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Machining Performance and Sustainability Analysis of Al_2O_3-CuO Hybrid Nanofluid MQL Application for Milling of Ti-6Al-4V

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Abstract

Machining of Ti-6Al-4V presents challenges due to its low thermal conductivity, and conventional cutting fluids (CCF) are inadequate in providing a productive and sustainable solution. This study aims to achieve more sustainable and productive machining of Ti-6Al-4V by utilizing Al_2O_3 and CuO-added Nanofluid Minimum Quantity Lubrication (NMQL) individually and in hybrid form with different concentrations. A comparison is made with pure-MQL, CCF and dry conditions. The study consists of three stages. In the first stage, the physical properties of the coolants, like contact angle and surface tension, are investigated. The second stage involves slot milling operations, and various outputs including cutting forces, surface roughness, surface topography, surface finish, and subsurface microhardness are analyzed. In the last stage, a sustainability analysis is conducted based on the Pugh Matrix Approach. The results indicate that Al_2O_3-NMQL exhibits lower contact angles and surface tensions compared to other conditions. Furthermore, HNMQL applications result in lower cutting forces (up to 46.5%), surface roughness (up to 61.2%), and microhardness (up to 6.6%), while yielding better surface finish and topography compared to CCF. The sustainability analysis demonstrates that HNMQL application is the most suitable option for achieving sustainable machining of Ti-6Al-4V.

Keywords: Ti-6Al-4V; Nanofluid minimum quantity lubrication; Cutting force; Surface quality; Microhardness; Sustainability assessment

Introduction

The aviation industry is one of the most important sectors in today's world. According to current data, almost 300 airlines that are members of the International Air Transport Association (IATA) serve in 120 countries (International Air Transport Association, 2023). However, the emissions of aircraft such as CO_2, CO, H_2O, HC, NOx cause high damage to the atmosphere, and it is necessary to reduce the amount of emissions in terms of sustainability (Wasiuk et al., 2015). In this context, reducing the economic and environmental impacts by reducing the fuel consumption of aircraft is one of the most important options. Reducing fuel consumption can be achieved by making aircraft parts lighter and reducing the use of unnecessary materials (Carou et al., 2017).

Ti-6Al-4V has features such as high strength-to-weight ratio and excellent resistance to corrosion, and ability to maintain its strength at high temperatures. In particular, its good strength despite its lightness has made Ti-6AL-4V a frequently used material in aircraft parts in order to reduce fuel consumption in the aviation industry and therefore sustainability (Carou et al., 2017). It has been reported that jet engines consist of titanium alloys at a rate of 30% in commercial ones and 40% in military ones (Honnorat, 1996). Machining is one of the most frequently used manufacturing operations in the production of aerospace parts from raw materials (Namlu and Sadigh, 2022). However, the extremely low thermal conductivity of Ti-6Al-4V causes high cutting zone temperatures, negatively affecting tool life, and maintaining its high strength at high temperatures makes it difficult to remove chips (Ezugwu and Wang, 1997). For such reasons, Ti-6Al-4V is often called difficult-to-cut (Ezugwu, 2005; Namlu et al., 2020, 2021) and its sustainable machining is quite challenging.

As mentioned before, the main obstacle to the machinability of Ti-6Al-4V is the high heat accumulated in the cutting zone due to its low thermal conductivity. Conventional Cutting Fluids

(CCF) are frequently used in machining operations to reduce the heat generated during cutting by sending coolant/lubricating fluids to the cutting zone (Ezugwu et al., 2007). However, the efficiency of CCF is both insufficient for difficult-to-cut materials such as Ti-6Al-4V and it is a low-efficiency option due to its high cost due to its excessive consumption (Namlu et al., 2021). It has also been stated that CCF has harmful effects on the environment and human health due to the chemicals it contains and its high consumption (Said et al., 2019; Zhang et al., 2016). For these reasons, methods such as dry cutting (Sun et al., 2015), abrasive jet machining (Routara et al., 2011), cryogenic (Khanna et al., 2022; Venugopal et al., 2007) and minimum quantity lubrication (MQL) (Namlu et al., 2022), which are more environmentally friendly and sustainable alternative techniques, have been tried in recent years instead of CCF.

Among these alternative methods, MQL stands out in terms of sustainability due to reasons such as low consumption, high performance efficiency, and the use of biodegradable or vegetable oils (Debnath et al., 2014). MQL generally sprays a mixture of low amount of oil and high-pressure air into the cutting area in aerosol form, increasing the cutting efficiency with its high penetration capability and it can also minimize the negative effects on the health of the operator and the environment, thanks to the features such as the low amount of consumed oil and the biodegradability of these oils (Das and Bajpai, 2023; He et al., 2023). Osman et al. (2019) systematically reviewed the MQL applications on titanium alloys -including Ti-6Al-4V- and their review study proved that MQL increases the efficiency of titanium alloy machining in general. Swain et al. (2022) compared MQL with dry conditions in the turning operation of Ti-6Al-4V. According to their results, MQL application yielded a 67% reduction in tool wear and extended tool life by 280%, thanks to its enhanced cooling and lubrication capabilities.

Although MQL provides many advantages over CCF, studies have recently started to increase the efficiency of MQL. Nanofluid-MQL (NMQL) technique, which is created by adding nanoparticles to the base fluid used in the MQL system, is one of the methods developed to increase MQL's efficiency (Makhesana et al., 2023; Yıldırım et al., 2019). The main purpose in NMQL is to obtain a nanofluid with better tribological and thermo-physical properties than base fluid with the nanoparticles used (Sharma et al., 2016). It has been mentioned in the literature that NMQL can enhance heat transfer rates (Roy et al., 2019) and may also serve as a sustainable option (Khatai et al., 2023).

NMQL has been successfully implemented to the machining of Ti-6Al-4V in numerous studies. Wang et al. (2023) compared the experimental and simulation-based graphene nanoparticle-enhanced NMQL application with diamond tool in the micro-milling operation of Ti-6Al-4V, relative to dry conditions. Their results reported that graphene nanoparticles enhanced cutting performance, leading to improvements in tool wear and surface quality during the cutting process. Jadam et al. (2020) employed Multi-Walled Carbon Nano-Tubes (MWCNTs)-enhanced NMQL in the turning of Ti-6Al-4V and compared it with dry cutting. The results demonstrated that NMQL reduced tool-tip temperature by 62.7%, cutting force by 8.69%, flank wear by 42%, and surface roughness by 12.8% in comparison to dry cutting. Gaurav et al. (2020) examined the impact of vegetable oil and mineral oil-based NMQL with MoS_2 nanoparticles on Ti-6Al-4V in hard machining operations. Their results revealed that NMQL prepared with vegetable oil reduced main cutting force by 34.39%, improved surface finish by 40.67%, and decreased tool wear by 47.37% compared to dry cutting. Additionally, they noted that vegetable oil generally outperformed commercially available mineral oil, highlighting the sustainability implications of this outcome. Liu et al. (2018) conducted an investigation based on grey relational analysis of Al_2O_3

nanoparticle-enhanced NMQL application in the grinding operation of Ti-6Al-4V, comparing the results with dry, flood, and pure-MQL conditions. Their findings indicate that under appropriate cutting conditions, NMQL application yielded superior surface quality results compared to other conditions. Taha-Tijerina et al. (2023) compared Al_2O_3 nanoparticle-enhanced NMQL with CCF and pure-MQL in the grinding operation of Ti-6Al-4V. The results indicated that, under appropriate experimental conditions, NMQL outperformed pure-MQL and, considering environmental and economic factors, NMQL and pure-MQL applications were found to be more suitable alternatives than CCF. Bai et al. (2019) studied different nanoparticles (Al_2O_3, SiO_2, MoS_2, CNTs, SiC, and graphite) with cotton oil for milling of Ti-6Al-4V and their results showed that Al_2O_3 provided the least cutting force and surface roughness values among all the other alternatives due to its spherical shape and high lubrication performance. Setti et al. (2014) investigated the grinding of Ti-6Al-4V with pure-MQL, NMQL and wet cutting and the study showed that NMQL outclass the pure-MQL by 12% in normal force, 15% in tangential forces and wet cutting 28% in normal force, 27% in tangential forces in terms of cutting forces. Also, NMQL provided better surface quality and morphology. Ali et al. (2017) examined the different concentrations (0.2%, 0.4% and 0.6%) of Al_2O_3 for the turning of Ti-6Al-4V. The results claim that, for different outputs, optimum conditions were changing, such as the best surface roughness was found at 0.4% concentration while the lowest tool wear was found at 0.6% and this shows that, optimum concentration of nanoparticle is vital adjustment for better cutting performance. Roushan et al. (2022) researched the micromilling of Ti-6Al-4V with CuO added NMQL and the results revealed that CuO-NMQL yielded better surface quality, lower burr width and tool wear compared to dry and deionized water. Setti et al. (2015) studied the grinding of Ti-6Al-4V with Al_2O_3 and CuO added NMQL and the study claims that, Al_2O_3 added NMQLs produced less cutting forces and surface roughness than

CuO added NMQL due to tribofilm effect of Al_2O_3 is more dominant than CuO due to Al_2O_3's higher melting point which leads to endure its form even at high temperatures. Edelbi et al. (2023) conducted a study on the utilization of ZnO and Al_2O_3 nanoparticle-infused NMQL in face milling operations involving the Ti–3Al–2.5V alloy. Their results indicated that, on average, ZnO, owing to its superior heat dissipation capability, led to a reduction of 18.49% in surface roughness, a 36.79% decrease in cutting temperature, and a 14.89% reduction in tool wear as compared to Al_2O_3.

A new approach in NMQL applications is the Hybrid-NMQL (HNMQL) application. HNMQL aims to increase the nanofluid performance by combining the advantages of nanoparticles by adding at least two different nanoparticles to the base fluid (Sarkar et al., 2015)**Error! Reference source not found.**. Haghnazar and Abedini (2021) examined the Al_2O_3 and CuO added HNMQL for the turning of AISI 4340 material, the results showed that HNMQL generated less cutting forces and surface roughness compared to Al_2O_3 and CuO separately. Kumar and Krishna (2020) studied the turning of AISI 1018 material with HNMQL application with Al_2O_3 and CuO compared to dry cutting, their results indicated that 13.72% surface roughness reduction achieved with 50:50 combination of HNMQL.

It is clearly seen in the literature that Al_2O_3 and CuO added NMQL applications have positive effects on Ti-6Al-4V. However, there are very few studies on the use of Al_2O_3 and CuO nanoparticles together in HNMQL, and even there is no study found on the milling of Ti-6Al-4V. This study aims to fill the following research gaps:

- Comparison of HNMQL method with Al_2O_3 and CuO particles added in Ti-6Al-4V material according to pure-MQL, CCF and dry conditions.

- Investigation of the effect of vol.% concentrations of Al_2O_3 and CuO nanoparticles on cutting performance in Ti-6Al-4V.

In this study, with the intention to achieve more sustainable and efficient cutting of Ti-6Al-4V due to the critical role of the material in aerospace industry, for the first time, effects of Al_2O_3 and CuO added HNMQL and vol.% concentrations of the nanoparticles investigated for the slot milling of Ti-6Al-4V in terms of cutting forces, surface roughness, surface topography, surface texture and microhardness. Finally, a comprehensive sustainability evaluation is conducted to assess the impacts of all coolant/lubrication conditions from a sustainable standpoint.

Thermophysical and Tribological Enhancements of Nanofluids

Heat Dissipation

In machining operations, one of the primary reasons for the need for coolants is to enhance heat dissipation in the cutting zone. Heat generation in machining operations is generally analyzed within three regions at the cutting tool-chip interface, as illustrated in Figure 1 where $\dot{Q}_{workpiece}$ represents the heat transfer rate in the workpiece and $\dot{Q}_{tool}$ indicates the heat transfer rate in the tool. Coolants play a crucial role in managing heat during machining operations. However, excessive use of traditional coolants is often necessary to meet the demand for efficient heat dissipation. This necessity arises from the inherent limitations in the thermal properties of conventional coolants, which require larger quantities to adequately fulfill their role in thermal regulation. These larger quantities of traditional coolants can lead to concerns regarding resource consumption, environmental impact, and economic considerations (Hegab et al., 2018). This underscores the importance of exploring and adopting more efficient and sustainable coolant alternatives in machining practices. Numerous studies in the literature have reported that the use of nanofluids, especially when employing nanoparticles with high thermal conductivity, yields better results as a thermal medium compared to conventional coolants or base fluids (Iqbal et al., 2017; Ramachandran et al., 2016).

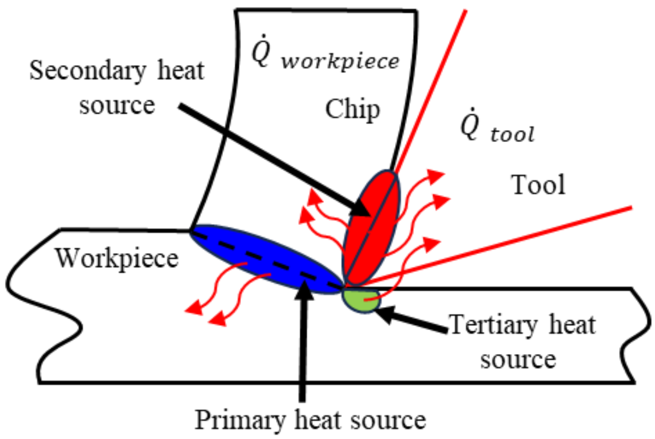


Figure 1 Heat sources during machining

The heat generated during chip removal adversely affects machining performance in various aspects. Inability to remove heat from the cutting zone leads to rapid tool wear, high cutting forces, and poor surface quality (Abukhshim et al., 2006). Therefore, the use of high thermal performance mediums like nanofluids enhances machining performance. In this study, Al_2O_3 and CuO nanoparticles were individually, and together (hybrid) added to the base fluid to create nanofluids and applied with an MQL system as an aerosol form. It has been observed in the literature that hybrid-nanofluids yield better results compared to mono-nanofluids in terms of thermal performance (Sajid and Ali, 2018). The reason for this is the differences in the thermo-physical properties and heat transfer mechanisms of hybrid-nanofluids compared to mono-nanofluids. The thermal conductivity (k) for mono-nanofluids as shown in Equation 1 (Hayat and Nadeem, 2017), where k_{nf} represents thermal conductivity of nanofluid, k_f denotes thermal conductivity of fluid, k_s symbolizes the thermal conductivity of nanoparticle, ϕ shows the volume fraction of nanoparticle and, n indicates the shape factor which is $\frac{3}{\Psi}$, where Ψ is the sphericity of the particles (since both Al_2O_3 and CuO nanoparticles are in spherical shape Ψ is 1 in this study).

$$\frac{k_{nf}}{k_f} = \frac{k_s + (n-1)k_f - (n-1)\phi(k_f - k_s)}{k_s + (n-1)k_f + \phi(k_f - k_s)} \tag{1}$$

The thermal characteristics of hybrid-nanofluids differ from those of mono-nanofluids, and Equation 2 represents the thermal conductivity of hybrid-nanofluids where k_{hnf} is the thermal conductivity of hybrid-nanofluid, k_{bf} indicates thermal conductivity of base fluid, k_{s1} and k_{s2} represents the thermal conductivity of nanoparticles, ϕ_1 and ϕ_2 shows the volume fraction of nanoparticles.

$$\frac{k_{hnf}}{k_{bf}} = \frac{k_{s_2} + (n-1)k_{bf} - (n-1)\phi_2(k_{bf} - k_{s_2})}{k_{s_2} + (n-1)k_{bf} + \phi_1(k_{bf} - k_{s_2})}$$

where (2)

$$\frac{k_{bf}}{k_f} = \frac{k_{s_1} + (n-1)k_f - (n-1)\phi_1(k_f - k_{s_1})}{k_{s_1} + (n-1)k_f + \phi_1(k_f - k_{s_1})}$$

As evident in Equations 1 and 2, the addition of nanoparticles contributes to the thermal conductivity of the base fluid, depending on the volume fraction of the nanoparticles and their thermal conductivity. In hybrid-nanofluids, this effect is more pronounced compared to mono-nanofluids, and numerous studies in the literature support this observation (Megatif et al., 2016; Wei et al., 2017).

As depicted in Figure 1, the main heat sources occurring at the chip-tool interface during cutting are conductive since the tool-chip interface is solid-to-solid contact. However, convective heat transfer also takes place during the cutting process. The boundaries of the convective heat transfer that occurs during cutting can be observed in Figure 2.

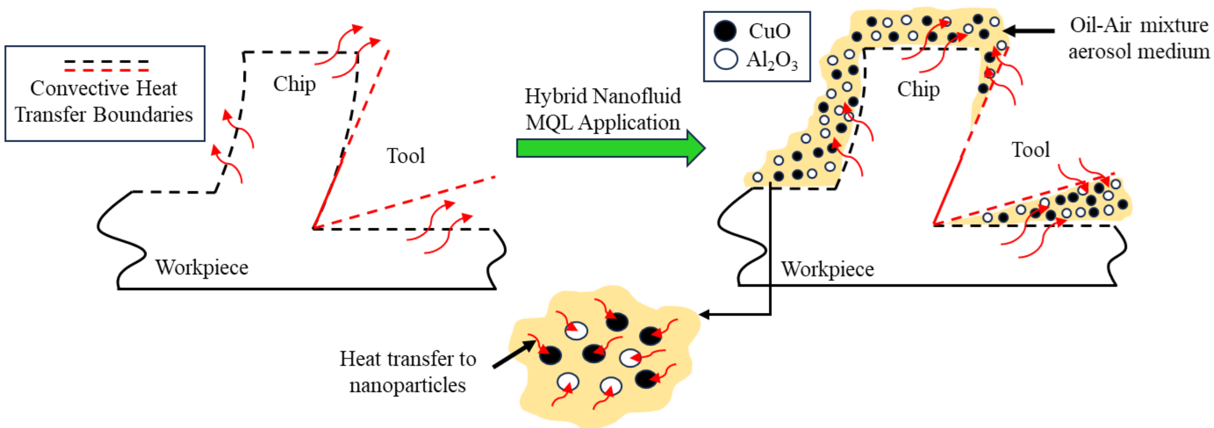


Figure 2 Heat transfer mechanism of nanofluids

As seen in Figure 2, increasing convective heat transfer is crucial in reducing the heat generation caused by the deformation zones during cutting through the influence of coolants. Equation 3 presents the general convective heat transfer formula where $\dot{Q}$ represents the rate of heat transfer, h_{nf} is the convective heat transfer coefficient of the nanofluid, A denotes the area of heat transfer and Δt indicates the temperature difference.

$$\dot{Q} = h_{nf} A \Delta t \quad (3)$$

The literature commonly suggests that elevating the convective heat transfer coefficient is closely linked to the increase of the thermal conductivity of the fluid (Farajollahi et al., 2010). As previously highlighted, the incorporation of nanoparticles can lead to the elevation of thermal conductivity in nanofluids compared to the base fluid. Consequently, this can boost convective heat transfer, yielding a coolant medium with enhanced thermal conductivity. Furthermore, as stated in Equations 1 and 2, nanofluids with a higher heat transfer capacity compared to conventional coolants can be used to increase the $\dot{Q}_{workpiece}$ and $\dot{Q}_{tool}$ thus enhancing total convective heat transfer. This results in higher heat dissipation in the cutting zone than conventional coolants, consequently reducing the adverse effects of heat generation on machining performance. In this context, the heat dissipation-enhancing effect of nanofluids can be further elevated with hybrid-nanofluids since they have higher thermal conductivity.

Tribological Aspects

One of the most significant factors contributing to the enhancement of efficiency in machining operations using nanofluids is their superior tribological performance compared to conventional cooling methods. Nanoparticles added to the base fluid can improve tribological performance through different mechanisms, depending on their shapes, sizes, and the materials from which they are composed. These mechanisms are generally categorized into four main groups: rolling, protective film formation, mending, and polishing effects. Figure 3 illustrates various nanofluid mechanisms.

The detailed explanations of the rolling, protective film formation, mending, and polishing effects in the context of nanofluids and their impact on the efficiency of machining operations can be explained as follows.

The rolling effect is a tribological mechanism that occurs when nanoparticles within the nanofluid roll over the contact surfaces involved in machining. This rolling action is made possible due to the nanoscale dimensions of the particles. As these nanoparticles roll, they create a ball-bearing effect that reduces the direct metal-to-metal contact between the machining tool and workpiece and consequently, friction and wear are diminished (Rahmati et al., 2014; The Long and Minh Duc, 2020; Wu et al., 2007). Hybrid nanofluids may present improved rolling effects compared to mono-nanofluids. Different nanoparticles may have varying sizes, shapes, and chemical properties, which can result in different interactions with the contact surfaces.

The protective film formation is another key tribological effect of nanofluids. In this mechanism, the nanoparticles suspend within the fluid create a thin, protective layer on the surfaces of both the tool and the workpiece. This protective film acts as a barrier, preventing direct contact between the tool and workpiece material and it serves to reduce friction and wear by providing lubrication and reducing adhesion between the surfaces (Gugulothu and Pasam, 2022). This effect helps to maintain tool sharpness and reduces the abrasive wear and adhesive wear on the cutting tool (Wang et al., 2017), leading to improved machining performance. When hybrid-nanofluids are used the formation of a protective film effects can be more complicated. When different nanoparticles are combined, their interactions with the surfaces and the base fluid may result in a more effective protective film. The combined effects of multiple nanoparticles may lead to a thicker, more robust protective layer, providing enhanced lubrication and wear resistance. However, it's also possible that certain combinations may hinder the formation of an effective protective film, so careful formulation is crucial.

The polishing effects involve the abrasive action of nanoparticles within the nanofluid. As the machining process progresses, the nanoparticles act as abrasive particles that smooth the contact surfaces. This leads to a reduction in surface roughness and improved surface finish on the workpiece (Rahmati et al., 2014). The abrasive action of the nanoparticles can also help remove asperities from the workpiece, resulting in a more precise and smoother machined surface (Abbas et al., 2021). Polishing effects are particularly advantageous for applications where a high-quality surface finish is critical. Hybrid nanofluids can provide enhanced polishing effects as well. By combining nanoparticles with different abrasive properties, the abrasive action on the contact surfaces can be more effective. This can lead to a smoother and finer surface finish, as the different nanoparticles work in combination to remove failures and reduce surface roughness.

The mending effects are associated with the ability of nanoparticles to fill in microcracks and surface defects on the workpiece material. When nanofluids are used during machining, the suspended nanoparticles can infiltrate and repair microcracks in the workpiece's surface. This process leads to the restoration of the workpiece's surface integrity, improving its surface quality (Rahmati et al., 2014). By mending effect, not only the workpiece surface but also the cutting tool's worn areas may fill and improve its service life (Liu et al., 2004). Hybrid nanofluids can offer improved mending effects due to the diverse properties of their nanoparticle constituents. Different types of nanoparticles may complement each other in repairing microcracks and surface defects more efficiently. The combined nanoparticles can fill in defects of various sizes and types, resulting in enhanced surface restoration and better workpiece integrity.

In summary, the detailed understanding of the rolling, protective film formation, polishing and, mending effects of nanofluids is crucial for comprehending their role in enhancing the efficiency of machining operations. These tribological mechanisms collectively contribute to reducing friction, preventing wear, and improving the overall quality of machined parts, making nanofluids a promising technology for advanced machining applications. Also, the use of hybrid nanofluids introduces a level of complexity and synergy in the tribological mechanisms during machining operations. The combination of different nanoparticles can lead to improved performance in tribological mechanisms, but the outcomes will depend on the specific combination of nanoparticles and their interaction with the machining process. Careful selection and formulation of hybrid nanofluids are essential to harness their full potential in optimizing the efficiency of machining operations.

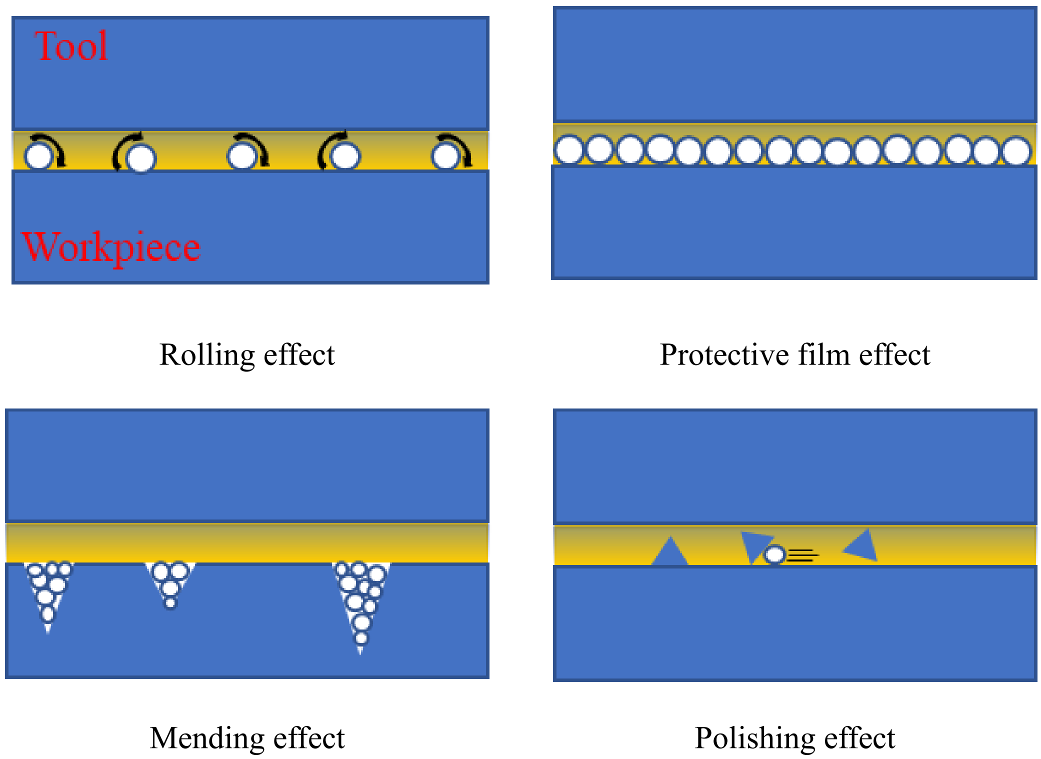


Figure 3 NMQL mechanisms

Methodology

Preparation of Nanofluids

The selected base oil was polymeric ester-based oil which is biodegradable in order to contain sustainability assessments. The nanoparticles were obtained from Nanografi Nanotechnology Company and two different nanoparticles, namely Aluminum Oxide (Al_2O_3) and Copper Oxide (CuO), were used and the nanoparticle properties taken from the manufacturer can be seen in Table 1. Besides from individually prepared Al_2O_3 and CuO added nanofluids, in order to see the hybrid nanofluid effects, Al_2O_3 and CuO nanoparticles were mixed volumetrically equal and a hybrid nanofluid is prepared.

Table 1 Nanoparticle properties

Nanoparticle	**Average size (nm)**	**Purity (%)**	**Density (g/cm^3)**	**Appearance**
Aluminum oxide	10±5	>99.5	3.95	White powder
Copper oxide	25	99.995	6.3	Black powder

While an increase in nanoparticle concentration may lead to positive results due to the higher quantity of nanoparticles, the literature generally suggests the presence of an optimal concentration (James and Mazaheri, 2023; Mahboob Ali et al., 2017; Maruda et al., 2023). Beyond this optimal point, the positive effects may tend to diminish. Therefore, the experiments have explored four different nanoparticle concentrations to determine this optimal concentration. The nanofluids were prepared by four different levels of volume concentration by 0.5% 1%, 1.5%, 2% in base oil. First, the nanoparticles were weighted by the help of digital analytical balance with 0.001 gr precision (ISOLAB, Germany) and added to base oil. Then, for mechanical mixing, a magnetic stirrer (Heidolph, Germany) was used at 500 RPM for 30 min. In order to improve dispersion of nanoparticles in base oil, an ultrasonic bath was used (Bandelin, Germany) with frequency of 35 kHz for 45 min. It needs to be determined how long nanofluids will remain in a stable state after the completion of nanoparticle dispersion. Notably, even after a period exceeding 24 hours, no precipitation or agglomeration was observed. Even in this case, the nanofluids were utilized in experiments immediately following their preparation. Since previous studies have suggested that the use of surfactants may adversely affect the properties of the base fluid, such as thermal conductivity, and considering that no agglomeration was observed after the preparation, no surfactant was used in this study (Yu and Xie, 2012). The preparation stages can be seen in Figure 4.

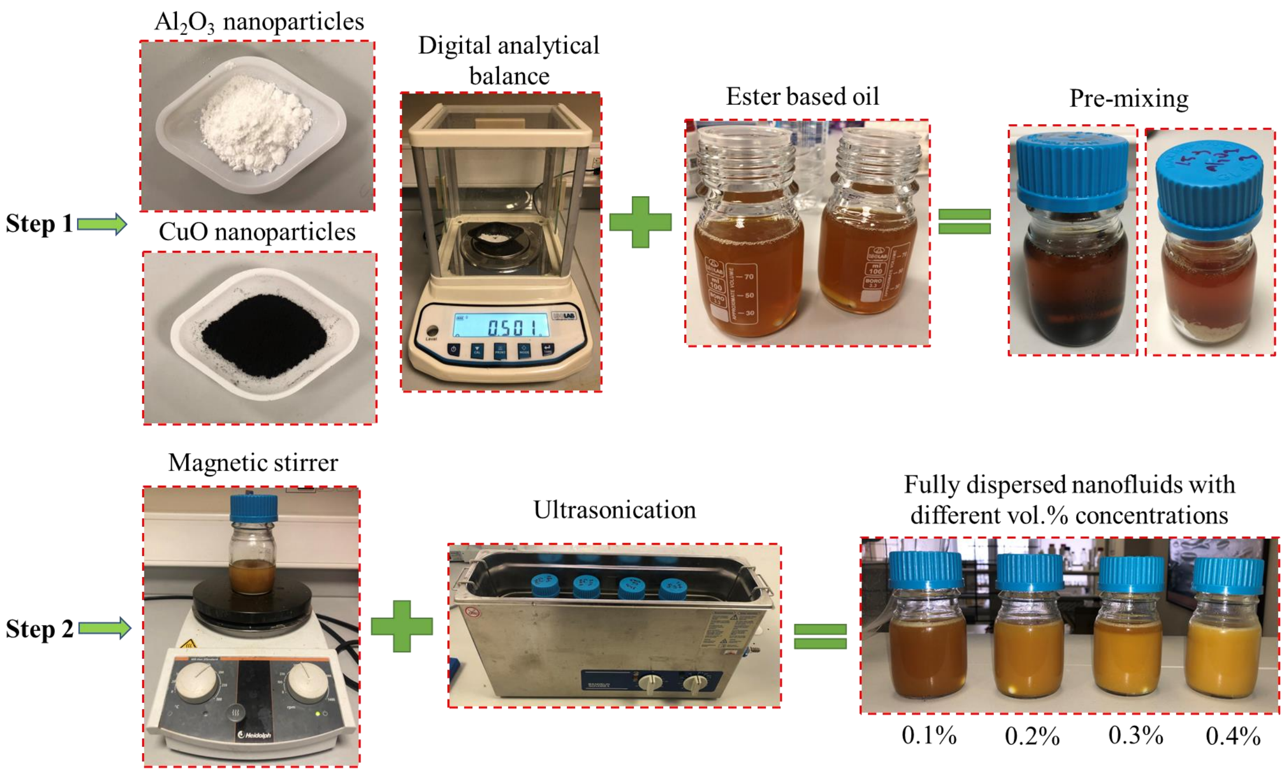


Figure 4 Steps for nanofluid preparation

Machining Conditions

Three pieces of Ti-6Al-4V workpiece material with dimensions of 75 mm x 78 mm x 15 mm were used. The mechanical properties of Ti-6Al-4V can be seen in Table 2. Microstructure of the workpiece material used in the experiments is shown in Figure 5. The slot milling experiments were carried out on Akira Seiki© SR3XP CNC milling center.

Table 2 Chemical composition of Ti-6Al-4V used in the experiments

Component	Ti	Al	V	Fe (Max.)	Other
Wt. %	90	6	4	0.25	0.4

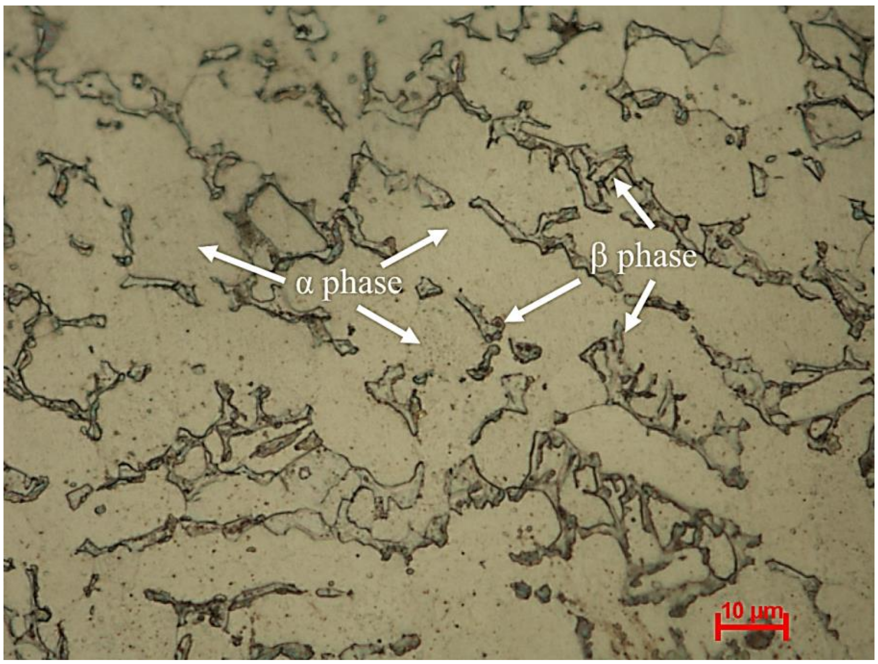


Figure 5 Microstructure of the Ti-6Al-4V workpiece

Different cooling types were employed in the experiments to compare them with the traditional methods of CCF and dry conditions. The characteristics of the oils employed in the experiments are presented in Table 3. For the CCF experiments, a vegetable-based oil was utilized as the cutting fluid, with an oil to water mixing ratio of 8%, a spray pressure of 3 bar, and an average flow rate of 500 l/h. In all MQL applications (pure-MQL, NMQL, and HNMQL), a biodegradable polymeric ester-based oil was used, featuring a spray pressure of 6 bar and an average flow rate of 50 ml/h. In both CCF and MQL applications, dual external nozzles were employed, and the spraying process was executed by configuring the angle to 45 degrees relative to the cutting area.

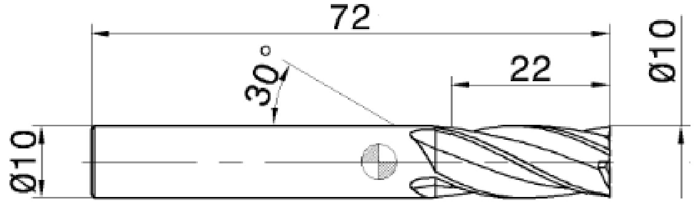
Table 3 Cutting oil properties

Coolant type	Base material	Density (g/ml @ 20°C)	pH	Appearance
Conventional Cutting Fluid	Vegetable based	1.03	9.5	Light brown
MQL Base Oil	Polymeric Ester	0.96	7.37	Brown

Iscar brand EC-A4 100-22C10-72 model four flute solid carbide end mills were used for all experiments. The detailed information of the cutting tool is given in Table 4. While cutting tool manufacturers typically offer recommended cutting conditions for certain materials, the potential for chatter issue remains a significant concern. Chatter is a notable issue in the milling process and can directly impact the outcomes (Budak and Altintas¸ Y., 1998). To mitigate the risk of chatter problems, tap testing was conducted on the cutting tool and assessed using CutPro© Simulation Software (Altintas, 2000; "MAL Manufacturing Automation Lab. Inc.," 2023) to obtain stability lobes to find out stable cutting zone. Based on the stability lobes obtained (as shown in Figure 6), the slot milling test parameters were determined as follows: a cutting speed of 94.82 m/min, a feed rate of 0.07 mm/tooth, and a depth of cut of 1 mm. A full slot with length of 78 mm was cut for each experiment. Three preliminary tests with dry cutting were conducted, and during the cutting tests, sound of cut was recorded with PCB brand 130A24 model microphone and National Instruments brand NI-9234 model data acquisition device and analyzed in CutPro Data Acquisition Module. Based on Fast Fourier Transform (FFT) of measured sound data (Figure 7), no chatter vibration was observed. The general experimental conditions can be seen in

Table 5 and the experimental setup is shown in Figure 8.

Table 4 Cutting tool specifications



Diameter (mm)	**Helix angle (°)**	**Effective length (mm)**	**Base material**	**Number of teeth**	**Coating**
10	30	22	Carbide	4	TiAlN

Table 5 The experimental factors

Cooling types	Dry	CCF	Pure-MQL	Al_2O_3-NMQL	CuO-NMQL	Hybrid-NMQL (Al_2O_3+CuO)
Nanoparticle Concentrations (vol. %)		0.5	1		1.5	2
Cutting speed (m/min)				94.82		
Feed (mm/tooth)				0.07		
Depth of cut				1		

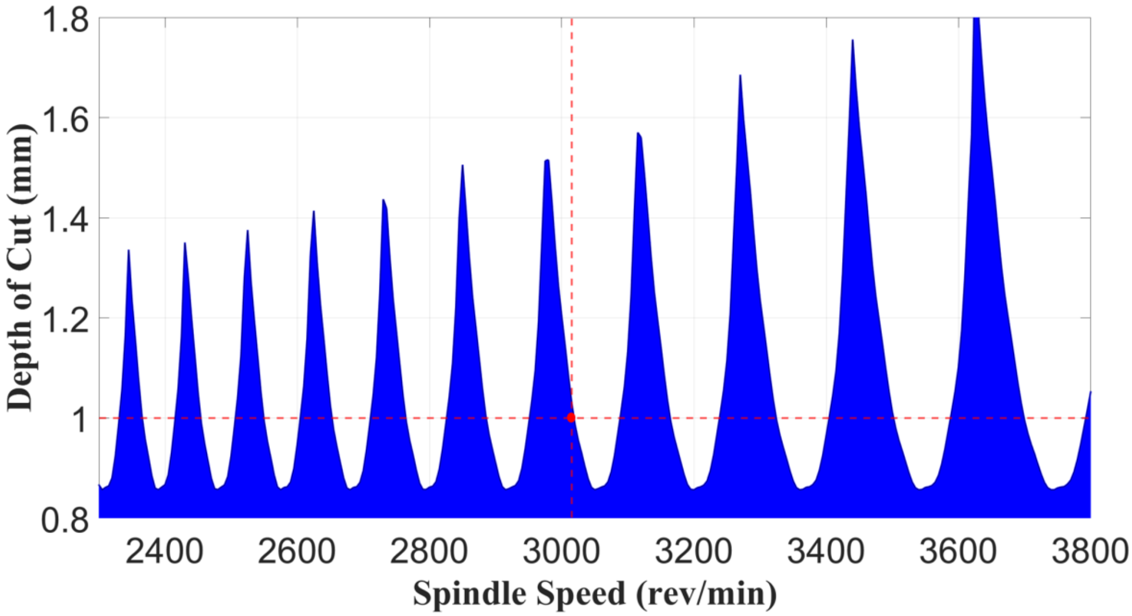


Figure 6 Stability lobes simulated from CutPro Simulation Software

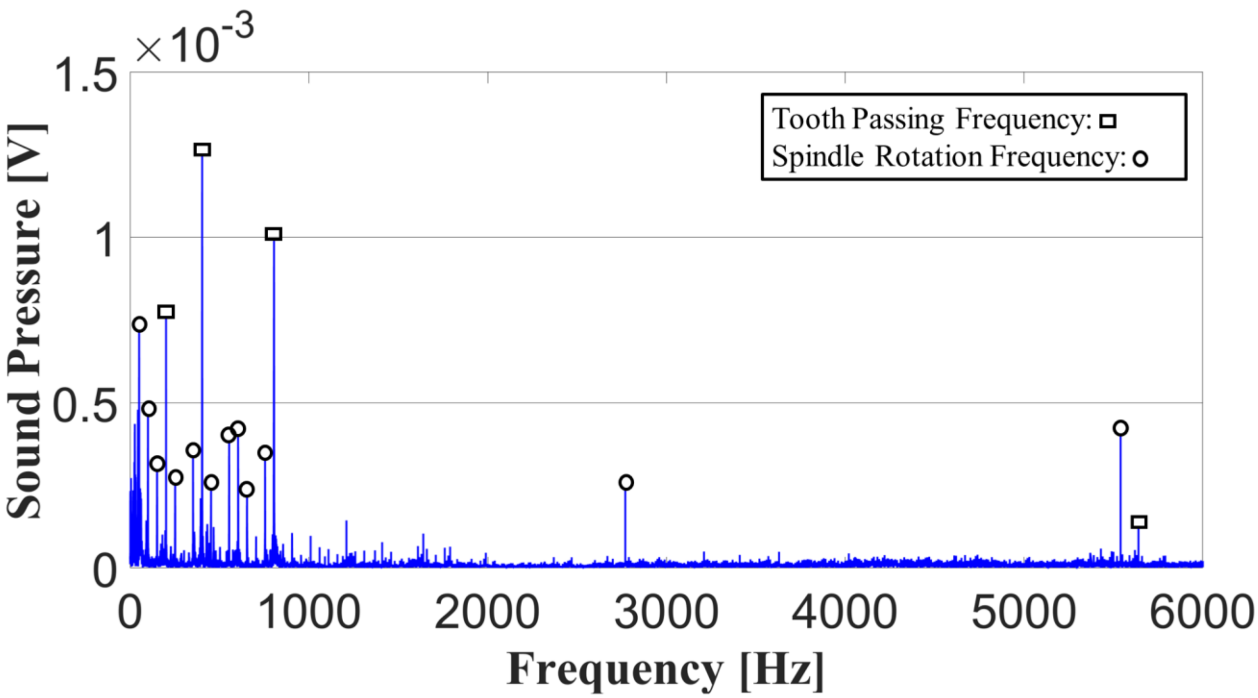


Figure 7 FFT of measured cutting sound data

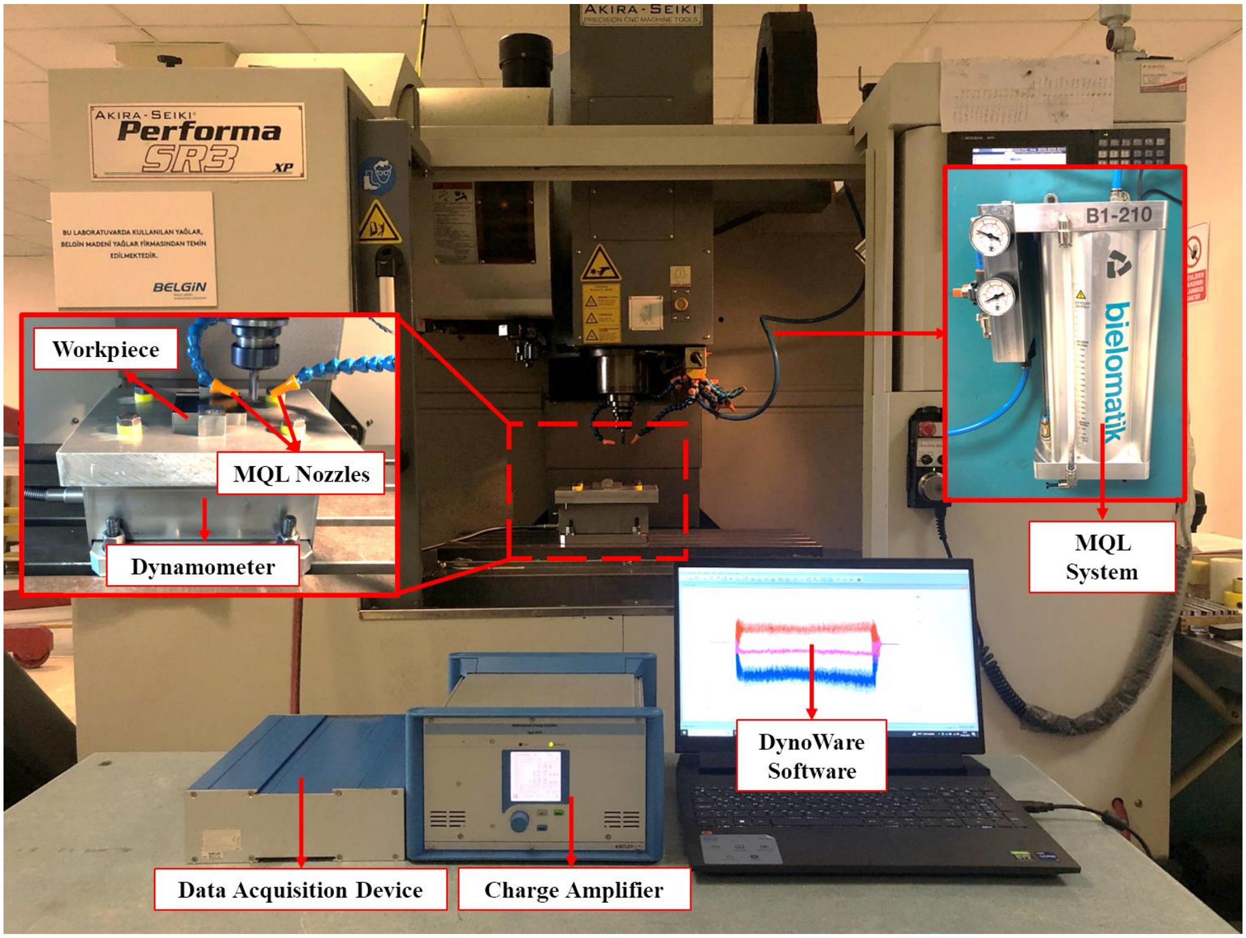


Figure 8 The experimental setup

Measurement Tools and Techniques

The wettability measurement setup was done by ThetaLite© Optical Tensiometer equipped with OneAttension© software. Optical Tensiometer was utilized to quantify the contact angle (θ) with the help of sessile drop test and surface tension (γ) with the help of pendant drop test. A syringe was employed to dispense the cutting fluid sample meticulously and accurately onto the surfaces of the polished Ti-6Al-4V workpiece. The drop was then allowed to stabilize for a 10 second period. The contact angle of the drop formed on the workpiece surface was subsequently precisely measured using the built-in software, alongside an image captured by the camera connected to the instrument. Prior to each test, the sample surfaces were thoroughly cleaned with ethanol and dried.

The cutting forces were measured using a three-component piezoelectric quartz crystal dynamometer (Kistler 9256B) equipped with a data acquisition system (Kistler 5697A1) and a charge amplifier (Kistler 5070). The acquired data were saved and processed using signal analyzer software (Kistler Dynoware). The sampling frequency of the measurements were set to 100 kHz. The average value of the resultant cutting force during the stable cutting phase (after excluding the slot enter and exit phases) was calculated.

After conducting the cutting tests, the Alicona InfiniteFocus, an optical 3D surface measurement device, was utilized to obtain the 3D surface form of the middle of the slots. The data acquired from Alicona InfiniteFocus was then evaluated using Gwyddion software (Nečas and Klapetek, 2012) to determine the areal surface roughness (Sa) and 3D surface topography. Optical microscope images were taken from Nikon LV150N industrial microscope for evaluation of surface texture to see surface defects.

The impact of cutting conditions on the microhardness below the machined surface was investigated through metallographic preparation of the specimens. This involved cutting the slots using Wire Electrical Discharge Machining (WEDM), followed by mounting, grinding with 60, 120, 300, 600, 1200, 2400-grit abrasive paper, polishing with 3 μm diamond solution, and etching with Kroll's reagent containing 2 ml HF, 6 ml HNO_3 and 92 ml H_2O for a duration of 20 seconds. The microhardness beneath the machined surface was assessed using ZwickRoell ZHV10 model Vickers hardness tester with a 300 g load applied for 10 seconds. Microhardness measurements were conducted at depths of 50, 100, 150, 200, 250, 300 and 350 μm along the radial direction underneath the surface and calculated by testXpert software. Three measurements were taken at each depth, and their average was calculated to determine the variation in microhardness. The flow and the measurement steps of the study can be seen in Figure 9. The measurement tools can be seen in Figure 10.

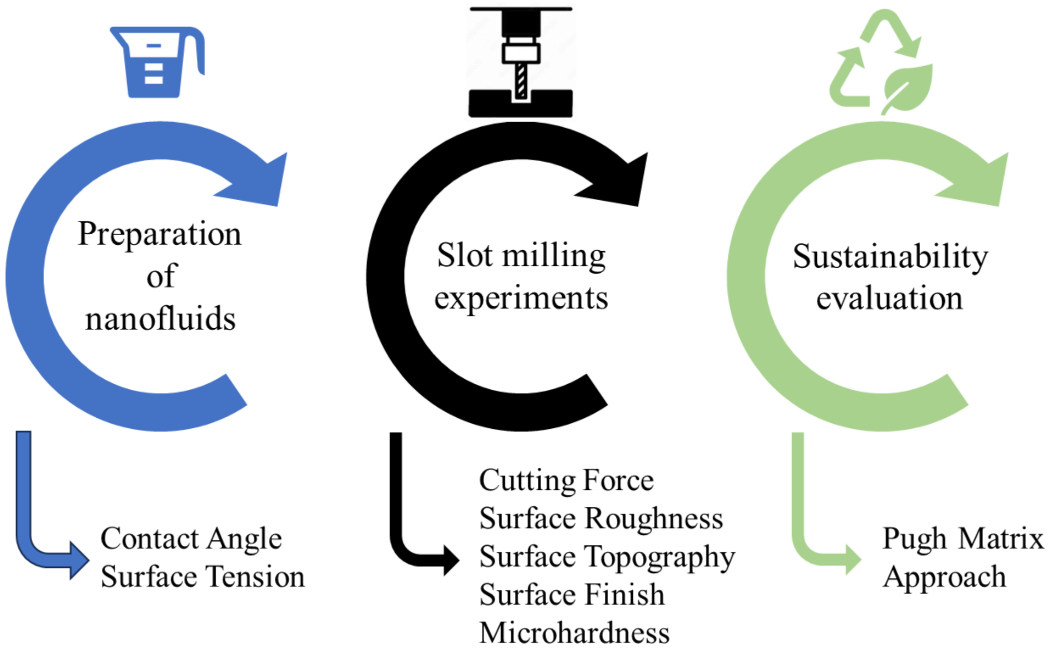


Figure 9 The flow and the evaluation steps of the study

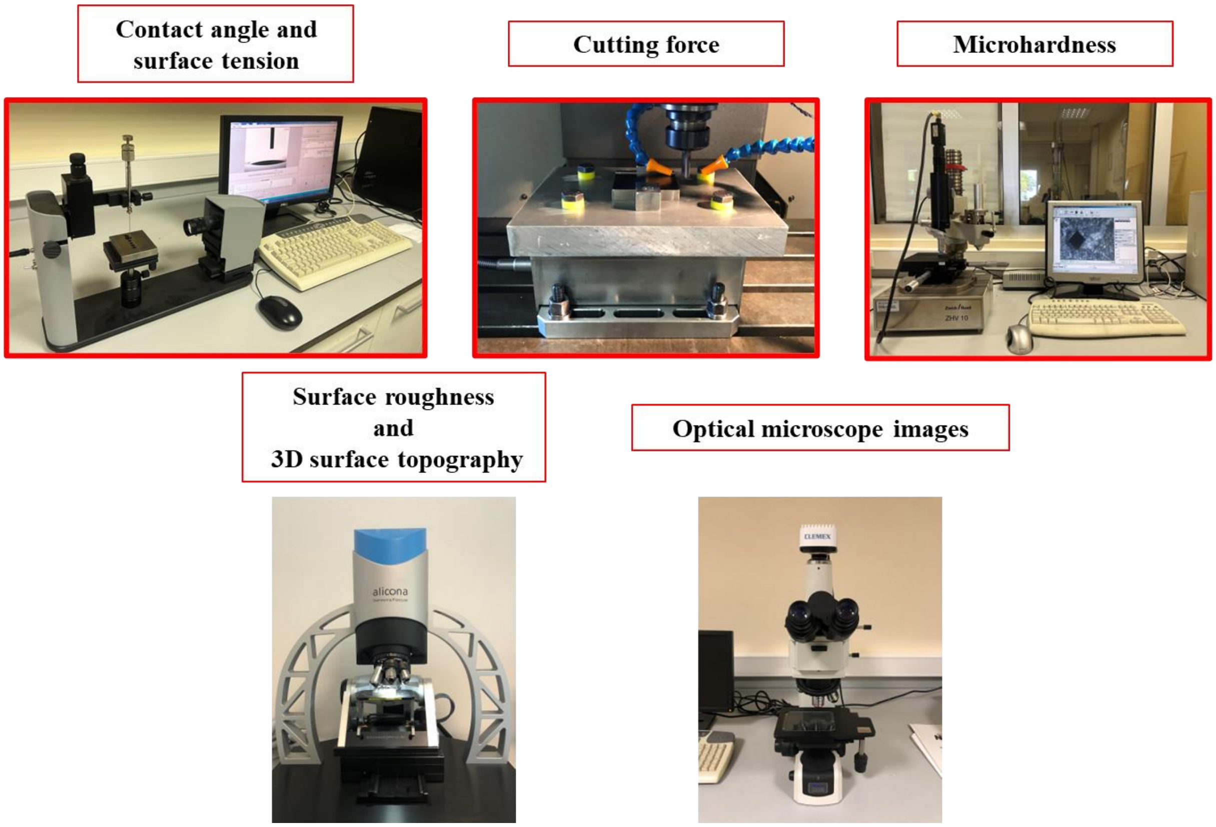


Figure 10 Measurement tools

Results and discussion

Physical Properties of Coolants

Contact Angle

Wettability is a term employed to characterize the capacity of a fluid to spread, infiltrate, and envelop both the tool and workpiece. It is generally based on the contact angle and surface tension. The degree of wettability of the fluid is inversely proportional to the contact angle, indicating that a smaller contact angle corresponds to a higher degree of wettability. Consequently, a smaller contact angle results in a larger area of liquid diffusion on the solid surface, thereby enhancing the lubrication effect. The determination of the contact angle (θ) relies on Young's formula (Young,

1805) which can be seen in Equation (4) where γ_{SG} indicates solid-gas, γ_{SL} denotes solid-liquid and γ_{LG} represents liquid-gas interfacial tensions.

$$\cos\theta = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}} \quad (4)$$

When MQL is administered in the form of an aerosol, it permeates the cutting zone in the form of small droplets. Analyzing the wettability of these droplets enables a clearer understanding of their contribution to the performance of the machining process.

As depicted in Figure 11, the contact angle of CCF is measured at 65 degrees, while that of the pure-MQL is recorded at 57 degrees. Given that a lower contact angle indicates higher wettability, the reduced contact angle of the MQL application, which exhibits a 12.3% decrease compared to CCF, signifies a more successful cutting performance by facilitating lubrication across a larger surface area (Tai et al., 2011). When comparing the contact angle of pure-MQL with that of the NMQL applications, it is observed that the incorporation of nanoparticles leads to a reduction in contact angle. Specifically, Al_2O_3-NMQL demonstrates a contact angle reduction of up to 64.4%, CuO-NMQL exhibits a reduction of up to 13.8%, and HNMQL showcases a substantial reduction of up to 53.5% compared to pure-MQL. This reduction in contact angle resulting from the presence of nanoparticles leads to an increased lubrication film size between the cutting tool and workpiece, thereby enhancing lubrication efficiency and augmenting the impact of nanoparticles within the NMQL system (Khandekar et al., 2012). Among the NMQL applications, Al_2O_3-NMQL yields the lowest contact angle, followed by HNMQL and CuO-NMQL, respectively. This observation can be attributed to the average particle size, according to Vafaei et al. (2006), smaller nanoparticle size leads to more surface-to-volume area and with Al_2O_3 nanoparticles, having the lowest average particle size, promoting greater wettability, whereas HNMQL and CuO-NMQL exhibit comparatively lower wettability due to their relatively higher average particle sizes. In the investigation of vol.% concentrations in NMQL applications, it was found that the contact angle increased as the mass fraction of nanoparticles escalated. This phenomenon can be attributed to the fact that as the quantity of nanoparticles in the MQL oil rises, there is a tendency for the nanoparticles to aggregate and form larger clusters due to increased adhesion. Existing literature suggests that an increase in nanoparticle size generally leads to an elevation in contact angle (Channa et al., 2022; Khan et al., 2019).

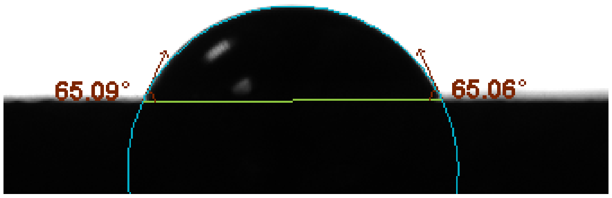
Surface Tension

Surface tension is the inherent property of a liquid at rest, whereby its surfaces tend to contract to achieve the minimal possible surface area. It is quantitatively described as the force exerted per unit length or the energy expended per unit area. The substantial surface tension of a liquid causes droplets to spread on a material surface, behaving akin to an elastic layer on the droplet's interface. Consequently, this limits the droplet's ability to provide sufficient lubrication between the cutting tool and the workpiece. The pendent drop technique is commonly employed for the precise measurement of surface tension in metals, alloys, and polymers (Jouyban and Fathi-Azarbayj, 2012). This technique utilizes the Bashforth and Adams equation, which is derived from Laplace's equation, to establish a correlation between the drop profile and the interfacial tension. The equation for calculating the interfacial tension through this method is shown in Equation 5:

$$\gamma = \frac{\Delta\rho g {D_e}^2}{H} \tag{5}$$

In the equation, the symbol g represents the gravitational constant, while $\Delta\rho$ indicates the disparity in densities between the droplet and its surrounding environment. The variable D denotes the equatorial diameter of the droplet at its apex, and H corresponds to the shape factor that encompasses the fluid's properties (Andreas et al., 1938).

According to Khandekar (2012), the overall surface tension of liquids is greatly influenced by Van der Waals forces, and the characteristic length scale associated with these forces ranges from approximately 1 nm to 100 nm, which aligns with the size range of nanoparticles. Consequently, the introduction of nanoparticles is anticipated to impact the net free energy of the interface between the pure fluid, solid substrate, and surrounding air. Figure 12 illustrates that the utilization of MQL leads to a reduction in surface tension compared to CCF. Furthermore, the decrease in surface tension is more pronounced in NMQL applications, with Al_2O_3-NMQL applications exhibiting the lowest average surface tension. Variations in the densities of nanoparticles give rise to alterations in the intermolecular attraction between the nanoparticles and oil molecules. Consequently, the Van der Waals forces at the liquid surface undergo modifications, leading to fluctuations in surface tension across different nanofluids. Notably, the nanofluid with the least density of Al_2O_3 exhibited the most minimal surface tension results, whereas the nanofluid with CuO-NMQL demonstrated the highest values (Bhuiyan et al., 2015). It has been observed that an increase in nanoparticle concentration elevates surface tension. This can be attributed to the attractive van der Waals forces counteracting the electrostatic repulsive forces between molecules. Consequently, the surface tension of nanofluids rises as the average distance between molecules and nanoparticles decreases with increasing concentration (Bhuiyan et al., 2015).



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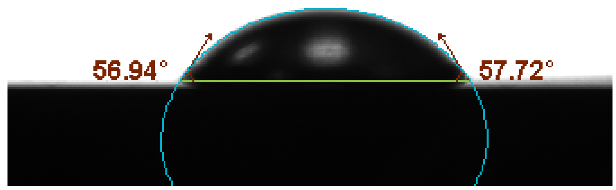
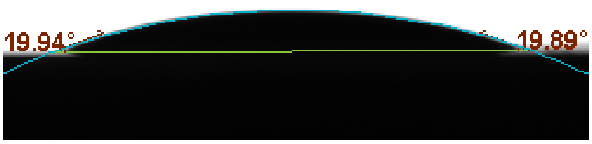


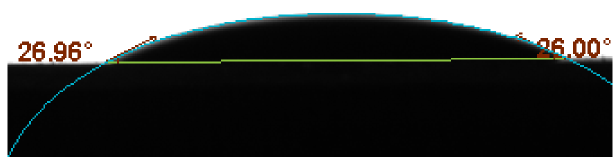
Pure-MQL



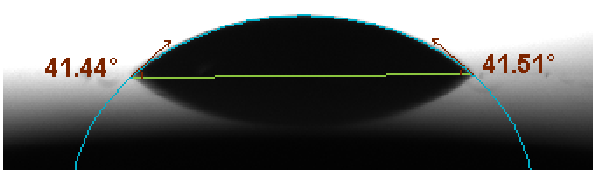
Al_2O_3-0.5%

Al_2O_3-1%

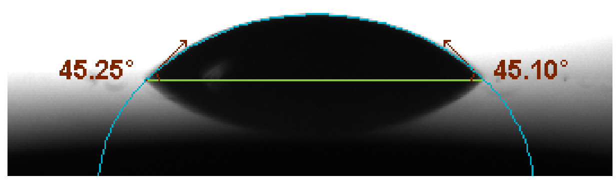
Al_2O_3-1.5%



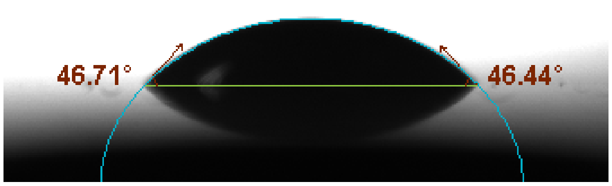
Al_2O_3-2%



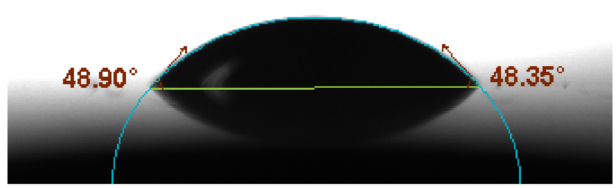
CuO-0.5%



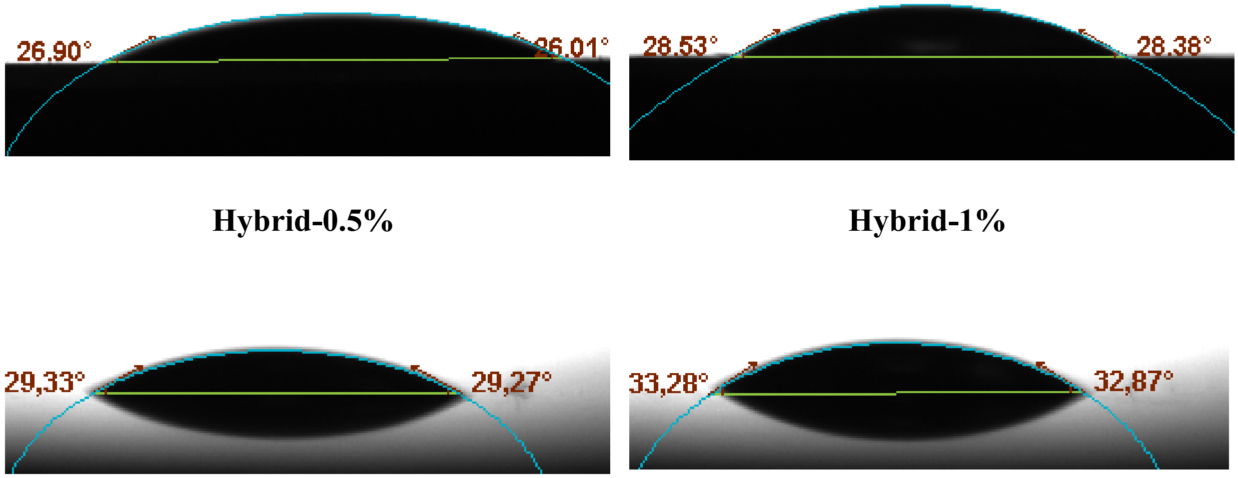
CuO-1%



CuO-1.5%



CuO-2%



Hybrid-0.5% **Hybrid-1%**

Hybrid-1.5% **Hybrid-2%**

Figure 11 Contact angle measurements 10 seconds after drop

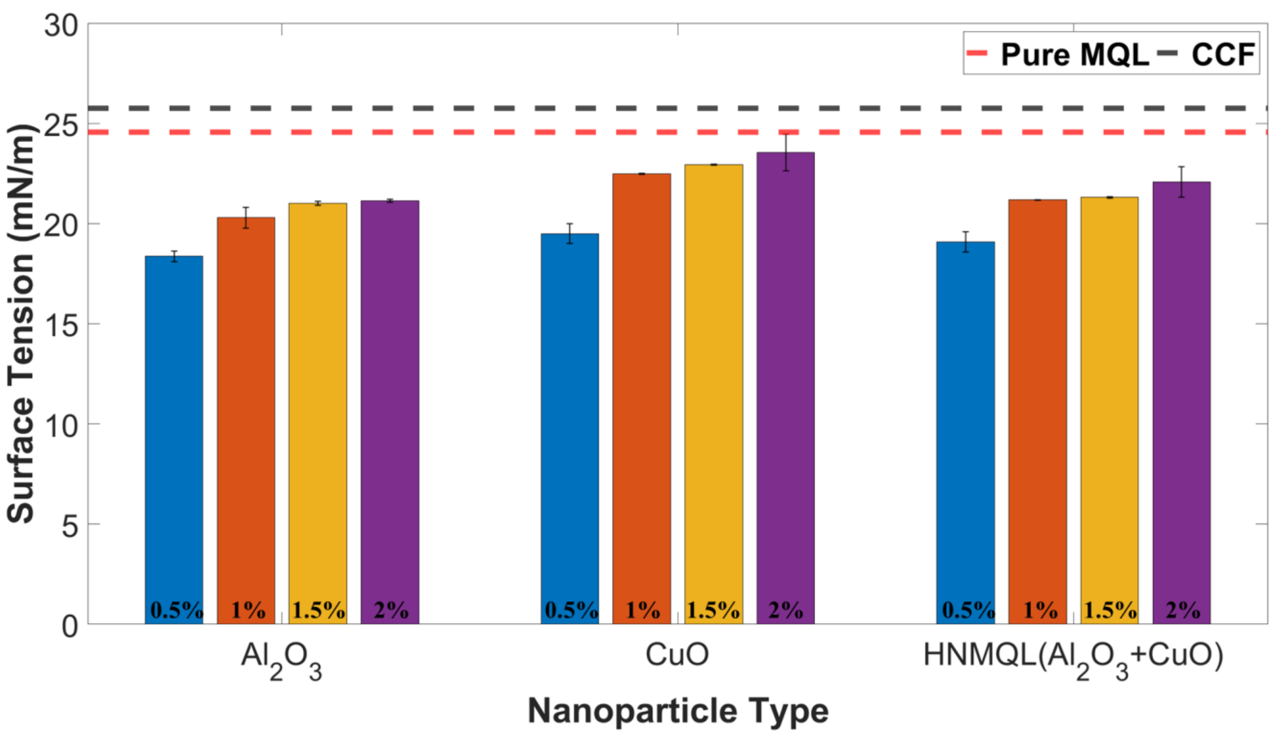


Figure 12 Surface tension results

Cutting Force

In order to measure the cutting forces, the entry and exit stages of the cutting process were eliminated, and the most stable phase of cutting was selected, as depicted in Figure 13Figure 14. The average value of the dynamic cutting forces during the stable phase was used to calculate the resultant cutting force, employing Equation 6 (Altintas, 2012).

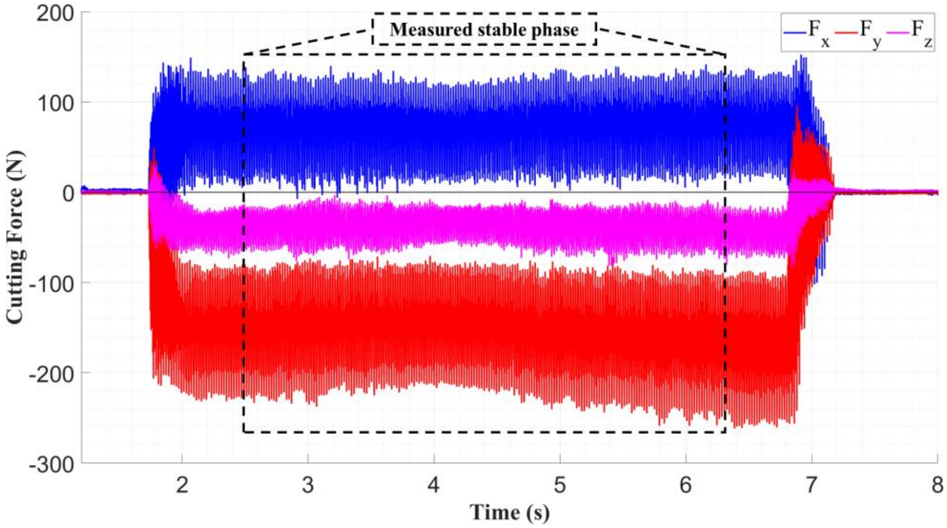


Figure 13 Cutting force signals during cutting

$$F_R = \sqrt{{F_X}^2 + {F_Y}^2 + {F_Z}^2} \quad (6)$$

The cutting force results obtained from all experiments are presented in Figure 14. The findings reveal that HNMQL exhibited the lowest cutting forces among all the cooling techniques investigated. CuO-NMQL and Al_2O_3-NMQL followed HNMQL, while pure-MQL showed slightly higher cutting forces. Dry cutting, on the other hand, resulted in the highest cutting forces.

Pure-MQL resulted in cutting forces that were 5.12% lower than CCF and 8.17% lower than dry cutting. In MQL applications, a mixture of cutting fluid and compressed air is sprayed into the cutting area in the form of an aerosol. This aerosol is capable of better penetration between the cutting tool and the workpiece, resulting in increased lubrication and cooling capacity (Airao et al., 2022). As a result, MQL is known to be a more efficient process compared to CCF and dry cutting method (Namlu et al., 2021). NMQL applications, on the other hand, resulted in increased reduction rates compared to pure-MQL. Specifically, Al_2O_3-NMQL decreased cutting forces by 3.13% to 13.26% compared to pure-MQL, while CuO-NMQL showed reductions of 9.78% to 20.28%. Previous studies have shown that the addition of Al_2O_3 nanoparticles can improve the machining efficiency of Ti-6Al-4V material by enhancing friction and wear reduction rates (Bai et al., 2019). Similarly, CuO nanoparticles are known to create a ball bearing effect due to their spherical structure and exhibit high thermal conductivity (Chaudhari et al., 2019).

While HNMQL provides a 9% to 41.56% reduction in cutting forces compared to Al_2O_3-NMQL, this reduction ratio is between 1% and 37.25% compared to CuO-NMQL. A noteworthy characteristic of HNMQL is its capacity to combine the advantageous properties of each nanoparticle with which it is mixed. According to the results, HNMQL exhibited the combined effects of both Al_2O_3 and CuO nanoparticles. The spherical shape of both nanoparticles enhances the ball-bearing effect, reducing friction, which is highly influential in cutting force formation and, thus, contributes to reduction. Furthermore, combining the high heat transfer capacity of CuO nanoparticles with Al_2O_3's enhanced wear reduction rate enhances efficiency compared to using nanoparticles individually, ultimately reducing cutting forces. It is worth noting that the literature also supports the idea that combining different nanoparticles to leverage their advantages plays a role in reducing cutting forces in HNMQL applications (Jamil et al., 2022; Şirin and Kıvak, 2021). Also, the implementation of HNMQL resulted in a significant reduction in cutting force, ranging from 27.5% to 48.39% compared to dry cutting and from 21.1% to 43.8% compared to pure-MQL.

When comparing the nanoparticles in NMQL application, it was observed that CuO-NMQL generally resulted in lower cutting forces up to 17.71% compared to Al_2O_3-NMQL. One of the key challenges in machining of Ti-6Al-4V material is its low thermal conductivity, which leads to concentrated heat in the cutting zone, causing tool damage and high cutting forces (Namlu et al., 2021) However, the high thermal conductivity of CuO nanoparticles, combined with their spherical shape that increases surface area, facilitates heat dissipation in the cutting zone, thereby reducing the accumulation of heat. This is supported by previous studies that have reported higher thermal conductivity of CuO compared to Al_2O_3 (Chaudhari et al., 2019).

When examining the cutting forces of different nanoparticle volume concentrations in NMQL applications, varying results were observed. In experiments with CuO-NMQL, cutting forces decreased by 5.7% when nanoparticle concentration increased from 0.5% to 1%, decreased by 4.3% from 1% to 1.5%, but increased by 11.6% from 1.5% to 2%. On the other hand, in Al_2O_3-NMQL, cutting forces decreased by 5.4% as nanoparticle concentration increased from 0.5% to 1%, but increased by 9.4% from 1% to 1.5%, and further increased by 1.2% from 1.5% to 2%. Similar trends were observed in HNMQL, where cutting forces decreased by 12.5% from 0.5% to 1%, but increased by 22.3% from 1% to 1.5%, and increased by 7.7% from 1.5% to 2%. These findings suggest that increasing nanoparticle concentration in NMQL applications leads to improvements in properties such as lubrication, friction, and heat transfer, likely due to special tribological mechanisms between the cutting tool and the workpiece. However, it appears that there is an optimum value for nanoparticle concentration, beyond which nanoparticles start to aggregate causing a significant increase in viscosity values. This high viscosity reduces flow between the cutting tool and the workpiece, which is contrary to the expected benefits of NMQL, resulting in increased cutting forces. Similar observations have been reported in numerous studies in the literature (Günan et al., 2020; Zaman et al., 2022).

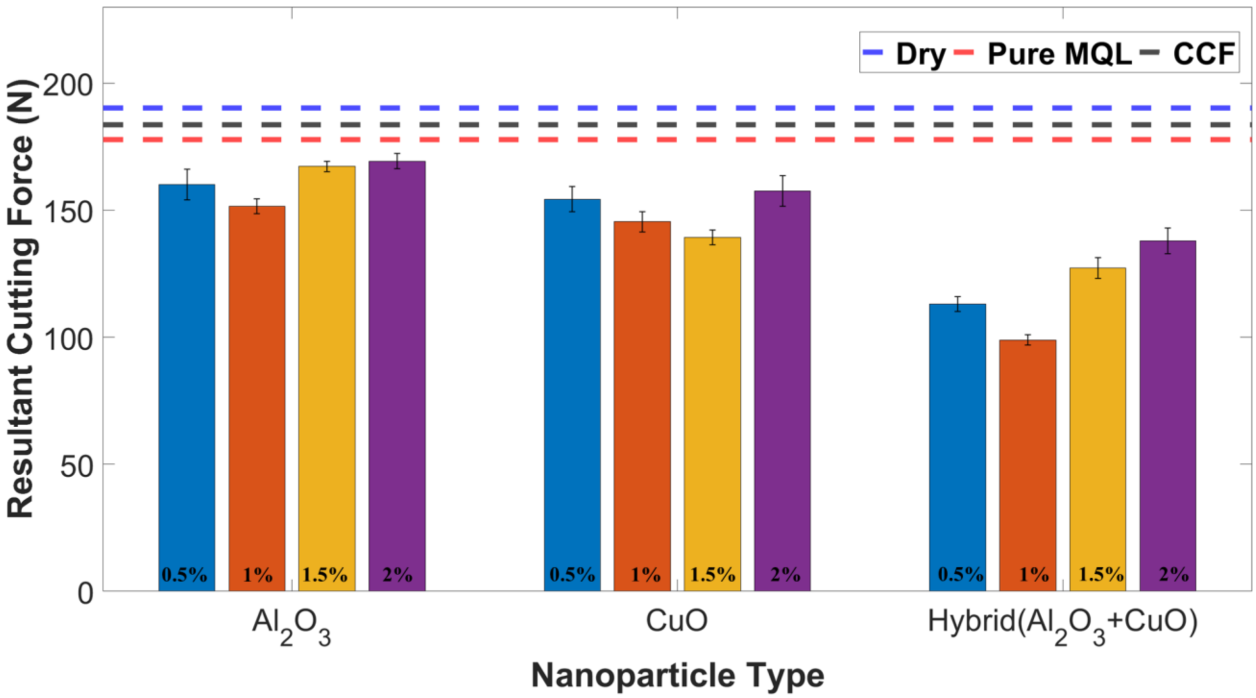


Figure 14 Cutting force results

Surface Roughness

The surface roughness is a critical parameter for evaluating the performance of machining operations, as it directly impacts the quality, performance, and cost of the final product. Therefore, achieving low surface roughness is of utmost importance in machining operations. The areal surface roughness values (Sa) obtained from the experiments are presented in Figure 15**Error! Reference source not found.**, where it can be observed that the highest performance in terms of surface roughness was achieved with HNMQL, followed by CuO-NMQL, Al_2O_3-NMQL, pure-MQL, CCF, and dry machining.

As previously mentioned, MQL demonstrates superior machining performance compared to CCF and dry machining due to its high penetration capability into the cutting zone. Pure-MQL reduced Sa values by 11.2% compared to CCF and 21.6% compared to dry machining. MQL achieves lower Sa values by enhancing the lubrication and cooling capacity between the cutting tool and the workpiece, as compared to CCF and dry machining. The advantages of MQL can be further enhanced with the addition of nanoparticles. Al_2O_3-NMQL resulted in 8.7% to 28.18% lower Sa values compared to pure-MQL. The spherical structure of Al_2O_3 nanoparticles reduces the coefficient of friction by minimizing sliding friction during cutting (Bai et al., 2019). This reduction in friction also leads to decreased tool wear, resulting in lower Sa values. In the case of CuO-NMQL, the reduction rates are between 24.8% and 29.83% compared to pure-MQL. The addition of CuO nanoparticles enhances the thermal conductivity capability of the base fluid, resulting in increased heat transfer rates into the cutting zone. The improved heat transfer capability of CuO-NMQL leads to lower Sa values by reducing the heat accumulation in the cutting zone.

In the case of HNMQL, the surface roughness values exhibited a decrease ranging from 8.94% to 52% when compared to Al_2O_3-NMQL a reduction of 6.5% to 41.7% when compared to CuO-NMQL, and a decrease between 34.6% to 56.2% compared to pure-MQL. This reduction in surface roughness can be attributed to the synergistic effects of Al_2O_3 and CuO nanoparticles, which contribute to friction reduction, enhanced lubrication and heat transfer capacity, and improved cutting performance at elevated levels.

In comparing the nanoparticles with each other, it was observed that CuO-NMQL resulted lower surface roughness values up to 23.4% compared to Al_2O_3-NMQL. This can be attributed to the higher heat transfer capacity of CuO compared to Al_2O_3, which is especially advantageous in machining Ti-6Al-4V due to its lower thermal conductivity (Chaudhari et al., 2019), as previously mentioned in cutting force section. The superior heat dissipation capability of CuO nanoparticles allows for more effective removal of heat accumulated in the cutting zone, leading to improved surface roughness values in CuO-NMQL compared to Al_2O_3-NMQL.

Nanoparticle concentration also plays a crucial role in determining the surface roughness values. Although it varies proportionally in Al_2O_3, CuO, and HNMQL, it has been observed that there exists an optimal nanoparticle volume percentage concentration for surface roughness improvement in each NMQL application. The lowest surface roughness values were obtained at concentrations of 1% in Al_2O_3-NMQL, 1.5% in CuO-NMQL, and 1% in HNMQL. As the nanoparticle concentration increases, the penetration of nanoparticles into the cutting zone also increases, leading to the formation of a protective film, which is one of the tribological mechanisms in NMQL applications, and subsequently reducing friction between the cutting tool and the workpiece. Moreover, higher nanoparticle concentration enhances the heat transfer capacity, resulting in increased heat removal from the cutting zone (Shabgard et al., 2017). However, beyond a certain concentration threshold, the increasing number of nanoparticles tends to aggregate, causing a decrease in the surface area per unit volume and consequently reducing the heat transfer rate. This aggregation also disrupts the spherical structure of nanoparticles, which in turn diminishes the effect of the rolling mechanism.

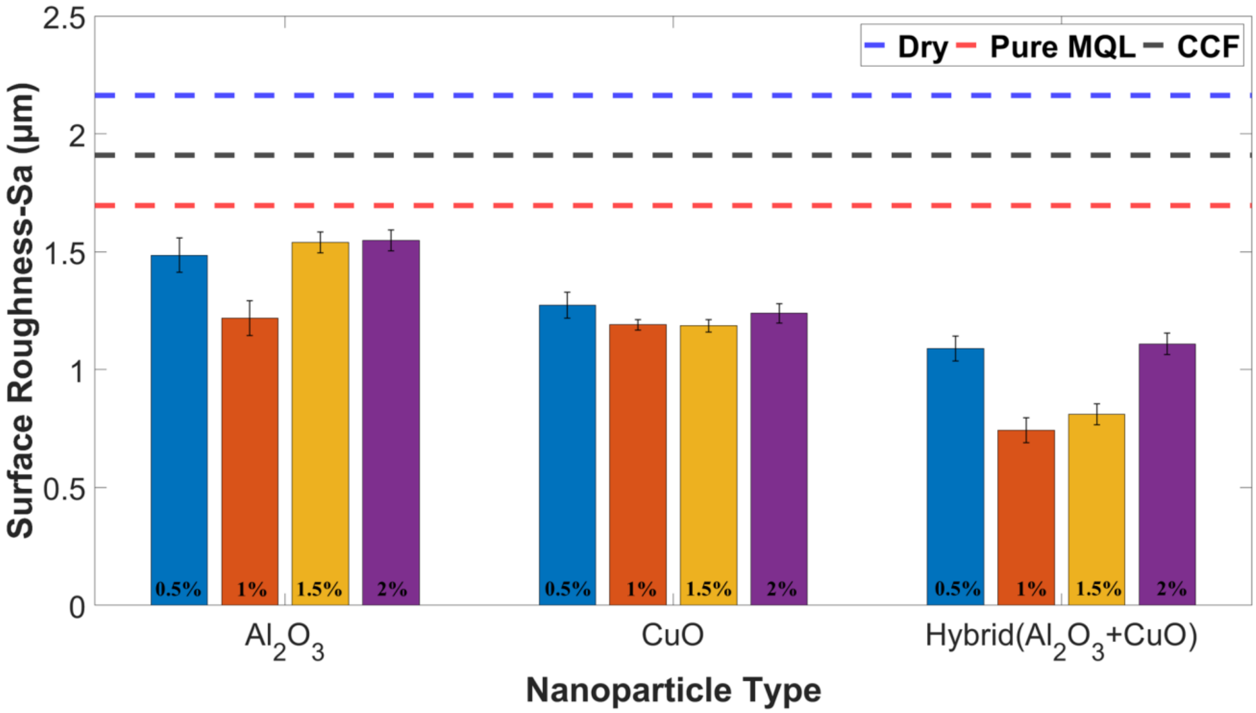


Figure 15 Surface roughness results

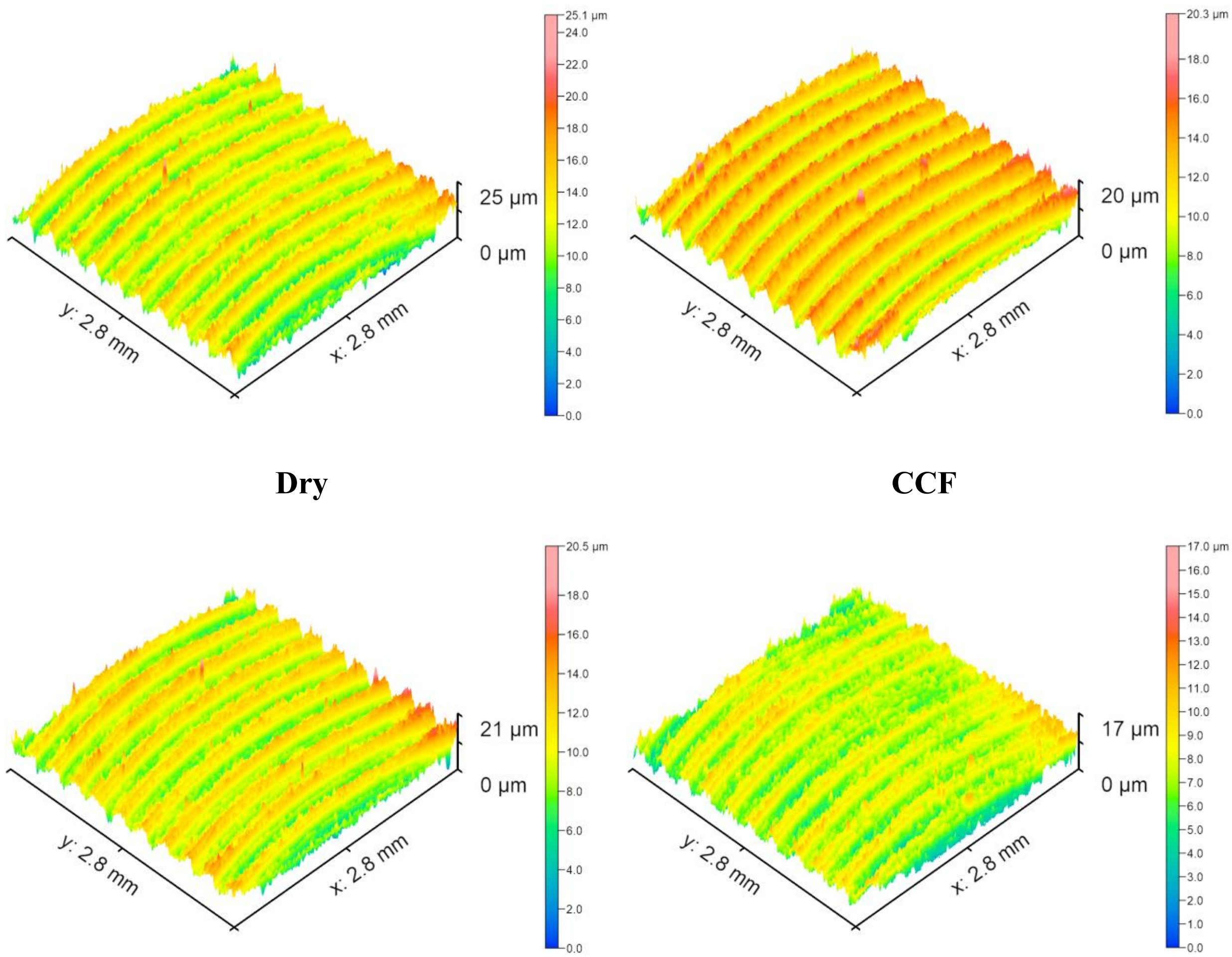
Surface Topography

Surface topography is a crucial and influential factor in establishing a relationship between process parameters and the performance of manufactured parts, as it directly impacts the service life of components. The analysis of three-dimensional (3D) surface topography aids in the detection of defects, porosities, and the evaluation of tribological behavior and surface appearance (Hassanpour et al., 2016). The experimental results of the 3D surface topography are depicted in Figure 16. It is noteworthy to mention that, in consideration of the surface roughness results, only the best surfaces of Al_2O_3, CuO, and HNMQLs are presented.

The applications of NMQL and HNMQL have been proven to exhibit highly desirable characteristics. These include the attainment of significantly lower peak-to-valley values, the generation of more uniform surfaces, and a diminished presence of surface dimples. Such attributes collectively signify the achievement of a smoother and more homogeneous surface texture, offering considerable advantages across a wide range of applications. The uniformity observed in the surfaces with NMQL and HNMQL techniques plays a vital role in enabling the provision of consistent and predictable performance characteristics. This becomes particularly advantageous in applications where the tribological behavior of components holds critical importance, specifically with regards to friction and wear. The ability to achieve and maintain uniform surfaces facilitates optimized lubrication, reduced frictional forces, and mitigated wear rates, thereby contributing to enhanced operational efficiency, prolonged lifespan of components, and improved reliability. By minimizing surface roughness variations and irregularities, NMQL and HNMQL techniques ensure a more controlled contact interface between mating components. This controlled contact aids in the distribution of loads more evenly, mitigating the concentration of stresses and potential localized damage. The resulting reduction in friction and wear enables smoother and more reliable operation, while also minimizing the risk of premature component failure.

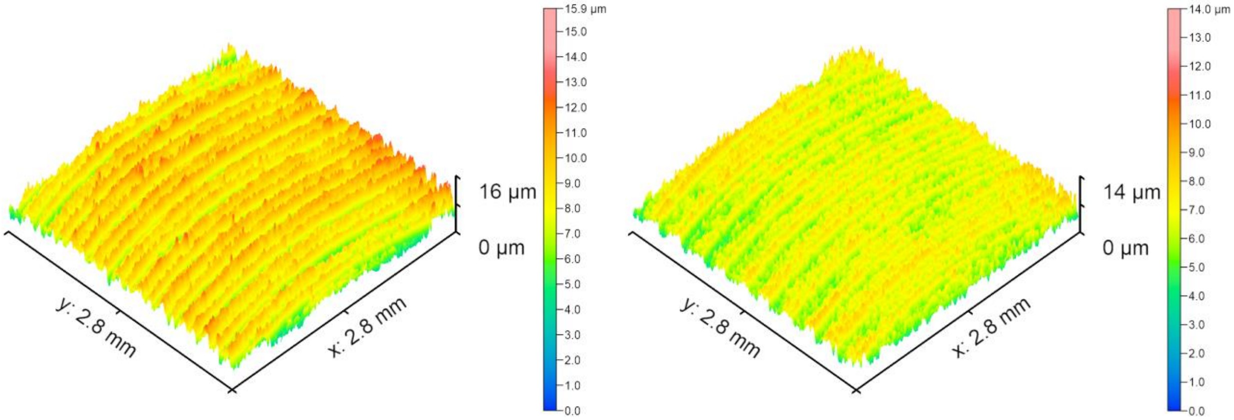
In contrast to the highly desirable characteristics observed in NMQLs and HNMQL, the outcomes under dry, CCF, and pure-MQL conditions are less favorable. These conditions are associated with relatively higher peak-to-valley values, resulting in surfaces that are characterized by unevenness and an increased occurrence of surface dimples. Such surface irregularities indicate a rougher and less uniform texture, which can have detrimental effects on the performance of components in various applications. The rough and uneven surface texture observed in dry, CCF, and pure-MQL conditions can lead to increased friction and wear. The higher peak-to-valley values create micro-scale peaks and valleys on the surface, resulting in more contact points and areas of localized stress during operation. As a consequence, the increased friction and stress concentration can accelerate wear, leading to reduced component lifespan and compromised reliability. Moreover, the presence of surface dimples in these conditions further exacerbates the tribological challenges. These dimples can act as potential stress concentrators, intensifying the contact pressures and frictional forces experienced by the mating components. The uneven surface texture and the increased occurrence of surface dimples create unfavorable conditions for effective lubrication and proper load distribution, further contributing to heightened friction and wear.

Notably, the application of NMQL enhances surface quality through unique capabilities, such as reduced friction in the case of Al_2O_3 and enhanced heat transfer capacity in the case of CuO, when compared to conventional methods. These results align with the areal surface roughness findings, further supporting the improved surface quality achieved through NMQL applications.



Dry **CCF**

Pure-MQL **Al_2O_3**



CuO **HNMQL**

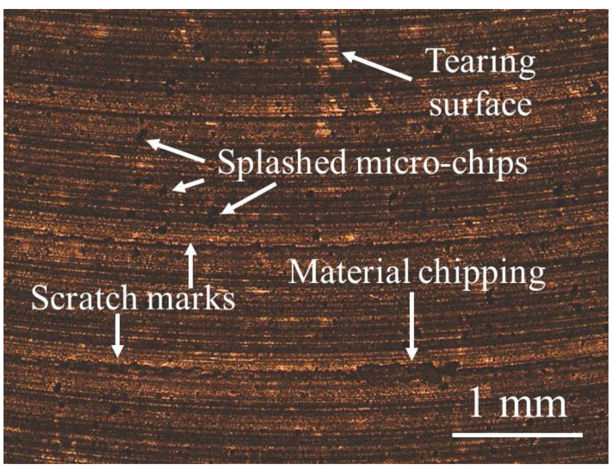
Figure 16 Surface topography images

Surface Texture

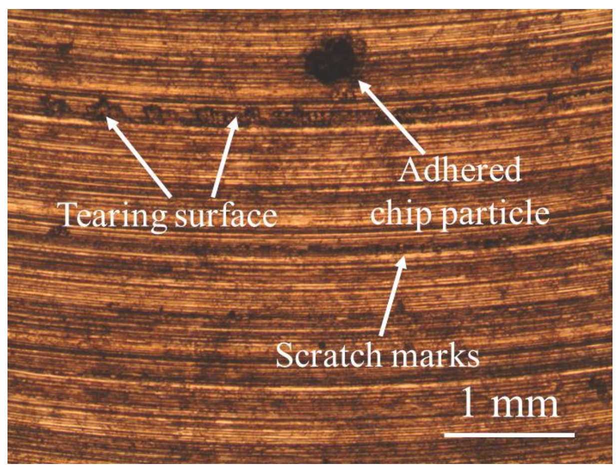
Optical microscope images play a pivotal role in assessing the surface texture by providing insights into the nature of defects, errors, and tribological phenomena that occur on a surface following an operation. Figure 17 displays the surface texture images acquired from the central region of the slots after conducting the experiments. It is worth noting that, given that nanoparticle concentrations do not exhibit visible distinctions in defect images when scrutinized under an optical microscope, the images of the superior surfaces obtained from each NMQL application, as indicated by the surface roughness results, are presented.

Based on the obtained images, it is evident that in dry cutting, the surface exhibits tearings and scratches. Additionally, material chipping and micro-chip adhesions are observed on the surface. In the case of the CCF image, apart from tearings and scratch marks, the surface showcases chip particles adhering to it. Conversely, no tearings are observed on the surface treated with pure-MQL however chip adhesions are noticed. NMQL applications yield more desirable surfaces with significantly lower defect rates. Among the NMQL applications, the HNMQL applied surface exhibits the fewest defects.

Tearings and scratch marks are generally indicative of plastic flow occurring on the material's surface, suggesting that the cutting quality is adversely affected, depending on the density of these observed defects. When chip particles adhere to the surface, it implies that the chip removal during cutting is not sufficiently smooth. Consequently, the evacuation of fragmented chips from the cutting area cannot be accomplished adequately, leading to their adherence to the surface. Considering these findings, it can be concluded that surfaces with NMQL and HNMQL methods possess higher quality, reduced defect occurrence, and greater uniformity. These results align with the data obtained from surface roughness and 3D surface topography analyses.



Dry



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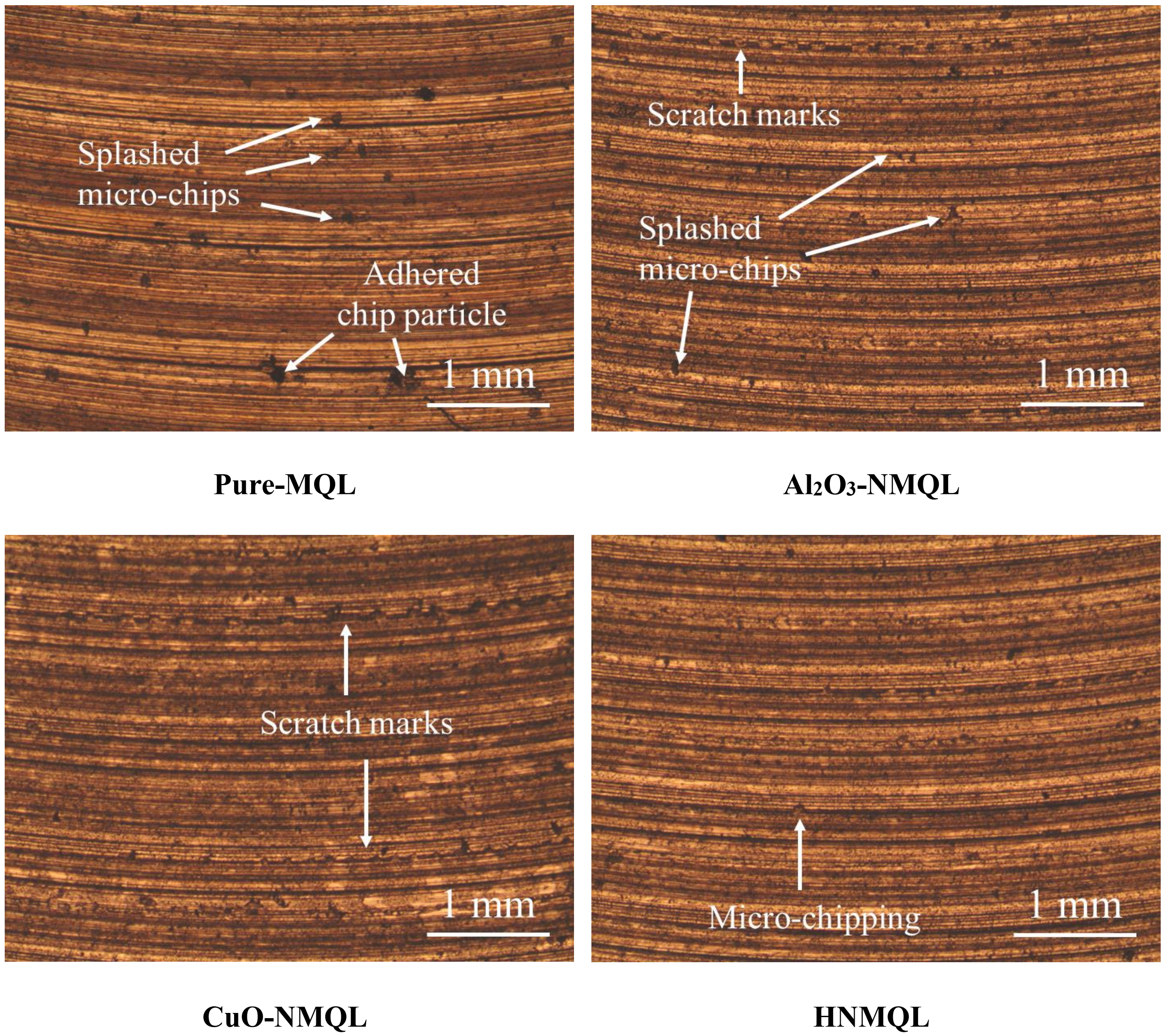

Figure 17 The optical microscope images

Microhardness

Microhardness serves as a valuable metric for assessing the subsurface characteristics of machined components, including surface integrity and the mechanical behavior of the material. To determine microhardness, the workpiece is cross-sectionally cut using a WEDM technique. Subsequently, surface treatments such as grinding, polishing, and etching are conducted to facilitate microhardness measurement. The representation of microhardness measurement steps can be seen in Figure 18.

Figure 19 presents the microhardness values obtained from the subsurface of the workpiece after each experimental trial. Distinct trends were observed with the application of various cooling techniques. In the case of dry cutting, the microhardness value initially decreases until reaching a depth ≈100 µm, followed by a subsequent increase. The material Ti-6Al-4V is recognized for its inadequate thermal conductivity. Consequently, in the absence of cooling and lubrication during dry cutting, thermal softening near the surface may transpire. This thermal softening effect can lead to a reduction in the microhardness of the material up to a specific depth (Makhesana et al., 2021). Once this specific depth is reached, the thermal softening effect diminishes, giving way to plastic deformation, which, in turn, leads to an increase in microhardness. Nevertheless, the dry condition consistently yielded the highest microhardness values in comparison to the other cooling conditions. In the investigation of other cooling strategies, the CCF condition exhibited higher microhardness values compared to pure-MQL, while the NMQLs demonstrated the lowest microhardness values among the investigated conditions. It is noteworthy to mention that among the different nanoparticle types, HNMQL resulted in the lowest microhardness values, followed by CuO and Al_2O_3. In all MQL and CCF applications, it is evident that the microhardness values of these conditions in the near surface region are higher compared to the microhardness of the bulk material. However, a consistent trend is observed as the microhardness gradually decreases towards the bulk hardness value when measurements are taken at greater distances from the surface. This trend is generally attributed to the work hardening effect resulting from plastic deformation, which facilitates the accumulation of atomic dislocations (Liao et al., 2021). The cutting force analysis indicated that higher cutting forces were observed in CCF, followed by pure-MQL, while the lowest forces were recorded in NMQL applications. The increase in cutting force leads to elevated cutting pressure, subsequently promoting greater work hardening and, ultimately, contributing to increased plastic deformation. Furthermore, it should be noted that pure-MQL and NMQL conditions are known to facilitate an accelerated cooling strategy in comparison to CCF and dry conditions. As a result, the thermal loads experienced during the cutting process may be reduced with the help of MQL applications. This thermo-mechanical load approach can offer an explanation for the observed trends in microhardness values during the operation, as it is analogous to the effects of the type of nanoparticle and concentrations of the nanofluids on microhardness values, similar to the outcomes obtained from cutting force analysis and plastic deformation measurements.

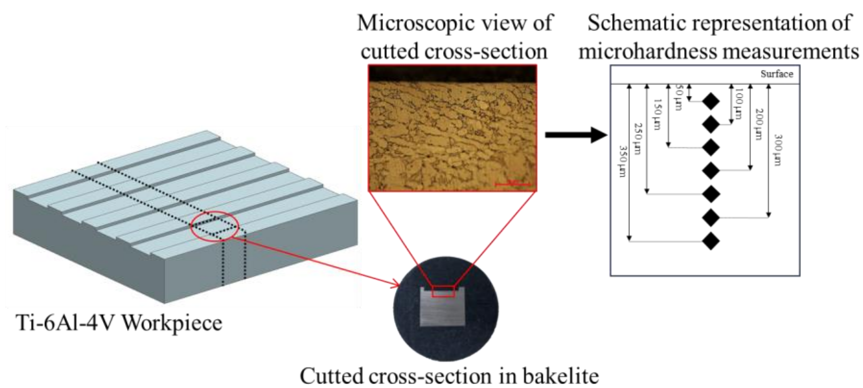

Figure 18 Microhardness measurement steps

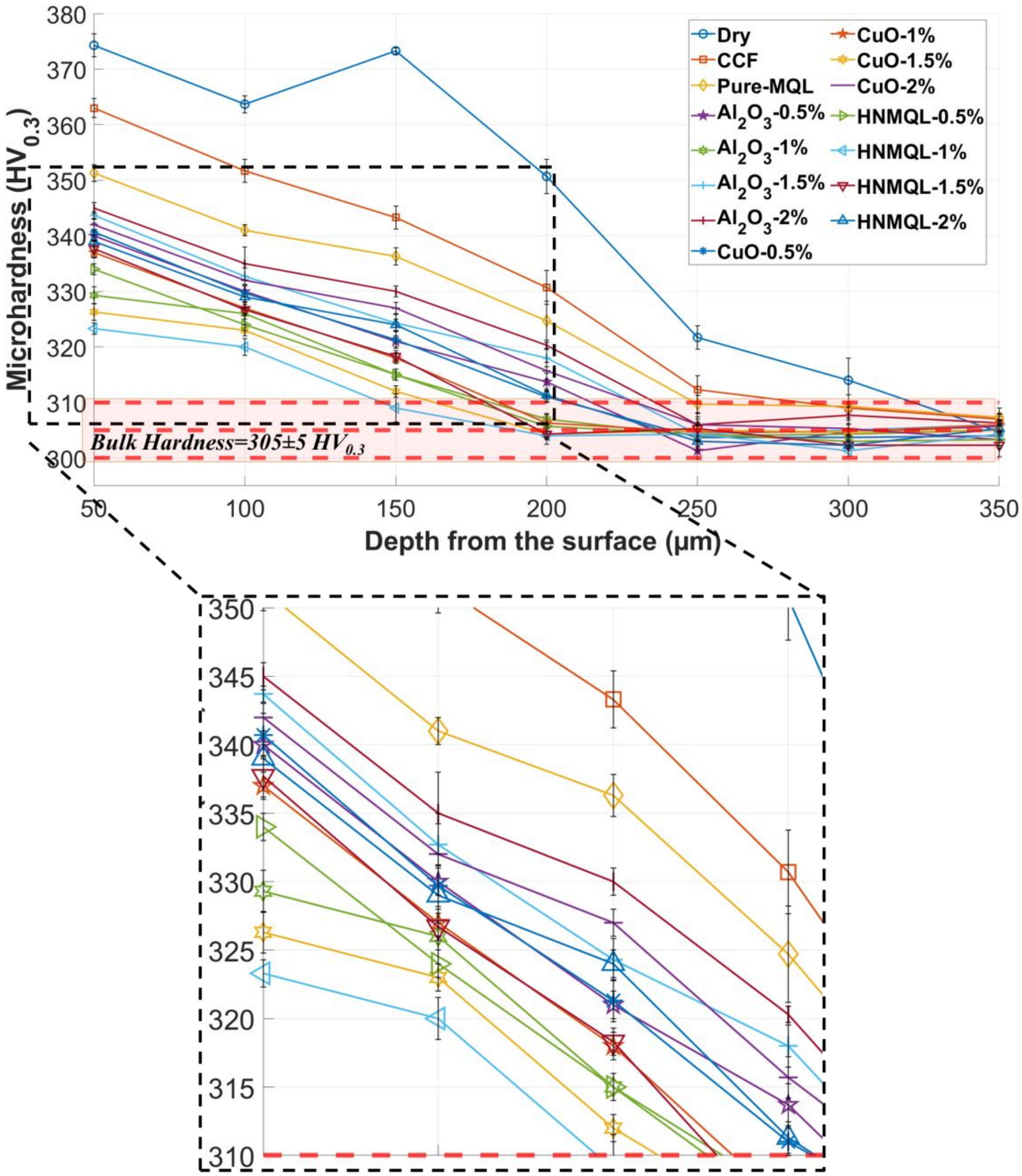

Figure 19 Microhardness measurement results

Sustainability Assessment

Although enhancing production efficiency remains a fundamental objective, in the contemporary world, the consideration of sustainability is imperative in conjunction with productivity (Haapala et al., 2013; Hegab et al., 2023). The United States Environmental Protection Agency (US EPA) offers a comprehensive definition of sustainable manufacturing: "Sustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources" (United States Environmental Protection Agency, 2023). Conforming to the US EPA's definition, it is crucial to minimize environmental impacts during the production process while also ensuring optimal efficiency by considering resource consumption (Sivalingam et al., 2023). Consequently, a sole emphasis on diminishing environmental impacts cannot serve as a standalone criterion for sustainability. Thus, it becomes paramount to evaluate diverse outcomes collectively and identify the most sustainable approach on average (Khanna et al., 2023). Sustainability analyses have previously been conducted in the literature to comprehensively examine MQL applications in comparison to dry machining (Sahoo et al., 2023).

Decision-making methodologies are commonly employed to identify the most optimized outcome by systematically assessing the impact of variables across various domains. Among these approaches, the Pugh Matrix Approach (PMA) stands out as a prominent decision-making tool that facilitates the selection process among multiple potential solutions or alternatives. Previous scholarly works have demonstrated the successful utilization of the PMA in sustainability applications within the area of machining (Masoudi et al., 2023; Ross et al., 2021).

The foundational steps of the PMA are outlined as follows:

Step 1 Criteria Selection: The initial stage involves the careful selection and determination of criteria, taking into consideration the relevant needs and requirements.

Step 2 Establishment of the Datum Criterion: A pivotal step in the process is identifying the datum criterion, which serves as an average indicator, data point, or baseline against which key performance aspects are measured.

Step 3 Comparative Evaluation: The subsequent phase entails comparing and assessing parameters by assigning relative weights, while considering preferences and levels of importance. As an illustration, criteria typically evaluated on a scale ranging from +3 to -3, with +3 assigned to the most favorable result and -3 to the least favorable result.

Step 4 Optimal Selection: The final stage entails selecting the best option or options by aggregating the values assigned to the respective criteria.

Within this study, an evaluation was conducted considering both environmental impact and operational efficiency. The importance of each criterion is selected between 1 to 3. Various conditions, namely CCF, pure-MQL, Al_2O_3-NMQL, CuO-NMQL, and Hybrid-NMQL, were assessed based on the following criteria. Each criterion was assigned a score ranging from +5 to -5, with the dry condition serving as the datum for sustainability assessment.

Environmental Impact: Environmental friendliness and impact on coolants is essential for complying with regulations and contributing to sustainable practices of the process. It not only benefits the environment but also helps businesses and communities by reducing risks, costs, and resource consumption (Silva et al., 2020). The dry condition, which involves the absence of additional products, is assigned a value of "0" to denote its neutral impact. In contrast, all other criteria are assigned values below "0" due to the utilization of additional products such as oils and nanoparticles. CCF utilization entails limited biodegradability oils, warranting a score of "-4". Pure-MQL application garnered a score of "-2" due to the adoption of environmentally friendly oils, and their minimal consumption obviated the need for recycling. NMQL applications, incorporating nanoparticles, received a score of "-3", representing a slight decrease in environmental friendliness compared to Pure-MQL since they contain additional nanoparticles.

Labor Safety: Addressing health issues related to the use of coolants is crucial for safeguarding the well-being of workers, conforming with regulations, maintaining productivity, and avoiding legal and financial consequences (Jayal et al., 2010; Wegman, 1996). Prioritizing the health and safety of employees is not only a moral imperative but also a sound business practice. CCF employment involves products that foster bacterial growth, emit unpleasant odors, and pose health risks to operators, resulting in a score of "-5". Conversely, all MQL applications obtained a score of "+4" due to their consumption in a manner that minimizes the presence of harmful chemicals.

Coolant Price: Coolant price is an important aspect since it directly impacts a manufacturer's financial bottom line, production efficiency, environmental responsibilities, and overall competitiveness (Ishfaq et al., 2021). Balancing cost considerations with performance and quality is essential to optimize operations. The study revealed that CCF consumes 500 l/h, while all MQL applications only require 50 ml/h. This significantly lower consumption enables prolonged oil usage and reduces the necessary coolant costs. Consequently, CCF received a score of "-5", while pure-MQL attained a score of "+5". In NMQL applications, when considering nanoparticle prices, Al_2O_3-NMQL with Al_2O_3 doping, which is the most affordable nanoparticle, earned a score of "+4". CuO-NMQL, relatively more expensive, was awarded a score of "+2". As for HNMQL, which utilizes a combination of both nanoparticles, it received a score of "+3".

Part Cleaning: Cleaning parts after the use of coolants is essential to ensure product quality, precision, safety, and the longevity of equipment and tools. It also helps maintain compliance with regulations, uphold environmental responsibility, and improve overall process efficiency (El

Baradie, 1996). Clean workpieces are a fundamental aspect of quality manufacturing and contribute to the overall success of the process. CCF exhibits a disadvantageous characteristic with its high consumption and utilization as an oil-water mixture, resulting in a poor part cleaning performance. Consequently, it receives a score of "-5". In contrast, MQL applications significantly enhance part cleaning due to the aerosol spraying of an oil-air mixture, warranting a score of "+5".

Coolant Disposal: Proper coolant disposal is a comprehensive practice that touches on legal compliance, resource conservation, and long-term risk management (Hubbard et al., 2008). The disposal of waste products generated from CCF usage necessitates adherence to health and safety standards, imposing additional costs and workload. Hence, a score of "-5" is assigned. Conversely, MQL applications are bestowed with a score of "+5" as they leave minimal residue in the machining area or on the machine tool.

Energy Consumption: Energy consumption in machining is a key aspect of sustainability as it impacts resource efficiency, cost-effectiveness, resource management, and the overall performance of a manufacturing operation (Camposeco-Negrete and de Dios Calderón-Nájera, 2019). Reducing energy consumption in machining is aligned with broader sustainability goals and has a positive impact on nature. Energy consumption is directly influenced by cutting forces (Sarhan et al., 2012). Evaluating the cutting force results obtained in this study, the following scores were assigned based on the corresponding criteria: "+1" for CCF (since the dry condition is “0”), "+2" for Pure-MQL, "+3" for Al_2O_3-NMQL, "+4" for CuO-NMQL, and "+5" for HNMQL.

Secondary Operation Needs: The requirement for secondary surface operations arises when the desired surface quality cannot be achieved directly. This need is closely associated with surface roughness and topography outcomes. Better surface roughness outcomes reduced the need for secondary operation of the workpiece and increased overall cost and therefore the sustainability of the process (Rotella et al., 2012). Based on the surface quality results from the study, CCF receives a score of "+1", pure-MQL earns a score of "+2", Al_2O_3-NMQL is rated at "+3", CuO-NMQL attains a score of "+4", and HNMQL is assigned a score of "+5".

Table 6 Pugh matrix comparison

Sustainability Assessment Criteria	**Weights**	**Dry**	**CCF**	**Pure MQL**	**Al_2O_3-NMQL**	**CuO-NMQL**	**Hybrid-NMQL**
Environmental Impact	3	0	-4	-2	-3	-3	-3
Labor Safety	3	0	-5	4	4	4	4
Coolant Price	2	0	-5	5	4	2	3
Part Cleaning	1	0	-5	5	5	5	5
Coolant Disposal	1	0	-5	5	5	5	5
Energy Consumption	3	0	1	2	3	4	5
Secondary Operation Need	3	0	1	2	3	4	5
Total +			6	44	48	50	58
Total -			-47	-6	-9	-9	-9
Score			**-41**	**38**	**39**	**41**	**49**

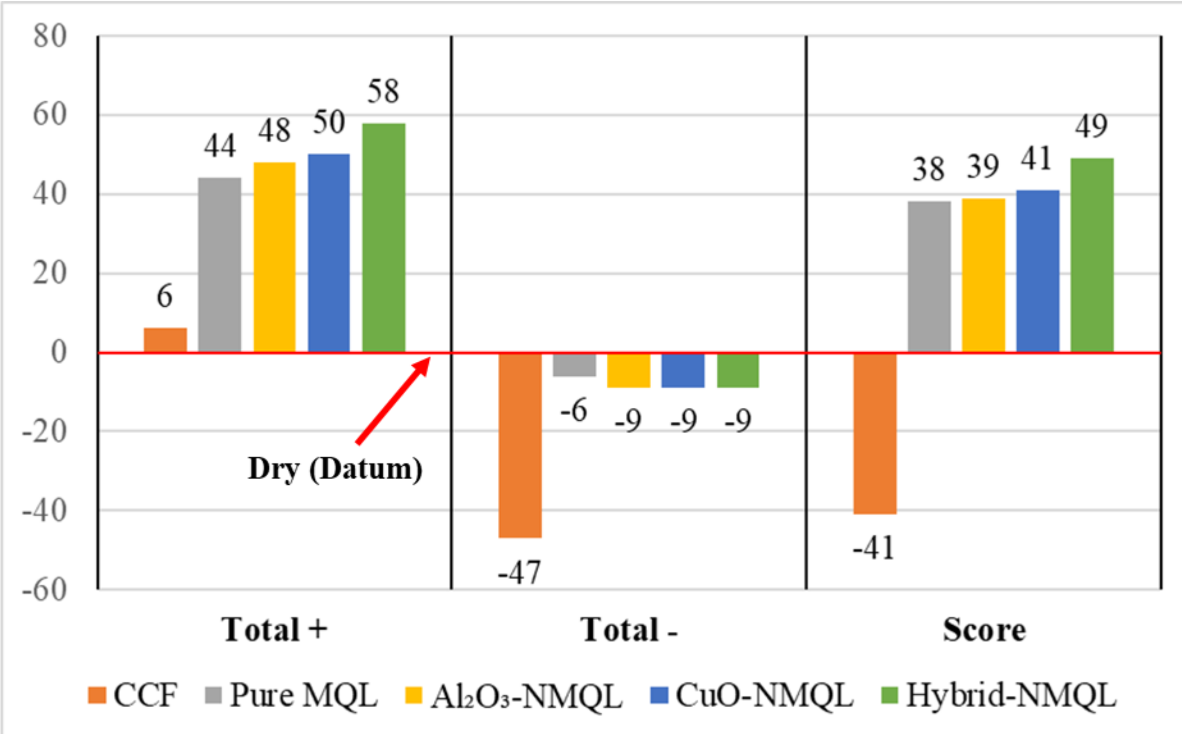

Figure 20 Sustainability scores according to Pugh matrix

The sustainability scores, as determined by PMA as can be seen in Table 6, are illustrated in Figure 20, while the distribution of these scores is depicted in the Kiviat radar diagram displayed in Figure 21. Based on the obtained results, it was determined that the HNMQL application exhibited the highest level of sustainability according to the PMA score. Conversely, the CCF application yielded the lowest score in terms of sustainability. Although the Al_2O_3-and CuO-NMQL applications demonstrated commendable machining performance, they exhibited marginally greater sustainability than pure-MQL due to the presence of nanoparticles within their composition.

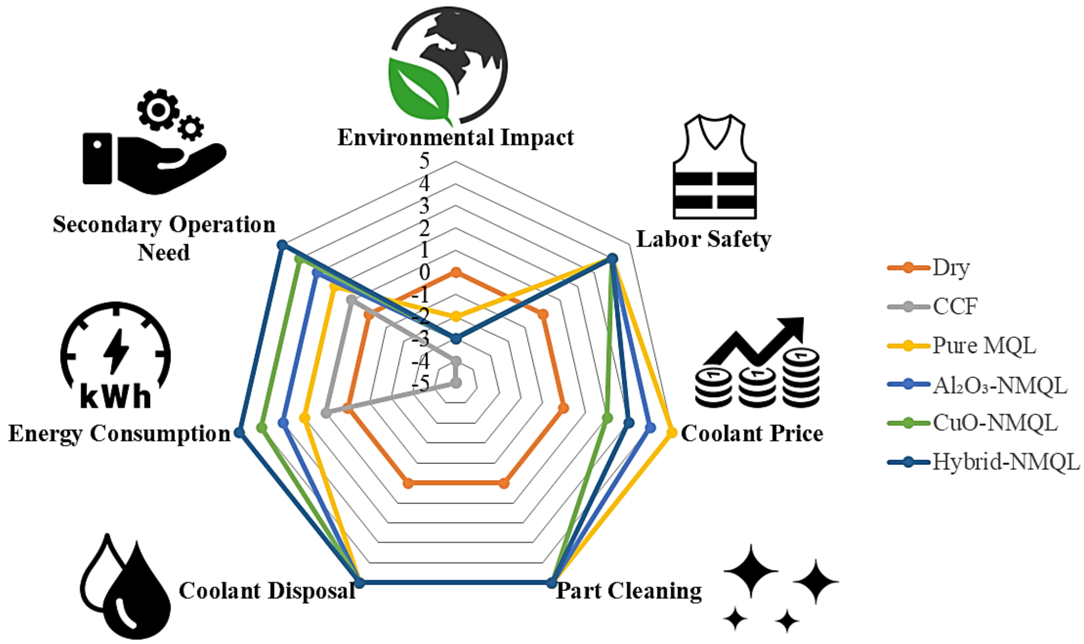

Figure 21 Kiviat radar diagram of sustainability criteria results

Conclusions

This study aimed to investigate the application of Al_2O_3 and CuO nanoparticles in Nanofluid-MQL (NMQL) and Hybrid-NMQL (HNMQL) during the slot milling operation of Ti-6Al-4V material, with a focus on sustainable manufacturing, while also examining the influence of varying volumetric concentrations of these nanoparticles on the machining performance of Ti-6Al-4V material for the first time. The obtained results were used to conduct a sustainability analysis. The main findings of this study can be summarized as follows:

- According to the cutting forces results, the highest forces were observed during dry cutting, whereas the lowest values were recorded when employing the HNMQL technique. In comparison to the pure-MQL method, the utilization of Al_2O_3-NMQL led to a reduction of cutting forces by up to 13.26%, while CuO-NMQL exhibited a decrease of up to 20.28%, and HNMQL demonstrated a remarkable reduction of up to 41.56%. This discrepancy can be attributed to the tribological and thermo-physical properties inherent in nanoparticles. Moreover, it was observed that the hybrid application of nanoparticles merges the advantages derived from their individual application, ultimately yielding enhanced productivity gains. In the NMQL applications, it was observed that the cutting forces initially decreased up to a specific threshold as the volumetric percentage concentrations of nanoparticles increased. However, upon surpassing this threshold, the cutting forces were observed to increase once again. This phenomenon can be attributed to the fact that an increase in nanoparticle concentration leads to an elevation in the viscosity of the mixture and a reduction in the penetration effect within the cutting zone.

- The surface roughness measurements showed that the lowest Sa values were attained through the utilization of HNMQL, followed by CuO-NMQL, Al_2O_3-NMQL, pure-MQL, CCF, and finally, dry machining. In comparison to the pure-MQL approach, Al_2O_3-NMQL exhibited a reduction in surface roughness values of up to 28.18%, while CuO-NMQL demonstrated a decrease of up to 29.83%, and HNMQL displayed a substantial decrease of up to 56.2%. These reductions can be attributed to the desirable properties of nanoparticles, such as friction reduction, enhanced lubrication, and increased heat transfer capacity, which collectively contribute to the mitigation of surface roughness. Furthermore, upon investigating the impact of volumetric concentrations, it was observed that the surface roughness initially decreased with increasing concentrations, reaching a certain threshold. However, beyond this threshold, the effectiveness of nanoparticles decreased due to aggregation, resulting in a subsequent decrease in surface roughness efficiency.
- The surface topography and texture images revealed that the HNMQL application yielded the most homogeneous, uniform, and lowest peak-to-valley values, exhibiting the least

amount of surface defects. Following HNMQL, CuO-NMQL, Al_2O_3-NMQL, pure-MQL, CCF, and dry conditions exhibited progressively inferior surface quality. In the experiments conducted with dry cutting, a minimum peak-to-valley value of 25 µm was observed, whereas in the case of Hybrid-NMQL, this value has decreased to as low as 14 µm. When examining surface texture, the defects commonly observed in traditional cooling methods such as tearing, material chipping, and scratch marks have been reduced to the extent that, when combined with Hybrid-NMQL, only micro-chipping is observable. This observation implies an enhancement in surface quality as a result of specific effects induced by the nanoparticles. For instance, the presence of Al_2O_3 nanoparticles facilitated friction reduction through a ball-bearing effect, while CuO nanoparticles exhibited high heat transfer capacity, thus mitigating heat generation in the cutting zone.

- The microhardness results indicate that among the various techniques, HNMQL exhibited the lowest microhardness values, followed by CuO-NMQL, Al_2O_3-NMQL, pure-MQL, CCF, and dry machining, respectively. The microhardness values, which initially began at the surface an average of 374 $HV_{0.3}$ in dry cutting, decreased to as low as 323 $HV_{0.3}$ with a 1% vol. concentration of Hybrid-NMQL, demonstrating a reduction of approximately 13.6%. This reduction in microhardness values can be attributed to the effective reduction of thermo-mechanical loads exerted on the surface during NMQL and HNMQL, leading to decreased microhardness.
- In the sustainability analysis conducted using The Pugh Matrix Approach, it was determined that HNMQL application emerged as the most favorable option in terms of sustainability. Conversely, the CCF application was deemed the least preferred among the

evaluated options. This finding underscores the significant potential of HNMQL applications as a promising method for promoting sustainability in machining processes.

Future Scope

The research on the nanofluid-MQL technique is an ongoing and dynamic field. Thus far, studies have primarily focused on different types of Nanofluid-MQLs in comparison to conventional coolants, concentrating on machining performance outputs such as cutting force, surface quality (e.g., roughness and topography), tool wear, and subsurface characteristics (e.g., microhardness and residual stress). The effects of the physical properties of nanoparticles remain an area in need of further investigation. Nanoparticles with different characteristics such as shape, size, and purity, even if composed of the same nanoparticle material, can exhibit varying effects. This research has the potential to identify the most optimal nanoparticles for use in nanofluids, facilitating the creation of a highly effective coolant medium.

Furthermore, the diversity of materials being processed can potentially influence the effects of nanofluids and therefore, material-specific applications must be revealed. As an example, nanoparticles with high thermal conductivity that work well with the cutting of materials of low thermal conductivity may not produce the expected results with materials where friction is the predominant issue. In such cases, it is essential to accurately identify the problem with the material during cutting and select nanofluids containing nanoparticles suitable for addressing that specific issue.

Industrial adaptation is another crucial aspect of nanofluid-MQL that requires attention. Due to the nature of nanofluids as suspensions, accumulation and sedimentation can occur after a certain period. The use of surfactants to address this issue can alter the expected thermo-physical properties of nanofluids, necessitating alternative solutions (Yu and Xie, 2012). Therefore, research efforts should focus on developing stable nanofluid suspensions that remain homogeneous over extended periods, formulation of these suspensions, or the development of surfactants that do not disrupt the structure of the nanofluid.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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