularly advantageous in high-speed and difficult-to-machine applications, as they suppress excessive thermal loads in the cutting zone, thereby mitigating tool wear and preserving workpiece integrity. By rapidly extracting heat from the tool–workpiece interface, cryogenic cooling contributes to improved dimensional accuracy, reduced thermal distortion, and extended tool life when compared to the conventional cooling strategies (Krishna and Rao, 2008; Shen et al., 2008; Prabhu and Vinayagam, 2010; Sarhan et al., 2012; ManojKumar and Ghosh, 2016; Sharma et al., 2016a; Sharma et al., 2016b; Uysal, 2017; Li et al., 2018; Jamil et al., 2019).

In parallel with cryogenic approaches, advanced cooling and lubrication techniques based on nano-technology have attracted significant research interest. Nano-lubricants, produced by dispersing nano-particles such as aluminum dioxide (Al_2O_3), titanium dioxide (TiO_2), silicon dioxide (SiO_2), molybdenum disulfide (MoS_2), hexagonal boron nitride (hBN), graphene, and carbon nanotubes (CNTs) into base oils, demonstrate enhanced thermal conductivity and superior tribological performance. Extensive experimental investigations have reported that the use of nano-fluids leads to substantial reductions in cutting forces, cutting zone temperature, tool wear, and surface roughness (Ra) in turning, milling, and grinding operations. These benefits have been consistently observed across a wide range of engineering materials including steels, aluminum alloys, titanium alloys, and nickel-based superalloys highlighting the broad applicability and effectiveness of nano-fluid-assisted machining (Park et al., 2011; Vasu and Reddy, 2011; Rahmati et al., 2014; Sayuti et al., 2014; Choudhary et al., 2018; Nam et al., 2018; Rapeti et al., 2018; Bakalova and Svobodová, 2019; Gajrani et al., 2019; Peña-Parás et al., 2019; Rahman et al., 2019; Şirin and Kıvak, 2019; Yıldırım, 2019; Yıldırım et al., 2019; Kulkarni et al., 2020; Sen et al., 2020; Peña-Parás et al., 2021).

Uysal (Uysal, 2017) conducted an experimental study using graphene nano-particles with Eraoil KT/2000 commercial vegetable oil in milling application with AISI 430 material and as a result, the surface characteristics were improved. Li et al. (Li et al., 2018) performed an experimental study including graphene nano-particles added to vegetable oil in various volumetric ratios with MQL method and experiments were carried out on titanium alloy TC4 (Ti-6Al-4V) in milling operations. As a result of the study, the cutting force was reduced. Jamil et al. (Jamil et al., 2019) experimentally carried out a study using hybrid nano-particles of Al_2O_3 and CNTs. In the study, cryogenic cooling with CO_2 and MQL-based hybrid nano-fluids were compared in turning operations with TC4 material. In the study, also, two different sustainable cooling or lubrication techniques were compared, and it was detected that hybrid nano-fluids were better in terms of average surface roughness, cutting force, and tool life. Yıldırım et al. (Yıldırım et al., 2019) performed an experimental study using hBN nano-particles in ester-based cutting oil. As a result of the study, high tool life, low tool wear, and roughness in the turning process on Ni-based inconel 625 material were achieved by using this nano-fluid.

In a study conducted by Park et al. (Park et al., 2011), graphene sheet nano-particles were added into vegetable oil at various volumetric ratios, and the resulting nano-fluids were employed in the milling of Ti-6Al-4V alloy using the MQL method. The findings revealed a reduction in both flank and central wear at the tool tip, along with improved thermal conductivity due to the addition of graphene nano-particles. Şirin and Kıvak (Şirin and Kıvak, 2019) conducted a similar investigation in which graphene nano-particles were dispersed in a vegetable oil-based fluid and used in milling operations on AISI 1040 steel under MQL condition. The study reported reductions in cutting force and friction at the tool–workpiece interface, along with enhancements in surface quality. Rahman et al. (Rahman et al., 2019) employed nano-fluids composed of Al_2O_3 nano-particles suspended in a vegetable oil base for turning operations on Ti-6Al-4V using MQL method. The results demonstrated notable improvements in surface roughness and reductions in cutting zone temperature. Sayuti et al. (Sayuti et al., 2014) conducted a study utilizing nano-fluids composed of Fuchs Ecocut SSN 322 mineral oil and SiO_2 nano-particles during the milling of Al6061-T6 alloy with MQL technique. The findings demonstrated significant improvements in both tool wear and cutting force parameters. In a different experimental study conducted by Kulkarni et al. (Kulkarni et al., 2020), copper (Cu)-coated Al_2O_3 nano-particles were added into mineral-based cutting oil at volumetric concentrations up to 1%. Obtained nano-fluids were utilized in the milling of Al7075-T6 alloy using MQL technique. The study reported improvements in cutting zone temperature, tool wear, and tool life.

Overall, the literature consistently indicates that the effectiveness of machining processes is strongly dependent on the selected cooling and lubrication strategy. In particular, MQL-assisted nano-fluid applications offer a promising balance between machining performance, tool life improvement, surface quality enhancement, and environmental sustainability, making them attractive alternatives to conventional cooling techniques for modern manufacturing applications (Deshpande and Deshpande, 2019).

In the literature, while the mixture of boron mineral oil–water is commonly used in the cutting process in machining, no studies have been encountered in which Al_2O_3, multi-walled carbon nanotube (MWCNT) or TiO_2 nano-particles have been added to the boron mineral oil–water mixture. Therefore, this experimental study aims to investigate the effect of adding Al_2O_3, MWCNT, and TiO_2 nano-particles to the traditional boron mineral oil–water mixture. Subsequently, through the MQL application, contact temperature and surface quality were evaluated during the machining of Ti-6Al-4V, a material that is widely utilized in the aerospace industry, under actual cutting conditions.

METHODOLOGY

Nano-Fluid Preparation

Prior to conducting all measurements, the nano-fluid preparation process was completed. In this context, nano-particles were added to a mixture of Fuchs Ecocool S 761B boron mineral oil and water, where the boron mineral oil constituted 7% of the total volume under the conditions specified in Table 1. The blending was performed using an ultrasonic mixer, as illustrated in Figure 1. Nano-particles used in the study were chosen based on their widespread use and ease of comparison in literature. Additionally, the influence of ceramic-based nano-particles on the workpiece was partially investigated. Throughout the experiments, the base fluid composition, which is 100% boron mineral oil + water, remained constant. The Fuchs Ecocool S 761B boron mineral oil was mixed with water at a 7% volumetric ratio using beakers, resulting in a white, lubricative liquid. Then pH and electrical conductivity of the prepared fluid were subsequently measured using calibrated reference instruments.

Table 1. Conditions of the experiments.

Condition	Explanation
Used nano-particles	Al_2O_3, MWCNT, TiO_2
Concentration percentages	0.5%, 1%, 1.5%
Ultrasonic mixer maximum temperature limit	30 °C
Mixing time	60 min
Mixing frequency	20 kHz – 25 kHz (via Ø8 apparatus)
Boron mineral oil + water mixture pH interval	8.9 – 9.8
Boron mineral oil + water mixture electrical conductivity interval	1 500 μS/cm – 2 000 μS/cm

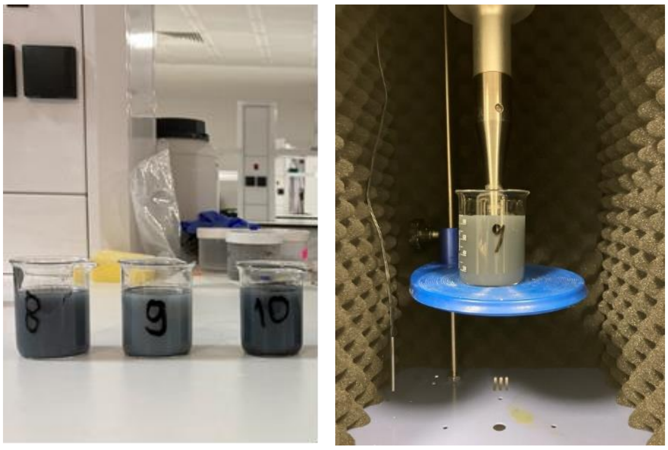


Figure 1. A general view of the nano-fluid samples before the mixing process and ultrasonic mixer.

The boron mineral oil–water mixture exhibits a structure that may gradually separate when left stationary, with stability typically lasting up to approximately fourteen days. This stability period is influenced by environmental factors such as ambient temperature, humidity, and exposure to organic materials or substances. A similar tendency is observed in nano-fluids when appropriate or optimal storage conditions are maintained. To mitigate issues such as bacterial growth or pH variation during prolonged use, stabilizing additives or conditioning agents are recommended for both boron-based mixtures and nano-fluids. Once the base boron mineral oil–water mixture is prepared, solid nano-particles are added at volumetric concentrations of 0.5%, 1%, and 1.5%. The mixtures are formulated as follows: 99.5% + 0.5%, 99% + 1%, and 98.5% + 1.5%, corresponding to the base fluid ratio (BR) and nano-particle ratio (NR), respectively. Precise volumetric measurements must be observed during the preparation process, and care must be taken to avoid loss or scattering of the nano-particles. Following the combination, each mixture is subjected to ultrasonic mixing for one hour under predefined boundary conditions. Throughout the mixing process, the temperature is continuously monitored and maintained within the range of 24.5 °C – 30 °C to ensure uniform dispersion and stability.

Nano-Fluid Density and Dynamic Viscosity Measurements

Obtained nano-fluids are respectively placed in the FPS2800B12C4 model fluid property sensor (FPS) assembly. The FPS assembly measures density and dynamic viscosity of the mixture with the help of waves of sensor. Here, it is necessary to wait for the stabilization of the sensor waves for a better measurement. When the waves stabilize, the results can be monitored instantly via the 'CAN Viewer' software as shown in Figure 2.

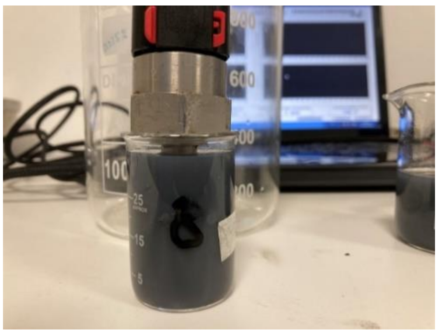


Figure 2. A view of the measurement process made with FPS.

Dynamic viscosity measurements were also made with the help of Anton Paar brand MCR 702-e model modular compact rheometer as shown in Figure 3. Rheometer measurements were made for three minutes each under a constant shear rate of 50 1/s with the help of a parallel sliding plate and dynamic viscosity results were obtained.

Figure 3. A photograph of Anton Paar brand MCR 702-e compact rheometer (Anton Paar Incorporation, 2023).

Nano-Fluid Thermal Conductivity Measurements

Thermal conductivity measurements were conducted using the KD-2 Pro device illustrated in Figure 4. The measurement probe comprises a needle that houses both a heating element and a temperature sensor. During the measurement process, an electric current is applied to the heater, and the system records the temperature changes of the sensor over time. Thermal conductivity of the fluid is then determined based on the temperature response of the sensor. For more accurate results, an appropriate probe type compatible with the sample characteristics was selected prior to each measurement.

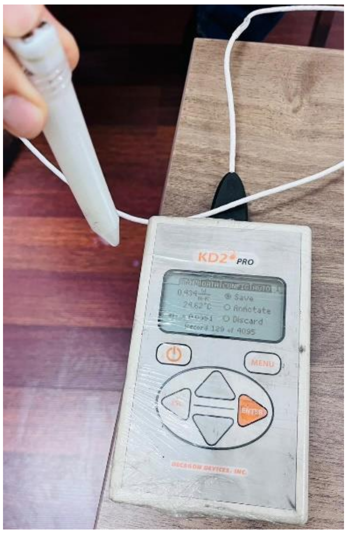


Figure 4. A view of measurement process made with KD-2 Pro thermal conductivity measurement device.

Working algorithm of the temperature sensor is as follows (Operator's Manual of KD-2 Pro, 2016): Heating is applied to a single needle for a time of t_h. Temperature in the region is monitored during and after the heating. Since the substance is liquid, a KS-1 needle with a diameter of 1.2 mm and a length of 6 cm is vertically inserted into the liquid sample (Operator's Manual of KD-2 Pro, 2016). Temperature for heating process is calculated by Eq. 1.

$$T(t) = T_0 + m_2 t + m_3 \ln t \quad (1)$$

Where T_0 is the ambient temperature during the heating process (which may include some offset due to contact resistance and the fact that the heating element is adjacent to the temperature sensor inside the needle), m_2 is the background temperature drift rate (°C/s), m_3 is the slope of the line connecting the temperature rise to the logarithm of the temperature (°C), and t is the total elapsed experimental time. Equation 2 represents the mathematical model for the cooling process.

$$T(t) = T_1 + m_2 t + m_3 \ln\left(\frac{t}{t-t_h}\right) \quad (2)$$

Where T_1 is the contact temperature when the heating process starts and t_h is the heating time. Then, thermal conductivity of the examined substance is calculated by Eq. 3 where q is the heat transfer rate.

$$k = \frac{q}{4\pi m_3} \quad (3)$$

Machining Experiments with Nano-Fluids

Machining experiments were conducted on an Accuway JT-150 model computer numerical control (CNC) lathe manufactured in Taiwan. Experimental procedure involved securing the Ti-6Al-4V workpiece in the lathe chuck followed by the installation of the selected cutting insert (YG brand, WNMG080408-SM code) onto the appropriate tool holder (AKKO brand, MWLNR2020K08 code). Subsequently, an Optris PI450 thermal imaging camera and an SKF Vario model MQL system were integrated into the setup. The machining process was initiated using a predefined numerical control (NC) program, during which real-time temperature measurements were captured via the thermal camera. The average interface temperatures recorded by the thermal camera were noted, and the operation halted upon completion of the temperature monitoring phase.

Following this, surface roughness measurements were conducted on the machined surface using a Mahr Marsurf PS10 surface profilometer enabling evaluation of the nano-fluid's effect on the surface finish of the workpiece. The CNC lathe and associated equipment, and the complete experimental setup are illustrated in Figure 5.

Figure 5. A photograph of the experimental setup for the machining.

The experiments were carried out using the test parameters in Table 2. The cutting parameters were selected from catalogs in accordance with the cutting tool and tool holder. The other parameters are the optimum operation values of the devices used. A photograph of cutting insert and cutting tool holder used in the machining experiments is shown in Figure 6.

Table 2. Machining experiments parameters.

Parameter	Value
Cutting speed (V_c)	60 m/min
Feed rate (f)	0.20 mm/rev
Diameter of workpiece ($Ø_w$)	47.6 mm
Volumetric flow rate ($\dot{Q}$)	75 mL/h
Pressure (p)	8 bar
Nozzle diameter ($Ø_n$)	2 mm
Nozzle distance from tool rake face (l)	30 mm
Emissivity of the thermal camera (ε)	0.6

Figure 6. A photograph of the cutting insert and cutting tool holder used in the machining experiments.

In order to examine the effect of the test conditions on the cutting tool tip, the cutting zones on the cutting tool are coded. For example, T1-1 indicates that the tip of the T1 tool, indicated by the number 1, was used. The classification of these zones is shown in Figure 7.

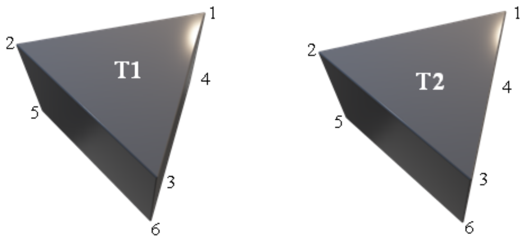


Figure 7. Coding of cutting points on cutting inserts.

RESULTS AND DISCUSSION

As outlined, prepared nano-fluid samples were subjected to a series of tests to evaluate both their thermo-physical characteristics and their effectiveness in machining applications. The experimental findings highlighted both the advantages and limitations associated with the use of nano-fluids. Evaluated parameters demonstrated that performance improvements are achievable up to certain optimal nano-particle volume fractions, beyond which adverse effects may occur. Additionally, scanning electron microscope (SEM) was employed to assess the condition of cutting tool tips following machining trials. The results confirmed that nano-fluids influence tool performance, particularly in terms of wear behavior and built-up edge formation. Detailed discussions of the findings for each test scenario are presented in the subsequent sections.

Results of FPS Measurements

Density and dynamic viscosity measurements of the prepared samples were conducted using an FPS system, with the results presented in Figure 8 and Figure 9. Figure 8 demonstrates density measurement results. As shown in Figure 8, the highest density was recorded for the sample containing 98.5% boron mineral oil + water and 1.5% TiO_2, whereas the lowest density corresponded to the base fluid. A general trend of increasing density with rising nano-particle concentration was observed across all nano-fluid samples, which can be attributed to the inherently higher density of the nano-particles compared to the base fluid. Figure 9 illustrates dynamic viscosity measurement results. As shown in Figure 9, the maximum viscosity was observed for the sample containing 99.5% boron mineral oil + water and 0.5% MWCNT, while the minimum viscosity was again observed in the pure base fluid. Interestingly, dynamic viscosity exhibited a decreasing trend as nano-particle concentration increased beyond a certain threshold. This reduction is attributed to precipitation and sedimentation phenomena (Özerinç et al., 2009), which lead to partial loss of dispersed nano-particles, effectively fluidizing the sample and diminishing its overall viscosity.

Results of Rheometer Measurements

Dynamic viscosity measurements of the prepared samples were also conducted using a rheometer, with the corresponding results illustrated in Figure 10. As shown, the highest dynamic viscosity was recorded for the sample comprising 99% boron mineral oil + water and 1% Al_2O_3, while the lowest value was observed in the pure base fluid. The observed trend closely aligns with the results obtained from the FPS measurements, thereby providing mutual validation between the two methods. Consistent with previous observations, an increase in nano-particle concentration led to a fluidizing effect, likely due to sedimentation and phase separation phenomena that reduce the effective particle dispersion in the fluid matrix.

Results of Thermal Conductivity Measurements

Thermal conductivity measurements of the prepared nano-fluid samples were carried out using the KD-2 Pro device, as previously described and the results are presented in Figure 11. According to the data, the highest thermal conductivity was recorded for the sample containing 99.5% boron mineral oil + water and 0.5% MWCNT, whereas the lowest value was observed in the sample comprising 98.5% boron mineral oil + water and 1.5% MWCNT. When each nano-fluid type was evaluated individually, it was found that increasing nano-particle concentration did not result in a continuous enhancement of thermal conductivity. Instead, thermal conductivity declined beyond a certain concentration threshold. This trend is attributed to alterations in the physical state of fluid, such as sedimentation or agglomeration, which negatively affect heat transfer efficiency despite the inherently high thermal conductivity of the nano-particles themselves. These findings are consistent with the previous studies (Park et al., 2011; Sharma et al., 2016a; Sharma et al., 2016b) including higher-viscosity fluids and highlighting the importance of optimizing nano-particle concentration to avoid performance degradation due to factors such as particle agglomeration and sedimentation.

Results of Machining Experiments

In the machining experiments, both the temperature at the tool–workpiece interface and surface roughness at the end of each operation were measured. The results are presented in Figure 12 and Figure 13, respectively. As illustrated in Figure 12, the lowest interface temperature was recorded for the sample containing 99.5% boron mineral oil + water and 0.5% MWCNT, while the highest temperature was observed under dry cutting conditions. Notably, increasing the nano-particle concentration did not lead to further temperature reduction, primarily due to precipitation and alterations in the fluid's behavior. Nevertheless, the application of nano-fluids demonstrated clear advantages over both dry cutting and base fluid. The most favorable condition achieved a 37.20% (in °C unit) reduction in interface temperature compared to dry machining and an 18.08% (in °C unit) reduction compared to the base fluid.

Comparable findings have been reported in the previous studies (Rahmati et al., 2014; Li et al., 2018; Gajrani et al., 2019; Jamil et al., 2019; Rahman et al., 2019; Yıldırım, 2019; Kulkarni et al., 2020;) including graphene; hybrid Al_2O_3-CNT; hBN and Al_2O_3; Al_2O_3, MoS_2, and TiO_2; MoS_2 and calcium fluoride (CaF_2); Al_2O_3@Cu and core@shell; MoS_2 nano-particles, respectively, despite using relatively higher-viscosity base oils. Observed temperature decreases provide significant economic advantages, particularly in machining which is difficult-to-cut materials such as Ti-6Al-4V commonly used in the aerospace sector. Mentioned significant economic advantages include extended tool life, lower consumption of cutting fluids, and reduced thermal damage.

As shown in Figure 13, the minimum surface roughness was achieved with the sample composed of 99.5% boron mineral oil + water and 0.5% Al_2O_3, whereas the highest surface roughness occurred in the sample with 98.5% boron mineral oil + water and 1.5% Al_2O_3. These results indicate that nano-fluids formulated with optimal nano-particle concentrations improve surface quality relative to both the base fluid and dry conditions. However, when the concentration of nano-particles exceeds a certain threshold, surface finish deteriorates (Sarhan et al., 2012; Jamil et al., 2019). This decline can be attributed to several factors such as changes in fluid behavior, abrasive effects of excess nano-particles on the workpiece surface, reduced capability of the fluid to penetrate the cutting zone due to increased film thickness, and the occurrence of precipitation.

In this study, a comparable pattern was identified in surface roughness measurements, mirroring the trends observed in the thermo-physical property evaluations. While nano-fluids with the relatively lower nano-particle concentrations led to a reduction in surface roughness, nano-fluids with the relatively higher nano-particle concentrations resulted in a deterioration of surface quality. This behavior of nano-fluids aligns with the findings reported in the previous studies (Nam et al., 2018; Rapeti et al., 2018; Bakalova and Svobodová, 2019; Jamil et al., 2019; Uysal, 2019; Yıldırım et al., 2019; Sen et al., 2020) utilizing higher-viscosity fluids.

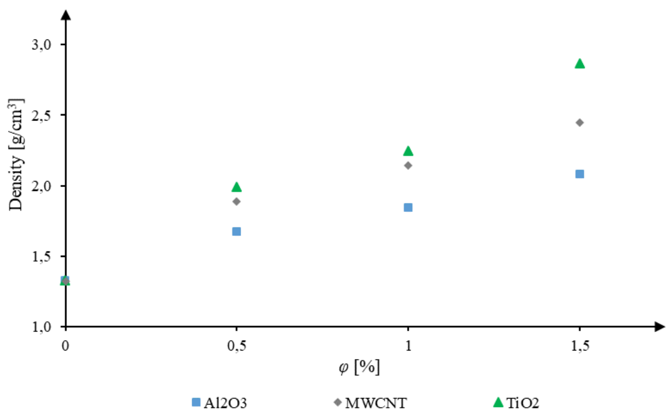


Figure 8. Density measurement results by using FPS (T = 24.5 °C and $p = p_{atm}$).

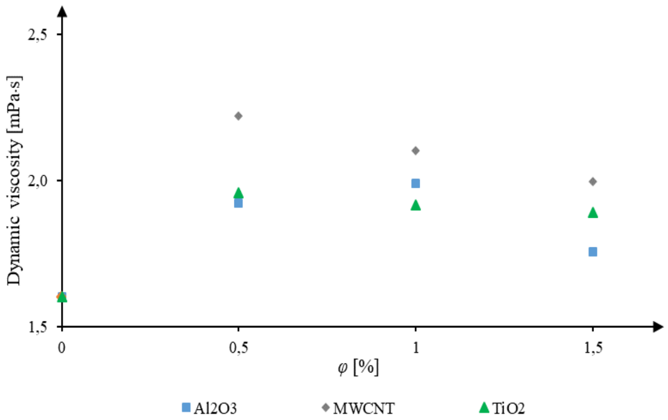


Figure 9. Dynamic viscosity measurement results by using FPS (T = 24.5 °C and $p = p_{atm}$).

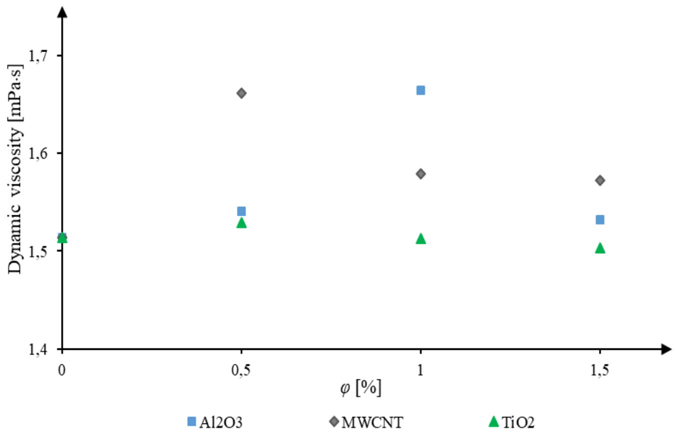


Figure 10. Dynamic viscosity measurement results with the rheometer (T = 24.5 °C and $p = p_{atm}$).

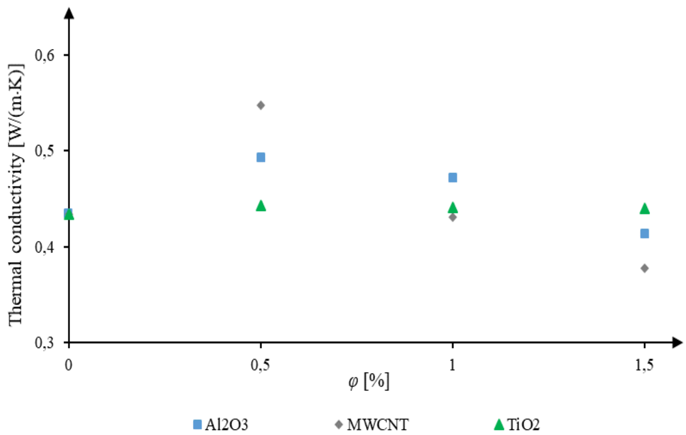


Figure 11. Thermal conductivity measurement results (T = 24.5 °C and $p = p_{atm}$).

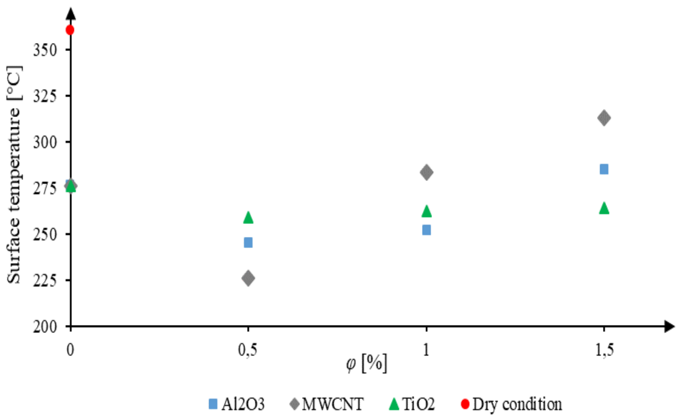


Figure 12. Temperature measurement results on the contact surface of the cutting tool and workpiece (T = 24.5 °C and $p = p_{atm}$).

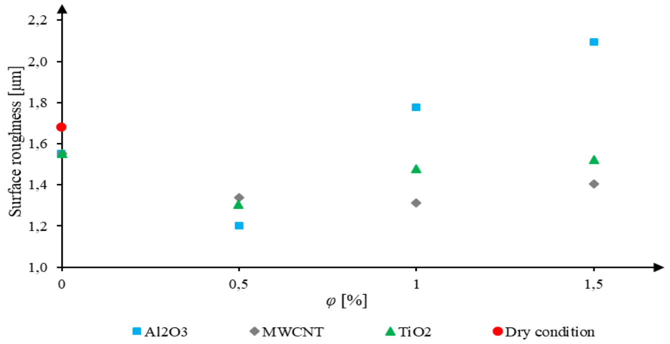
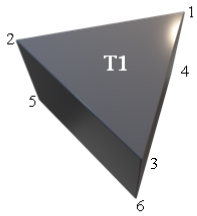
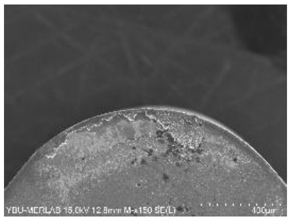
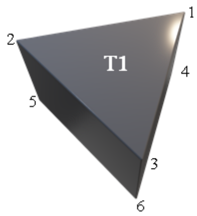
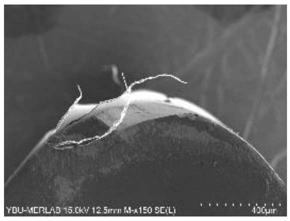
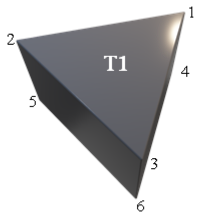
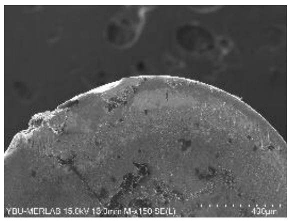
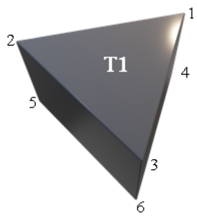
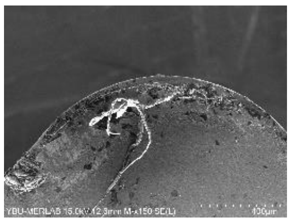
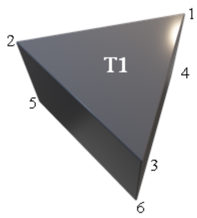
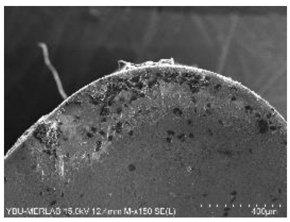
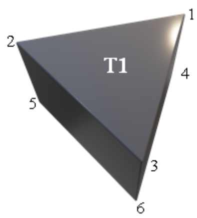
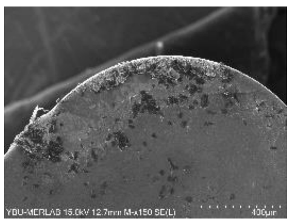


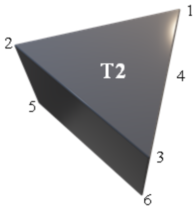
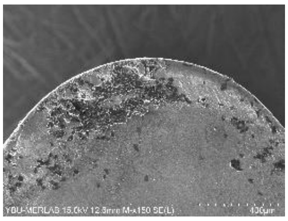
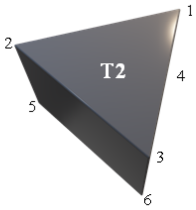
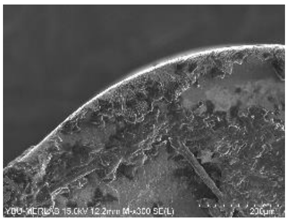
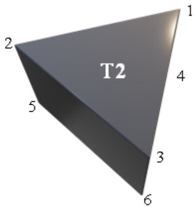
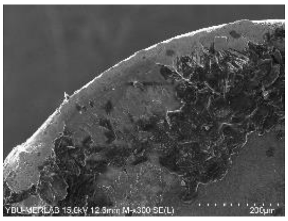
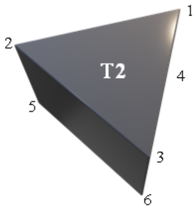
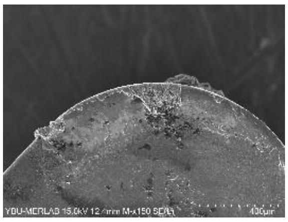
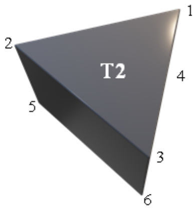
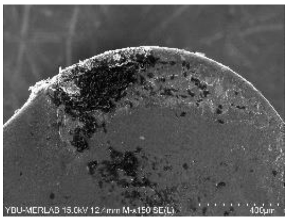
Figure 13. Workpiece surface roughness measurement results by using Mahr Marsurf PS10 surface profilometer ($T = 24.5$ °C and $p = p_{atm}$).

Results of SEM Imaging of Used Cutting Inserts

The cutting tool inserts used in the machining experiments were individually examined using SEM images, and the findings are summarized in Table 3. The investigation focused on wear resistance and the formation of BUE as a function of increasing nano-particle volume fraction. The results indicated that higher nano-particle concentrations led to BUE formation, primarily attributed to deposit accumulation on the tool surface. This phenomenon was exacerbated by MQL system, which directly delivered the fluid and thus the deposits to the cutting edge. Furthermore, evaluation of crater and flank wear revealed that the application of nano-fluids provided significant improvements over dry cutting conditions. Although nano-fluids demonstrated superior wear resistance overall, SEM images confirmed that exceeding optimal nano-particle concentrations increased the likelihood of BUE formation. This outcome mirrors the behavior observed in the thermo-physical property measurements, reinforcing the importance of maintaining appropriate volumetric ratios for consistent and efficient machining performance.

Table 3. SEM images of cutting inserts used in the experiments and some observations.

#	Cutter appearance	Point code	Used coolant	SEM image	Observation
1		T1-1	93% water + 7% boron mineral oil		Crater wear was observed.
2		T1-2	99% water + boron mineral oil mixture + 1% Al_2O_3		Nose side flank wear was observed.
3		T1-3	99.5% water + boron mineral oil mixture + 0.5% Al_2O_3		Nose side flank wear was observed.
4		T1-4	98.5% water + boron mineral oil mixture + 1.5% Al_2O_3		Crater wear and BUE were observed.
5		T1-5	99.5% water + boron mineral oil mixture + 0.5% MWCNT		Crater wear was observed.
6		T1-6	99% water + boron mineral oil mixture + 1% MWCNT		Crater wear and BUE were observed.

7		T2-1	98.5% water + boron mineral oil mixture + 1.5% MWCNT		Crater wear was observed.
8		T2-2	99.5% water + boron mineral oil mixture + 0.5% TiO_2		Crater wear and nose side flank wear were observed.
9		T2-3	99% water + boron mineral oil mixture + 1% TiO_2		Crater wear was observed.
10		T2-4	Dry cutting		Flank wear and crater wear were observed.
11		T2-6	98.5% water + boron mineral oil mixture + 1.5% TiO_2		Crater wear and BUE were observed.

CONCLUSIONS

The fundamental objectives mentioned in the methodology section, such as reducing the cutting tool–workpiece interface temperature and improving surface quality, were partially achieved at the optimal nano-particle concentrations given below. In particular, contrary to the current literature, which commonly uses high-viscosity base fluids, this study demonstrated that similar or even superior improvements in processing performance can be achieved using relatively lower-viscosity nano-fluids.

At the end of this experimental study including determination of density, dynamic viscosity, and thermal conductivity of the used nano-fluids, and containing machining experiments with the usage of nano-fluids, following results were reached.

1. All of the nano-fluid samples showed a general trend of increasing density as the quantity of nano-particles increased. This can be explained by the fact that the nano-particles have a higher density than the base fluid.
2. Increasing the nano-particle volume fraction generally had an impact on dynamic viscosity. For example, addition of 0.5% TiO_2 to the boron mineral oil–water mixture (resulting in a 99.5% base fluid composition) led to an approximate 2% increase in dynamic viscosity compared to the pure base fluid. In contrast, increasing TiO_2 concentration to 1.5% (yielding a 98.5% base fluid composition) resulted in a 1.3% decrease in dynamic viscosity relative to the base fluid. These findings suggest that beyond a certain concentration threshold, nano-particles may contribute to instability in fluid properties, potentially due to agglomeration or sedimentation effects.
3. Addition of 0.5% Al_2O_3 to the boron mineral oil–water mixture resulting in 99.5% base fluid composition led to approximately 13.5% increase in thermal conductivity compared to the base fluid. However, when Al_2O_3 concentration was increased to 1.5% resulting in 98.5% base fluid composition, thermal conductivity decreased by approximately 5.4% relative to the base fluid.
4. Implementation of nano-fluid composed of 99.5% boron mineral oil + water and 0.5% Al_2O_3 led to an approximate 25% improvement in surface roughness compared to the base fluid. In contrast, the use of a 98.5% boron mineral oil + water mixture with 1.5% Al_2O_3 nano-particles resulted in a 27% increase in surface roughness, indicating that excessive particle loading may negatively affect surface finish potentially related to agglomeration-driven particle accumulation on the machined surface.
5. This study revealed that employing nano-fluid composed of 99.5% boron mineral oil + water and 0.5% MWCNT resulted in an 18%, in °C unit, reduction in the temperature at the tool–workpiece interface resulting in some advantage

including extended tool life, lower consumption of cutting fluids, and reduced thermal damage. Nevertheless, excessive nano-particle concentrations may negatively influence machining performance due to precipitation and sedimentation. Therefore, proper agitation and circulation within the cooling system are essential to maintain fluid homogeneity. While the desired outcomes were successfully obtained under MQL conditions owing to the pressure-driven delivery, such effectiveness may not be guaranteed in conventional or centralized cooling systems.

6. SEM images further support the observed trends, revealing that increasing nano-particle volume fraction may lead to undesirable wear mechanisms at the cutting tool edge. Specifically, use of nano-fluid composed of 98.5% water + boron mineral oil and 1.5% TiO_2 resulted in the formation of BUE, in contrast to the 0.5% TiO_2 formulation under identical base fluid conditions. Presence of BUE compromises cutting efficiency by impairing the tool's functionality, leading to unstable machining performance. These findings highlight the importance of selecting nano-fluid concentrations based on a careful balance of thermo-physical properties and surface temperature data to ensure optimal tool performance and minimize wear-related failures.

As a result of the study, it is observed that the use of nano-fluids increases efficiency and improves both the cutting tool and cooling process at appropriate volumetric ratios. It is also evaluated that this effect can be better in hard materials such as Ti-6Al-4V or steel, because thermal problems are more crucial in the machining of these materials. When appropriate chemical conditions and cooling installations are provided, an increase in efficiency in the machining field can be achieved.

The following suggestions can be made for future researchers who will work on this subject.

- Different geometries and different materials can be tried for cutting inserts.
- Usage of nano-particles examined in this study or other type nano-particles together as binary or ternary, i.e. hybrid, can be added to the boron mineral oil + water mixture.
- As in almost all studies, a cost-benefit study, i.e. an economic analysis of the improvements or innovations made can be carried out.

ACKNOWLEDGEMENT

The authors are grateful to Ankara Yıldırım Beyazıt University and Gazi University for their valuable support to this research. Besides, the authors express their gratitude to Turkish Aerospace Incorporation for their precious support.

REFERENCES

Anton Paar Incorporation, Rheometer machine introduction. https://www.anton-paar.com (Date of access: May 02, 2023)

Bakalova, T. & Svobodová, L. (2019). Quality assessment of milling technology and the biocidal effects of SiO_2 or TiO_2 nanoadditives in cooling lubricant emulsions. *Journal of Manufacturing Processes*, 45, 509–519. https://doi.org/10.1016/j.jmapro.2019.07.032

Choudhary, A., Naskar, A., & Paul, S. (2018). An investigation on application of nano-fluids in high speed grinding of sintered alumina. *Journal of Manufacturing Processes*, 35, 624–633. https://doi.org/10.1016/j.jmapro.2018.09.013

Davim, J. P. (2011). Machining of Hard Materials, Springer, USA.

Deshpande, S. & Deshpande, Y. (2019). A review on cooling systems used in machining processes. *Materials Today*, 18, 5019–5031. https://doi.org/10.1016/j.matpr.2019.07.496

Gajrani, K. K., Suvin, P., Kailas, S. V., & Mamilla, R. S. (2019). Thermal, rheological, wettability and hard machining performance of MoS_2 and CaF_2 based minimum quantity hybrid nano-green cutting fluids. *Journal of Materials and Processing Technology*, 266, 125–139. https://doi.org/10.1016/j.jmatprotec.2018.10.036

Groover, M. P. (2010). Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, John Wiley & Sons.

Jamil, M., Khan, A. M., Hegab, H., Gong, L., Mia, M., Gupta, M. K., & He, N. (2019). Effects of hybrid Al_2O_3-CNT nanofluids and cryogenic cooling on machining of Ti–6Al–4V. *The International Journal of Advanced Manufacturing Technology*, 102, 3895–3909. https://doi.org/10.1007/s00170-019-03485-9

Krishna, P. R. & Rao, D. N. (2008). Performance evaluation of solid lubricants in terms of machining parameters in turning. *International Journal of Machine Tools & Manufacture*, 48, 1131–1137. https://doi.org/10.1016/j.ijmachtools.2008.01.012

Kulkarni, H. B., Nadakatti, M. M., Kulkarni, S. C., & Kulkarni, R. M. (2020). Investigations on effect of nanofluid based minimum quantity lubrication technique for surface milling of Al7075-T6 aerospace alloy. *Materials and Today Proceedings*, 27, 251–256. https://doi.org/10.1016/j.matpr.2019.10.127

Li, M., Yu, T., Zhang, R., Yang, L., Li, H., & Wang, W. (2018). MQL milling of TC4 alloy by dispersing graphene into vegetable oil-based cutting fluid. *The International Journal of Advanced Manufacturing Technology*, 99, 1735–175. https://doi.org/10.1007/s00170-018-2576-7

ManojKumar, K. & Ghosh, A. (2016). Assessment of cooling-lubrication and wettability characteristics of nano-engineered sunflower oil as cutting fluid and its impact on SQCL grinding performance. *Journal of Materials Processing Technology*, 237, 55–64. https://doi.org/10.1016/j.jmatprotec.2016.05.030

Najiha, M., Rahman, S., & Yusoff, M. M. A. (2016). Environmental impacts and hazards associated with metal working fluids and recent advances in the sustainable systems: A review. *Renewable and Sustainable Energy Reviews*, 60, 1008–1031. https://doi.org/10.1016/j.rser.2016.01.065

Nam, J., Kim, J. W., Kim, J. S., Lee, J., & Lee, S. W. (2018). Parametric analysis and optimization of nanofluid minimum quantity lubrication micro-drilling process for titanium alloy (Ti-6Al-4V) using response surface methodology and desirability function. *Procedia Manufacturing*, 26, 403–414. https://doi.org/10.1016/j.promfg.2018.07.048

Operator's Manual of KD-2 Pro. (2016). Decagon Incorporation.

Özerinç, S., Kakaç, S., & Yazıcıoğlu, A. G. (2009). Enhanced thermal conductivity of nanofluids: A state-of-the-art review. *Microfluidics and Nanofluidics*, 8, 145–170. https://doi.org/10.1007/s10404-009-0524-4

Park, K. H., Ewald, B., & Kwon, P. Y. (2011). Effect of nano-enhanced lubricant in minimum quantity lubrication balling milling. *Journal of Tribology*, 133, 031803. https://doi.org/10.1115/1.4004339

Peña-Parás, L., Maldonado-Cortés, D., Rodríguez-Villalobos, M., Romero-Cantú, A. G., Montemayor, O. E., Herrera, M., Trousselle, G., González, J., & Hugler, W. (2019). Optimization of milling parameters of 1018 steel and nanoparticle additive concentration in cutting fluids for enhancing multi-response characteristics. *Wear*, 426–427, 877-886. https://doi.org/10.1016/j.wear.2019.01.078

Peña-Parás, L., Rodríguez-Villalobos, M., Maldonado-Cortés, D., Guajardo, M., Rico-Medina, C. S., Elizondo, G., & Quintanilla, D. I. (2021). Study of hybrid nanofluids of TiO_2 and montmorillonite clay nanoparticles for milling of AISI 4340 steel. *Wear*, 477, 203805. https://doi.org/10.1016/j.wear.2021.203805

Prabhu, S. & Vinayagam, B. K. (2010). Nano surface generation of grinding process using carbon nano tubes. *Sādhanā*, 35, 747–760. https://doi.org/10.1007/s12046-010-0048-3

Rahman, S. S., Ashraf, Z. I., Amin, A. N., Bashar, M., Ashik, F. K., & Kamruzzaman, M. (2019). Tuning nanofluids for improved lubrication performance in turning biomedical grade titanium alloy. *Journal Cleaner Production*, 206, 180–196. https://doi.org/10.1016/j.jclepro.2018.09.150

Rahmati, B., Sarhan, A. A., & Sayuti, M. (2014). Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS_2) nanolubrication in end milling machining. *Journal of Cleaner Production*, 66, 685–691. https://doi.org/10.1016/j.jclepro.2013.10.048

Rapeti, P., Pasam, V. K., Gurram, K. M. R., & Revuru, R. S. (2018). Performance evaluation of vegetable oil based nano cutting fluids in machining using grey relational analysis-A step towards sustainable manufacturing. *Journal of Cleaner Production*, 172, 2862–2875. https://doi.org/10.1016/j.jclepro.2017.11.127

Sarhan, A. A., Sayuti, M., & Hamdi, M. (2012). Reduction of power and lubricant oil consumption in milling process using a new SiO_2 nanolubrication system. *The International Journal of Advanced Manufacturing Technology*, 63, 505–512. https://doi.org/10.1007/s00170-012-3940-7

Sayuti, M., Erh, O. M., Sarhan, A. A., & Hamdi, M. (2014). Investigation on the morphology of the machined surface in end milling of aerospace Al 6061-T6 for novel uses of SiO_2 nanolubrication system. *Journal of Cleaner Production*, 66, 655–663. https://doi.org/10.1016/j.jclepro.2013.11.058

Sen, B., Gupta, M. K., Mia, M., Mandal, U. K., & Mondal, S. P. (2020). Wear behaviour of TiAlN coated solid carbide end-mill under alumina enriched minimum quantity palm oil-based lubricating condition. *Tribology International*, 148, 106310. https://doi.org/10.1016/j.triboint.2020.106310

Sharma, A. K., Singh, R. K., Dixit, A. R., & Tiwari, A. K. (2016a). Characterization and experimental investigation of Al_2O_3 nanoparticle based cutting fluid in turning of AISI 1040 steel under minimum quantity lubrication (MQL). *Materials Today: Proceedings*, 3, 1899–1906. https://doi.org/10.1016/j.matpr.2016.04.090

Sharma, A. K., Tiwari, A. K., Singh, R. K., & Dixit, A. R. (2016b). Tribological investigation of TiO_2 nanoparticle based cutting fluid in machining under minimum quantity lubrication (MQL). *Materials Today: Proceedings*, 3, 2155–2162. https://doi.org/10.1016/j.matpr.2016.04.121

Shashidhara, Y. M. & Jayaram, S. R. (2010). Vegetable oils as a potential cutting fluid-an evolution. *Tribology International*, 43, 1073–1081. https://doi.org/10.1016/j.triboint.2009.12.065

Shen, B., Shih, A. J., & Tung, S. C. (2008). Application of nanofluids in minimum quantity lubrication grinding. *Tribology Transactions*, 51, 730–737. https://doi.org/10.1080/10402000802071277

Shokrani, A., Dhokia, V., & Newman, S. T. (2012). Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids. *International Journal of Machine Tools & Manufacture*, 57, 83–101. https://doi.org/10.1016/j.ijmachtools.2012.02.002

Şirin, Ş. & Kıvak, T. (2019). Performances of different eco-friendly nanofluid lubricants in the milling of Inconel X-750 superalloy. *Tribology International*, 137, 180–192. https://doi.org/10.1016/j.triboint.2019.04.042

Uysal, A. (2017). An experimental study on cutting temperature and burr in milling of ferritic stainless steel under MQL using nano graphene reinforced cutting fluid. *Advanced Materials Proceedings*, 2, 560–563. https://doi.org/10.5185/amp.2017/038

Vasu, V. & Reddy, G. P. K. (2011). Effect of minimum quantity lubrication with Al_2O_3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy. *Proceedings of the Institution of Mechanical Engineers Part N. Journal of Nanoengineering and Nanosystems*, 225, 3–16. https://doi.org/10.1177/1740349911427520

Yıldırım, Ç. V. (2019). Experimental comparison of the performance of nanofluids, cryogenic and hybrid cooling in turning of Inconel 625. *Tribology International*, 137, 366–378. https://doi.org/10.1016/j.triboint.2019.05.014

Yıldırım, Ç. V., Sarıkaya, Kıvak, M., T., & Şirin, Ş. (2019). The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of Ni-based Inconel 625. *Tribology International*, 134, 443–456. https://doi.org/10.1016/j.triboint.2019.02.027