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Machining performance evaluation of eco-friendly copper oxide-based nanofluids in turning operations

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ABSTRACT

Introduction. There is a growing demand for eco-friendly cutting fluids in machining due to their non-toxicity, sustainability, high performance, and ability to improve surface quality. These fluids support green manufacturing practices and promote a safe working environment. Copper oxide-based nanofluids offer the combined benefits of enhanced heat transfer, increased safety, and reduced tool wear and cutting forces. **The purpose of the work.** This research focuses on evaluating the performance of copper oxide-based cutting fluids in turning processes to support sustainable and eco-conscious manufacturing. The study investigates the turning of *SS 304* steel using varying concentrations of copper oxide nanofluids. **The methods of investigation.** In this study, the turning process was tested under various machining conditions using different concentrations of copper oxide nanoparticles (0.3 %, 0.6 %, 0.9 %, 1.2 %, and 1.5 %). Corn oil was selected as the base oil, and the copper oxide nanoparticles were dispersed in the corn oil to prepare the nanofluid. Machining trials were conducted under different lubrication environments: dry, wet, minimum quantity lubrication (*MQL*), and nano-enhanced *MQL* (*nMQL*). A comparative study was performed to assess cutting temperature and cutting forces. **Results and discussion.** The results showed that the use of 1.2 % copper oxide nanofluid led to significant reductions in cutting force and cutting temperature, by approximately 17.54 % and 29.53 %, respectively, compared to traditional dry and wet machining environments. Furthermore, the nanofluid was observed to form a protective film at the tool-workpiece interface, reducing tool wear. These findings highlight the potential of copper oxide-based green cutting fluids to improve turning operation efficiency and promote environmentally sustainable practices.

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Introduction

In traditional machining operations, chemical-based cutting fluids are typically used to reduce friction and improve the efficiency of machining processes by providing cooling and lubrication [1]. However, the use of these fluids has raised substantial environmental concerns and poses health hazards to workers due to their toxicity [2]. Therefore, there is an increasing demand for sustainable manufacturing approaches that reduce or eliminate the use of conventional cutting fluids [3]. Consequently, a promising alternative

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in this regard is *MQL*, which delivers a small, controlled amount of lubricant mixed with compressed air directly to the cutting zone, thus offering both ecological and economic benefits [4-5]. This technique not only reduces lubricant consumption but also improves machining performance [6].

Recent advancements have demonstrated that the addition of nanoparticles to biodegradable vegetable oils in *MQL* systems significantly enhances cutting performance while eliminating health and environmental risks [7]. Nanoparticles like graphene have been shown to reduce tool wear and improve surface finish during machining operations [8]. For example, studies have reported better machining outcomes with nano-SiO_2-enhanced lubrication compared to conventional systems [9-10]. Similarly, *Emami et al.* [11] observed improved grinding performance of ceramics using *MQL*. Furthermore, vegetable oil-based *MQL* fluids demonstrated enhanced tool life and surface finish when machining *Inconel* alloys [12]. Studies utilizing different vegetable oils, such as sunflower and neem, in *MQL* applications have also shown improved machining performance [13].

During metal cutting, tool tip temperatures often rise, accelerating tool wear and machine downtime. Selecting the right cutting fluid and lubrication strategy is essential to reduce such effects and prolong tool life [14]. Studies have shown that nanofluids enhance both heat dissipation and lubrication due to superior wettability and thermal conductivity [15]. *Estelle et al.* [16] studied carbon-nanotube-based water-based nanofluids and found enhanced thermal conductivity and viscosity. *Mia et al.* [17] compared dry, conventional, and *MQL* methods during hardened steel machining and observed lower cutting forces with *MQL*. Additionally, extreme pressure (*EP*) additives in vegetable-oil-based lubricants reduced cutting forces in *AISI 304L* steel machining, although higher *EP* concentrations led to increased surface roughness. Nevertheless, vegetable-based cutting fluids were still considered a viable alternative to hazardous petroleum fluids. *Srikant et al.* [18] demonstrated that copper oxide nanofluids in water-based systems significantly reduced tool tip temperatures due to enhanced heat extraction capabilities. *Padmini et al.* [19] also confirmed the tribological and thermal advantages of properly formulated nanofluids in metal cutting. *Shrivastava* and *Gangopadhyay* [20] conducted microdrilling tests under compressed air, pure vegetable oil *MQL*, and nanodiamond-enhanced vegetable oil *MQL*. The best performance was achieved with a 2.0 vol% nanodiamond mixture. *Azami et al.* [21] observed improved milling performance with 0.1 wt% graphene nanoparticle (*GnP*)-enhanced vegetable oil compared to plain oil. *Sharma et al.* [22] emphasized the application of nanofluid-based *MQL* for machining ultra-hard materials. *Manikanta et al.* [23] reported that the material removal rate and surface finish during *SS304* machining are significantly influenced by both cutting speed and nanofluid concentration. *Virdi et al.* [24] demonstrated improved surface finish and lower temperatures in *Ni-Cr* alloy grinding using *MQL* with 0.5–1 wt% *CuO* nanofluids. *Gaurav et al.* [25] evaluated jojoba-oil-based nanofluids in *MQL* machining of titanium and observed reduced cutting forces and improved machining quality due to enhanced cooling and lubrication.

A review of the literature reveals that researchers have explored the use of various nanofluids in machining. However, the application of copper oxide-based nanofluids appears to be limited in turning operations. Therefore***, the objective of this study*** is to investigate the impact of varying concentrations of CuO nanofluids under dry, wet, *MQL*, and *nMQL* conditions.

Methods

A stainless steel bar served as the workpiece material for the experiments. Machining processes were performed using a *Turn Master 35* lathe. The lathe was operated under the following parameters: a speed of 900 rpm, a feed of 80 mm/min, and a depth of cut of 0.30 mm, following standard machine specifications.

The turning operation was performed under four lubrication conditions: dry, wet, *MQL*, and nano-enhanced *MQL*. For wet machining, a commercially available traditional cutting fluid was used. For the *MQL* setup, a cutting fluid was applied at a flow rate of 450 mL/hr. The *nMQL* experiments used a green cutting fluid based on corn oil, containing copper oxide nanoparticles at concentrations of 0.3%, 0.6%, 0.9%, 1.2%, and 1.5% by volume.

During the machining operation, the temperature at the tool tip was measured using a digital pyrometer. A piezoelectric dynamometer was used to measure the cutting forces produced during the turning operations.

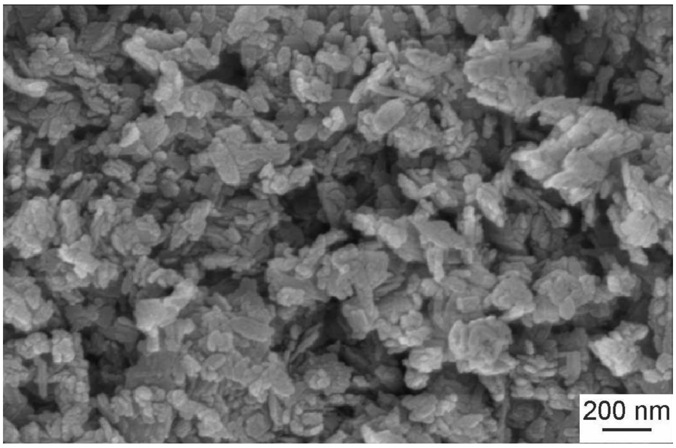


Fig. 1. SEM image of copper oxide nanoparticles

The diffusion process was carried out at different weight concentrations of *CuO*. Fig. 1 presents a field emission scanning electron microscope (*FESEM*) image of the copper oxide nanoparticles used in the study. To achieve a homogeneous blend, magnetic stirring was applied to uniformly disperse the nanoparticles throughout the base fluid. Moreover, to improve dispersion stability and inhibit nanoparticle agglomeration, *lauryl sodium sulphate* (*LSS*) was added at a quantity equal to 0.1% of the nanoparticle weight. Fig. 2 illustrates the appearance of the prepared copper-oxide-based nanofluids.

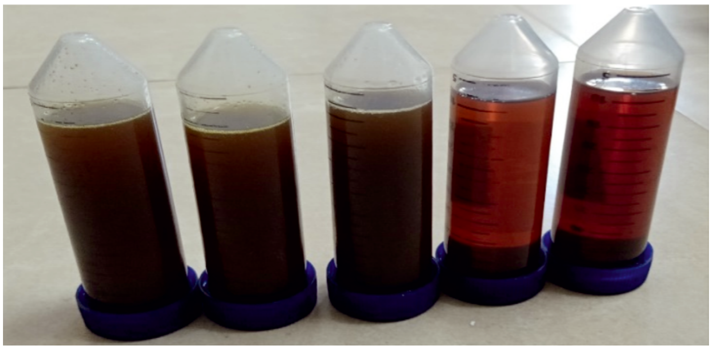


Fig. 2. Copper-oxide-based nanofluids

Experimental setup details

Parameter	Description
Machine tool	Center lathe machine, *Turn-master-35*, (*Kirloskar*)
Workpiece material	*SS 304* alloy
Workpiece size	50 mm diameter, 200 mm length
Tool holder	*PSBNR2525 M-12*
Cutting tool	*SNMG 120408 NSU* (coated carbide)

Results and Discussion

Extreme cutting forces during turning can accelerate tool wear, reduce tool life, increase the need for frequent tool changes, and degrade surface quality due to vibration and chatter. Fig. 3 shows the cutting forces recorded under various machining conditions, including dry, conventional (wet), *MQL*, and nano-enhanced *MQL* modes, using different cutting fluids such as conventional cutting fluid (*CCF*), green cutting fluid (*GCF*), and *GCF* blended with copper oxide nanoparticles at concentrations of 0.3 wt.%, 0.6 wt.%, 0.9 wt.%, 1.2 wt.%, and 1.5 wt.%. The highest cutting force, 120.7 N, was observed under dry conditions due to the absence of lubrication. In contrast, conventional wet machining using CCF resulted in a reduced cutting force of 103.2 N. An additional decrease was noted under *MQL* conditions with *GCF*, where the cutting force measured was 99.2 N. The application of copper oxide-based nanofluids in *MQL* led to a further reduction in cutting forces, indicating improved lubrication and reduced tool-workpiece friction.

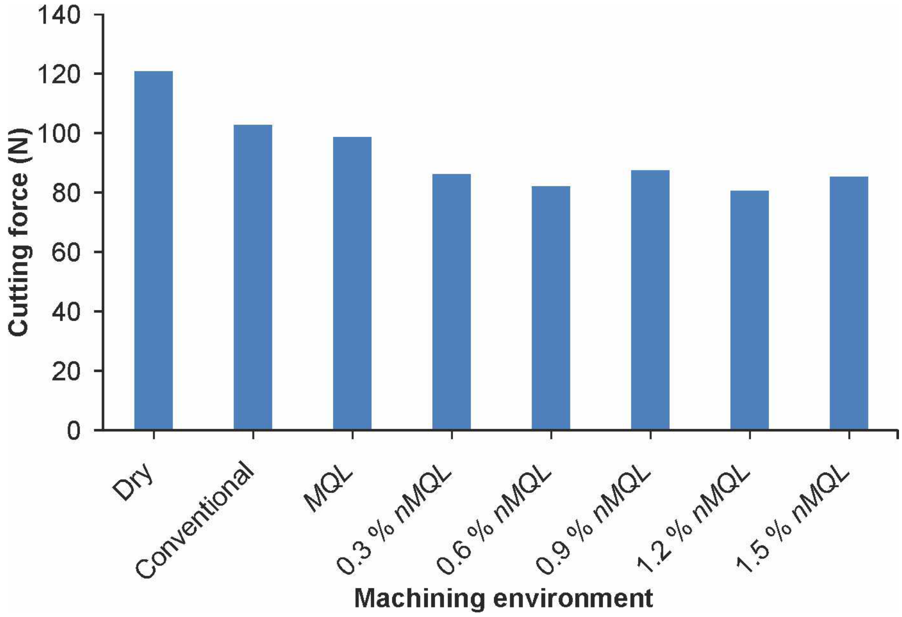


Fig. 3. Cutting forces under different machining environments

The use of 0.3 wt.% *CuO*-based nanofluid resulted in a decrease in cutting force to 86.7 N at the cutting zone. Further increases in *CuO* concentration to 0.6 wt.%, 0.9 wt.%, and 1.2 wt.% yielded cutting forces of 82.8 N, 87.7 N, and 81.3 N, respectively, compared to the 0.3 wt.% condition. This reduction was attributed to enhanced lubrication, as the nanoparticles formed a stable lubricating film on the workpiece surface, thereby promoting efficient heat dissipation. The improved thermal conductivity and lubricating properties at higher *CuO* concentrations helped diminish friction and reduce heat generation at the cutting zone. However, when the concentration reached 1.5 wt.%, the cutting force increased to 85.9 N, a value higher than that observed at 1.2 wt.%. This was due to nanoparticle agglomeration, which negatively affected the dispersion stability and diminished the overall effectiveness of the nanofluid.

Elevated cutting temperatures accelerate tool wear by softening the tool material, which contributes to rapid deterioration and a significant reduction in tool life. Moreover, high temperatures can adversely affect the surface finish due to thermally induced vibrations and instability during the turning operation. In extreme cases, the heat generated during cutting can change the microstructure of the workpiece material, potentially damaging its mechanical properties, such as hardness, tensile strength, and residual stress distribution. Fig. 4 shows the cutting temperatures recorded under various turning conditions, including dry (conventional), *MQL*, and *nMQL* modes. The tests were conducted using different cutting fluids such as conventional cutting fluid (*CCF*), green cutting fluid (*GCF*), and *GCF* blended with copper oxide nanoparticles at concentrations of 0.3 wt.%, 0.6 wt.%, 0.9 wt.%, 1.2 wt.%, and 1.5 wt.%.

Under dry machining mode, the highest cutting temperature was noted at 84 °C, primarily due to the absence of any cooling medium. When conventional cutting fluid (*CCF*) was used in wet machining, the cutting temperature decreased to 52 °C. A further decrease to 50 °C was detected with *MQL* using green cutting fluid. The use of copper oxide nanofluids under *MQL* conditions demonstrated enhanced cooling effectiveness, as evidenced by the significant temperature reductions measured during the turning operations.

With the application of 0.3 wt.% *CuO* nanofluid, the cutting temperature at the tool-chip interface was reduced notably to 45 °C. As the *CuO* concentration increased to 0.6 wt.%, 0.9 wt.%, and 1.2 wt.%, the

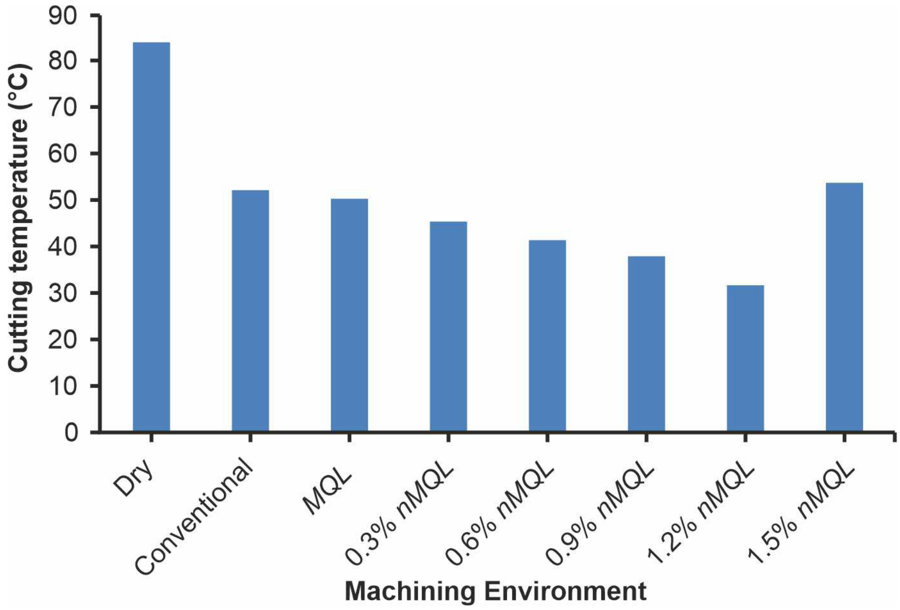
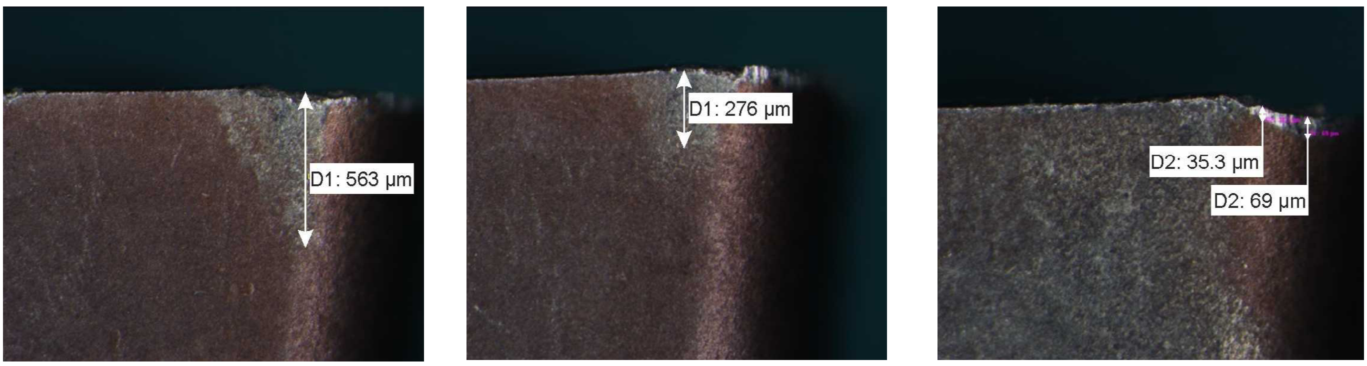


Fig. 4. Cutting temperature under different machining environments

identified temperature reductions were 41 °C, 38 °C, and 32 °C, respectively, compared to the 0.3 wt.% baseline. This consistent decline in temperature was mainly attributed to improved lubrication and higher thermal conductivity offered by the nanofluids. The dispersed nanoparticles formed a stable and sturdy lubricating film on the metal surface, while the characteristic high thermal conductivity of *CuO* facilitated fast heat dissipation. Moreover, the increased nanoparticle concentration provided additional lubrication, reducing frictional forces and consequently decreasing heat generation.

However, at 1.5 wt.% *CuO* concentration, the cutting temperature rose to 54 °C, which is higher than that observed at 1.2 wt.%. This increase was attributed to nanoparticle agglomeration, which adversely affected dispersion stability and reduced the cooling and lubricating performance of the nanofluid.

Fig. 5 shows the tool wear in different machining environments. Dry, wet, and *nMQL* metal cutting methods significantly affect tool wear during machining operations, particularly when nanofluids are used. In dry machining, the absence of lubricant leads to high cutting temperatures, accelerating tool wear due to thermal stress and poor chip removal. Wet machining, using conventional flood coolants, reduces heat and friction but raises environmental and disposal concerns. *MQL*, particularly when enhanced with biodegradable nanofluids containing nanoparticles such as copper oxide, offers a sustainable alternative. These nanofluids improve lubrication and thermal conductivity, forming a protective film at the tool-workpiece interface, which reduces abrasion, adhesion, and diffusion wear. As a result, *MQL* with nanofluids significantly reduces tool wear compared to dry and even traditional wet machining, enhancing tool life and machining performance.



a *b* *c*

Fig. 5. Tool wear in (*a*) dry, (*b*) *MQL*, and (*c*) *nMQL* machining environments

Conclusions

In this study, an investigation was conducted on corn oil-based cutting fluid with variable concentrations of copper oxide nanoparticles. A relative evaluation has been reported for various cooling systems such as conventional dry, wet, and *MQL*. The findings reveal that the integration of copper oxide nanoparticles at concentrations of 0.3%, 0.6%, 0.9%, 1.2%, and 1.5% into the corn-based green cutting fluid significantly improved machining performance under the tested conditions. The use of *nMQL* using the copper oxide-enhanced green cutting fluid led to notable reductions in both cutting force and cutting temperature, contributing to prolonged tool life. The greatest favorable results were observed at a concentration of 1.2 wt.% *CuO*, where the lowest cutting force and temperature were recorded. The 1.2% *nMQL* is proposed as the ideal lubricant for machinability improvement and reduced tool wear. These findings will be helpful for real-time process monitoring using a simple controller to maintain force and cutting temperature within targets.

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Conflicts of Interest

The authors declare no conflict of interest.