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Investigation of the Effects of CNC Nanoparticle-Added Nanofluids on the Machinability of Cupral 4M Alloy

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Crystalline nano cellulose

Abstract: The machinability of copper-nickel-based alloys, such as Cupral 4M, is known to be quite challenging in the manufacturing industry due to their high thermal conductivity, sticky chip formation, and susceptibility to tool wear. Conventional cooling and lubrication methods are insufficient for improving the machinability of these materials, resulting in a negative impact on machinability metrics such as production quality and tool life. In this study, the effects of adding 0.5 wt% CNC nanopowder to the MQL fluid on the milling process of Cupral 4M material were investigated. The experiments were conducted under two different cutting speeds (125-150 m/min), two different feed rates (0.04-0.06 mm/rev), and three different cooling/lubrication conditions (dry, pure MQL, and CNC nanoparticle MQL). As a result of the experiment, surface roughness, tool wear, and energy consumption were measured, and the obtained data were compared. The addition of CNC nanopowder to MQL fluid provided significant improvements (up to 66% in surface quality, 39% in tool wear, and 10% in energy consumption) in all three results compared to dry and MQL conditions. These results indicate that the addition of CNC nanoparticles has a friction-reducing and tribofilm-protecting effect in the cutting zone. This study fills one of the essential gaps in the literature on improving the sustainable millability of Cupral 4M material and reveals the effectiveness of nanoparticle-added MQL fluids.

CNC Nanopartikül Katkılı Nanoakışkanların Cupral 4M Alaşımının İşlenebilirliği Üzerine Etkilerinin Araştırılması

Anahtar Kelimeler
Cupral 4M,
Nanosıvı,
Minimum miktarda yağlama,
Kristalin nano selüloz

Öz: Cupral 4M gibi bakır-nikel esaslı alaşımların işlenebilirliği, yüksek termal iletkenlik, yapışkan talaş oluşumu ve takım aşınmasına yatkınlık nedeniyle imalat endüstrisinde oldukça zorlu işlenebilirliğe sahip olarak bilinir. Geleneksel soğutma ve yağlama yöntemleri bu malzemelerin işlenebilirliğinde yetersiz kalmakla birlikte, üretim kalitesi ve takım ömrü gibi işlenebilirlik metrikleri üzerinde olumsuzluğa neden olmaktadır. Bu çalışmada, ağırlıkça %0,5 CNC nanotozu katkılı MQL sıvısının Cupral 4M malzemesinin frezeleme işlemi üzerindeki etkileri incelenmiştir. Deneyler iki farklı kesme hızı (125-150 m/dk), iki farklı ilerleme hızı (0,04-0,06 mm/dev) ve üç farklı soğutma/yağlama koşulu (kuru, saf MQL, CNC nano parçacık MQL) altında gerçekleştirilmiştir. Deney sonucu olarak yüzey pürüzlülüğü, takım aşınması ve enerji tüketimi ölçülmüş, elde edilen veriler karşılaştırmalı olarak irdelenmiştir. CNC nanotoz ilaveli MQL sıvısı, kuru ve MQL ortamına göre her üç sonuçta da anlamlı iyileşmeler (yüzey kalitesinde %66'ya, takım aşınmasında %39'a, enerji tüketiminde ise %10'a kadar) sağlamıştır. Bu sonuçlar, CNC nano partikül ilavesinin kesme bölgesinde sürtünme azaltıcı ve tribo-film koruyucu bir etki oluşturduğunu göstermiştir. Bu çalışma, Cupral 4M malzemesinin sürdürülebilir frezelenebilirliğini artırmaya yönelik literatürdeki önemli boşluklardan birini doldurmakla birlikte ve nano partikül katkılı MQL sıvılarının etkinliğini ortaya çıkarmıştır.

1. INTRODUCTION

Machining is one of the fundamental principles of producing precise, economical, and efficient parts in modern manufacturing. Machining, particularly milling, plays a central role in the production of complex geometries in industries requiring high precision, such as aerospace, automotive, mould, and energy [1]. This method enables the machining of complex geometries, such as slots, precision molds, and complex forms, with high accuracy [2]. One of the most decisive factors in the success of these processes is the adequate cooling and lubrication of the cutting zone.

There are many different cooling/lubrication (C/L) methods used in machining (flood, cryogenic, minimum quantity lubrication, etc.). Minimum quantity lubrication (MQL) is widely used to reduce power consumption, ensure environmental sustainability, improve surface quality, effectively lubricate the cutting zone, and extend tool life. Traditional (flood) cutting and lubrication (C/L) media, commonly used in machining, are achieved by using high volumes of water and solvent-based cutting fluids. This not only wastes fluid but also creates a significant environmental waste burden. [3, 4]. This poses a significant disadvantage in terms of both liquid waste and energy and cost. However, MQL media offer an environmentally friendly and economical alternative to traditional lubrication systems by spraying the liquid in tiny particles [4, 5]. The minimum quantity lubrication (MQL) method is widely used in industry and scientific studies to reduce production costs, extend tool life, improve surface quality, and ensure environmental sustainability [6-9]. MQL fluid provides the necessary amount of lubrication to the cutting area, reducing cutting temperatures and improving friction conditions, thereby enhancing tool wear and surface quality [10-12]. Thanks to these advantages, MQL systems stand out as a solution that increases environmental sustainability and process efficiency in manufacturing processes [13]. However, research was conducted to further enhance the benefits of MQL systems in machining, and as a result, modifying the MQL fluid content has been proposed as an alternative method.

In recent years, researchers have reported that adding nano-sized additives to MQL fluids has improved the tribological and thermal properties of the fluids. [14]. The addition of nanoparticles to MQL fluids significantly reduces friction in the cutting zone and significantly improves lubrication performance. For example, in the milling of Ti-6Al-4V material, MQL fluids containing Al_2O_3 nanoparticles were found to substantially reduce cutting force and surface roughness compared to MQL fluids without additives [15]. Similarly, in hybrid nanopowder-added MQL systems, it was found that a synergistic improvement in wear and thermal transport performance is achieved by combining different ionic and carbon-based nanoparticles [16]. Additionally, positive effects on friction and wear were demonstrated in nanofluid MQL systems utilising MoS_2–CNT mixtures, enhancing the machinability of Ni-based alloys [17]. Positive results of adding nanopowders to MQL liquids have also been mentioned explicitly in the literature [18-20]. As a result, MQL fluids with nanopowder additives offer advantages in thermal conductivity and tribological efficiency compared to pure MQL fluids. They also increase cutting efficiency and productivity in difficult-to-machine materials. These developments demonstrate the potential of nanostructured additives, particularly in cutting operations of difficult-to-machine materials.

Machining copper-nickel-based alloys is challenging due to problems such as high thermal conductivity, chip formation, rapid wear, and surface quality. The selection of appropriate cutting parameters and effective cooling/lubrication environments is critical for the machinability of these materials. Original data on the machinability of these materials is relatively limited in the literature. Furthermore, there is no study investigating the effects of MQL fluids containing CNC (Cellulose Nanocrystal) nanopowder on the machinability of Cupral 4M. This lack highlights the need for more comprehensive investigation of the potential effects of new-generation MQL fluids on this particular alloy. This study aims to investigate the effects of MQL fluid containing 0.5 wt% CNC nanopowder on the surface quality, tool wear, and power consumption on the machinability of Cupral 4M alloy. In this context, different cutting speeds and feed rates, along with three different cooling/lubrication environments, were used in the experiments. This study makes an original contribution to the literature by demonstrating the feasibility of a new, environmentally friendly cooling/lubrication strategy to enhance the machinability of Cupral 4M.

2. MATERIAL AND METHOD

In this study, the CuAl10Ni5Fe4 (commercial name "Cupral 4M") material, which is frequently used in press moulds, bearing bushes, aircraft landing gear, and welding electrodes, was employed. Two 21 x 50 x 50 mm pieces of this workpiece, used for milling experiments, were supplied by Sağlam Metal. The chemical composition, mechanical properties, and physical properties of the workpiece are listed in Tables 1, 2, and 3, respectively.

Table 1. Chemical composition of Cupral 4M

Chemical Composition (wt.%)					
Al	**Fe**	**Ni**	**Mn**	**Cu**	**Other**
8.5-11.5	3-5	4-6	Max. 1	75-85	difference

Table 2. Mechanical properties of Cupral 4M

Mechanical Properties	
Hardness (HB)	170-220
Tensile Strength (N/mm²)	650-800
Yield Strength (N/mm²)	270-400
Moduls of Elasticity (GPa)	124
Compressive Strenght (N/mm²)	1200

Table 3. Mechanical properties of Cupral 4M

Physical Properties	
Electrical Conductivity (MS/m)	5
*Thermal Expansion Coefficient (1/K * 10^{-6})*	16
Thermal Conductivity (20°C, W/mK))	42
Density (g/cm^3)	7.45

A three-axis (x-y-z) Dahlih MCV-860 vertical machining centre (VMC) was used for machinability tests on the Cupral 4M workpiece. The workpiece was clamped in a precision vice and fixed to the VMC. Before the test, a 1 mm pass was removed from the workpieces with a surface scanning tool to ensure the flatness of the workpiece surface and to remove material slag. Two different cutting speeds (125-150 m/min), two different feed rates (0.04-0.06 mm/rev), and three different C/L media (Dry-MQL-Nano) were selected as experimental variables. Parameters were determined from preliminary experiments. To fully explore the relative effects of the variables, a complete experimental design system (22 × 31) was adopted. Both surfaces of the materials were used in the tests. Four experiments were conducted on each workpiece surface, totalling 12 experiments (Figure 1).

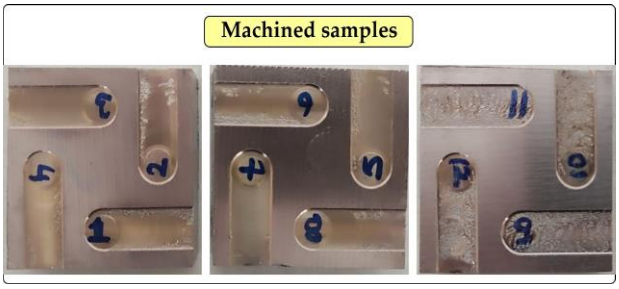

Figure 1. Machined workpiece surface

A collet tool holder was used in the experiments on this machine with a BT-40 taper. A new insert (ISCAR HM 90 APKT 1003PDR IC908) was used for each experiment. The insert was clamped onto a 12 mm diameter indexable milling cutter (SMOXH ST90 AP10D12W12L120Z01). The milling cutter was mounted in a MAS 403 BT 40 tool holder with a clamping length of 50 mm. A "Zig" tool path was generated in the experiments using commercial CAM software. The milling length (L) was kept constant at 30 mm, and the cutting width or step (ae) was kept constant at 12 mm. The cutting depth (ap) was set at 0.5 mm for each experiment.

Dry and MQL media were used in the experiments to investigate the usability of the nano C/L medium produced with CNC nanopowder on the workpiece. A Werte-STN 15 device was used for the MQL and nanofluid media. KT-2000 synthetic oil was chosen for the MQL medium due to its high hydrodynamic lubrication properties [21]. The operating pressure of the device was set at 6 bar. The 3 mm diameter MQL nozzle was kept fixed at a distance of 75 mm from the workpiece during the experiments. The operating flow rate of the MQL device was determined as 50 mL/h. Water-soluble and environmentally friendly Cellulose Nanocrystal (CNC) nanopowder was used for the nanofluid. More details about the preparation of the CNC nanofluid, which was added to pure water at a concentration of 0.5% by volume, can be found in the relevant literature [21]. This synthetic oil, prepared with pure water, was sent to the experimental area with the MQL device without mixing.

After the experiments, the workpiece surface was cleaned with alcohol and air to prepare it for surface roughness measurements. Surface roughness measurements were performed with an Insize ISR-C100 surface roughness measuring device. The device was first calibrated with a calibration sample. Five different measurements were taken from each machined surface, and the average of these measurements was determined as the surface roughness value. The average surface roughness value (Ra) was taken into account when determining the surface roughness value. Another result obtained from the experiments was the maximum flank wear (Vbmax). After the experiments were completed, each cutting edge was cleaned with compressed air, and the maximum wear amounts were measured and recorded under a digital microscope (Insize ISM PM200SB). Finally, the power consumption for each machinability test was performed using a HIOKI PW 3198 device. The device is capable of performing precise measurements for all test parameters according to international measurement standards. The current and voltage values obtained from three phases during the tests were used to obtain energy consumption results using the device software. Figure 1 represents the experimental schematic.

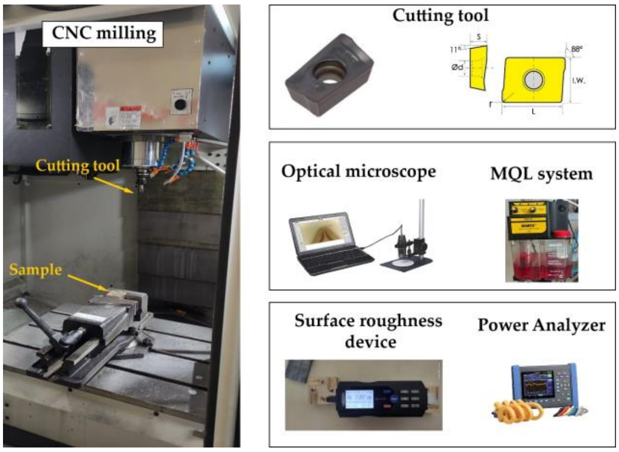

Figure 2. Experimental setup

3. RESULTS

This study examined the differences between CNC nanopowder-added MQL fluid and other C/L methods in the milling of Cupral 4M material. Machinability metrics, including surface roughness, flank wear, and energy consumption, were analysed.

3.1. Analysis of surface roughness results

In terms of machinability, surface roughness (R_a) is a critical parameter in studies evaluating environmentally friendly and high-performance manufacturing methods [22]. Surface roughness is considered one of the most essential indicators of machinability and is a quality criterion that directly affects the functional performance of parts produced by machining [23]. The surface quality of a part is not only an aesthetic element, but also a determinant of numerous engineering parameters such as fatigue resistance, wear behaviour, lubrication capacity, sealing performance, and assembly fit [24, 25]. Especially in precision components used in the aerospace, automotive, mold and die making, and energy sectors, surface roughness must be kept within specific tolerance ranges. Figure 3 shows the effects of experiments conducted under different cutting parameters and different C/L conditions on the surface roughness value. The best surface quality (R_a = 1.235 µm) was achieved in the C/L condition of CNC nanoparticle-added MQL at a cutting speed of 150 m/min and a feed rate of 0.04 mm/rev. In this cutting parameter group, where the best surface quality was achieved, other surface roughness values were obtained: R_a = 3.679 µm for the dry environment and R_a = 2.57 µm for the MQL fluid. The lowest surface quality (R_a = 4.204 µm), as expected, was achieved in the dry environment, at the lowest cutting speed and highest feed rate. In this cutting parameter group, where the worst surface quality was achieved, other surface roughness values were obtained: R_a = 3.32 µm for the MQL fluid and R_a = 2.42 µm for the CNC nanoparticle-added MQL fluid. In general, experiments conducted with the CNC nanoparticle-added MQL fluid showed improvements in surface roughness values between 42% and 66% compared to the dry environment and between 27% and 52% compared to the MQL fluid alone.

The effect of CNC nanopowder-added MQL fluid on surface quality is essential for demonstrating the potential of nanoadditives to improve lubrication and heat transfer [26]. Thanks to the high specific surface area of CNC nanopowder, it is expected to reduce friction in the cutting zone and improve temperature distribution. This results in a more balanced interaction between the tool and the workpiece. These effects are directly reflected in surface roughness, resulting in smoother, more homogeneous, and functional surfaces. Studies in the literature support these findings [21, 27]. Furthermore, the performance comparisons under different cutting and feed speeds, as shown in Figure 3, indicate that the CNC-added MQL fluid yielded the best results across all parameter combinations. This study not only demonstrates the feasibility of an environmentally friendly and innovative cooling condition but also provides concrete data on how production quality can be sustainably improved by influencing cutting parameters. This analysis of surface roughness quantitatively demonstrates the superiority of nanotechnology-based lubrication systems over conventional MQL and dry conditions, guiding future production strategies.

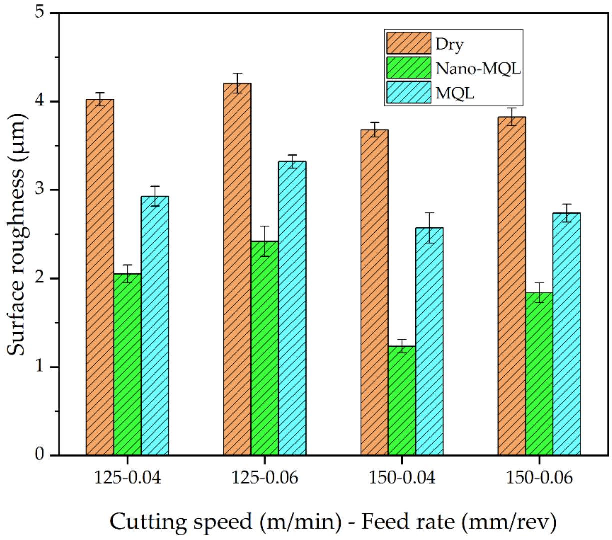

Figure 3. Effect of different C/L conditions and different cutting parameters on surface roughness

3.2. Analysis of flank wear results

Tool wear is one of the most critical determinants of productivity and cost in machining processes. Therefore, flank wear is a fundamental wear factor that directly affects the performance of the cutting tool [28]. Flank wear is a type of wear that occurs on the side surface of the tool in contact with the workpiece and grows over time in parallel with the feed rate. This type of wear generally occurs due to friction, temperature, and plastic deformation during the cutting process [29]. As flank wear increases, tool sharpness decreases, cutting forces increase, surface roughness deteriorates, and cutting temperature increases, creating a feedback loop that accelerates wear [30]. Furthermore, as wear progresses, deviations from dimensional tolerances increase, and the risk of component failure increases. Therefore, flank wear is not only an indicator of tool life but also an important criterion that determines the stability and economic efficiency of the production process. Figure 4, illustrates the effects of different C/L environments and cutting parameters on flank wear. The lowest flank wear value (V_b = 0.280 mm) was obtained in the CNC nanopowder-added MQL C/L condition at a cutting speed of 150 m/min and a feed rate of 0.04 mm/rev. In these cutting parameters, where the lowest flank wear value was obtained, other flank wear values were determined as 0.439 mm and 0.373 mm for dry environment and MQL fluid, respectively. The highest wear value (V_b = 0.480 mm) was achieved in a dry environment, at the highest cutting speed and feed rate. In this cutting parameter group where the highest flank wear value was obtained, other wear values were obtained as V_b = 0.397 mm for MQL fluid and V_b = 0.304 mm for CNC nanoparticle added MQL fluid. In experiments conducted with CNC nanoparticle-added MQL fluid, it was observed that flak wear values improved by 36-39% compared to a dry environment and by 23-31% compared to MQL fluid.

Upon examination of the graph (Fig. 4), it is evident that the CNC nanoparticle additive significantly reduces flank wear values. Carbon-based nanoparticles, such as CNC, have a very high surface-to-area ratio. Thanks to this property, when dispersed in the cutting zone, they easily penetrate the friction zone between the tool and the workpiece. It is believed that this can reduce flank wear values by reducing the friction coefficient and resulting in less mechanical friction in the cutting zone. Furthermore, CNC particles, especially in the MQL system, pulverise and reach the cutting zone, forming a lubricating film on the tool surface [31]. This directly prevents contact between the tool and the workpiece, eliminating the microscopic causes of wear initiation. Studies in the literature support the obtained results [21, 27, 31].

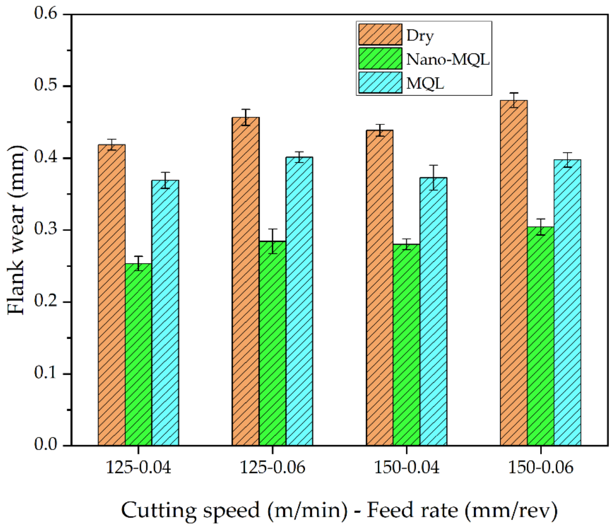

Figure 4. Effect of different C/L conditions and different cutting parameters on flank wear

3.3. Analysis of energy consumption

In the modern manufacturing industry, energy consumption has become one of the fundamental performance criteria encompassing not only technical but also environmental and economic dimensions of machinability [32]. While traditional machinability analyses are often evaluated based on mechanical outputs such as surface roughness, tool wear, and chip formation, energy efficiency has emerged as a key factor that should be assessed in conjunction with these outputs [33]. The total energy consumption of a cutting process directly affects production costs and determines the carbon footprint and environmental impact. Especially in Industry 4.0-focused systems where sustainable production targets are adopted, achieving high-quality outputs with low energy consumption is a primary goal of process optimization. Therefore, examining energy consumption in cutting processes is crucial. Figure 5 shows the effects of different cutting fluids on the machinability of Cupral 4M material with different cutting parameters. The CNC nanopowder-added MQL fluid exhibited the lowest energy consumption across all cutting parameters. The power consumption of the MQL device, which sprays the fluids onto the cutting zone, was neglected in the comparisons. For this type of cutting process, the effect of cutting media on power consumption is evident. The lowest power consumption in the experiments was 19.92 kJ, at a cutting speed of 150 m/min and a feed rate of 0.06 mm/rev. It was determined that lower power consumption would occur because the unit material would be processed in less time at high cutting speeds and feed rates. It can be said that the power consumption values are lower due to the reduction in cutting time at high cutting and feed speeds, the thermal softening of the workpiece, and the reduction of friction between the tool and the material, resulting from the presence of nanoparticles [34-37]. The highest power consumption, 25.65 kJ, occurred at the lowest cutting parameters. In other experiments, CNC nanopowder-added MQL fluid was found to reduce energy consumption by 1.6-9.9% compared to dry media and by 0.8-6.5% compared to MQL fluid.

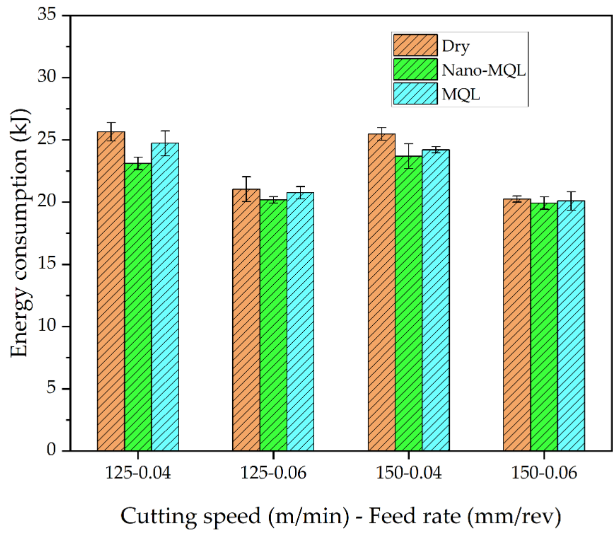

Figure 5. Effect of different C/L conditions and different cutting parameters on energy consumption

4. CONCLUSION

This study examined how the machinability of Cupral 4M material was affected by CNC nanopowder-added MQL fluid under various cutting conditions. In this article, the proposed CNC nanopowder-added MQL fluid was compared with dry media and pure MQL fluid to examine its advantages and disadvantages. The key results obtained from the experiments are listed below:

- Surface roughness results indicate that the MQL fluid containing 0.5% CNC nanopowder significantly improved surface roughness compared to other media. Experiments with the MQL fluid containing CNC nanoparticles demonstrated improvements in surface roughness of 42-66% compared to dry media and 27-52% compared to the MQL fluid. It can be concluded that the CNC nanopowder additive enhances surface quality by reducing friction in the cutting zone and creating a more uniform lubricant film. The results demonstrate that the MQL fluid containing CNC nanoparticles provides an effective solution for precision applications that require high surface quality.

- The effect of 0.5% CNC nanopowder-added MQL fluid on flank wear compared to other conditions has been extensively studied. Experiments with the CNC nanoparticle-added MQL fluid showed improvements in flank wear values between 36% and 39% compared to dry conditions and between 23% and 31% compared to MQL fluid. The addition of CNC nanoparticles to the MQL fluid resulted in a significant reduction in flank wear. Thus, the study demonstrated that an environmentally friendly cutting fluid can be used to mill difficult-to-machine alloys, such as Cupral 4M.

- The addition of CNC nanopowder to MQL fluid also resulted in improved power consumption. In other experiments, MQL fluid with CNC nanopowder added reduced energy consumption by 1.6-9.9% compared to dry conditions and by 0.8-6.5% compared to MQL fluid alone. The study offers a comprehensive evaluation of key industry issues, including energy efficiency and environmental sustainability. Furthermore, this study presents a compelling case for the widespread adoption of CNC nanopowder in MQL fluids within the manufacturing industry

Future studies can investigate the effects of CNC nanoparticles on machinability by adding them to mineral-based coolants. Furthermore, the wear phenomena affecting cutting temperatures, cutting forces, and tool wear can be examined in more detail. It is also essential to investigate the effects of CNC nanopowder additives on the machinability of steels frequently used in the manufacturing industry. This will enable the expansion of industrial applications for environmentally friendly nanoadditives. While CNC nanopowder additives to MQL fluids have positive effects on machinability, their industrial use is limited by the cost of powder production. As the cost of obtaining nanopowder decreases with the advancement of production technologies, its use in industry is expected to increase.

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