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Investigation of vegetable-based hybrid nanofluids on machining performance in MQL turning

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ABSTRACT

Introduction. Vegetable-based hybrid nanofluids are increasingly important in the context of *Minimum Quantity Lubrication* (*MQL*) turning due to its enhanced lubrication properties and environmental benefits. These nanofluids, which typically combine vegetable oils with nanoparticles like graphite or titanium dioxide, improve machining performance by reducing friction and cutting forces, leading to better surface finish and tool life. **The purpose of the work.** Coated carbide tools are widely used for machining *SS 304* stainless steel due to its wear resistance and high temperature resistance. The purpose of the current work is to evaluate the machining performance of *SS 304* steel under different concentrations of hybrid nanofluids. **The methods of investigation.** In this study, an attempt was made to use copper oxide/aluminum oxide (CuO/Al_2O_3) hybrid nanoparticles mixed with corn oil. A total of six hybrid cutting fluids with 100 ml volume and different mass concentration (0.4 %, 0.8 %, 1.2 %, 1.6 %, 2 %, and 2.4 %) were developed and its performance on *SS 304* steel was investigated. **Results and discussion.** The finding revealed that with an increase in the mass concentration, the thermophysical properties improve. In addition, it is shown that friction decreases with an increase in the particle concentration to 1.6 wt. %. At a concentration of 1.6 wt. % of CuO/Al_2O_3 hybrid cutting nanofluid showed the best performance characteristics. This study also provides a comparison with dry turning. The highest tool wear was observed in dry turning, followed by turning using corn oil. A 32 % reduction in cutting force is observed. The surface roughness when using CuO/Al_2O_3 hybrid cutting nanofluid is reduced by 27.7 %. However, when using a hybrid nanofluid (2.4 % of CuO/Al_2O_3), low tool wear is observed. In this study, the possibility of using vegetable-based hybrid nanofluids for metal turning with a minimum amount of lubricant is considered.

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Introduction

During machining, a large amount of heat is generated in the cutting zone and friction occurs, which reduces performance [1]. Therefore, effective cutting fluids and methods of introducing lubricant between the rubbing surfaces are required. Cutting fluids help to maintain a low temperature in the contact zone of the tool and the workpiece [2, 3]. To some extent, traditional cooling methods and cutting fluids serve this objective, but intensive use of conventional cutting fluids leads to environmental pollution and is also toxic

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to human beings [4]. Dry machining is an alternative to conventional cooling to ensure clean metal cutting operations without any environmental and worker health problems [5–7]. Some researchers have conducted metal cutting under dry conditions and found positive results in terms of machining performance. However, in most cases, dry machining with large cutting depths and high speeds cannot be the preferred method, since machining under such conditions reduces tool life [8–9]. In view of the above, a potential method of minimum quantity coolant (*MQL*) turning aims to reduce the consumption of cutting fluid. In this method, a small amount of cutting fluid is supplied to the machining zone. Generally, base fluids have good lubricating properties, but its low cooling capacity limits its use in high-speed cutting operations using *MQL*. Currently, nanometer-sized are combined with traditional fluids to improve performance [10–13].

Song et al. [14] added multi-walled carbon nanotubes to conventional cutting fluid and found a 200 % improvement in thermal conductivity. *Usluer et al.* [15] investigated the effect of hybrid nanofluid in *MQL* turning. The results showed that the feed rate had the most significant effect on the cutting force and axial thrust force (86.8 and 65 %, respectively), while the cutting conditions had the greatest effect on the cutting temperature (93.2%). *Senkan* et al. [16] added silicon dioxide (SiO_2) nanoparticles to sunflower oil and used the resulting hybrid nanocoolant in turning *AISI 304* steel. The results showed that the surface roughness was greatly affected by the feed rate. The cooling method had a significant effect on the cutting zone temperature and tool wear.

Ngoc et al. [17] investigated the performance of Al_2O_3/MoS_2 hybrid nanofluid and Al_2O_3 and MoS_2 mono-nanofluids in *MQL* turning of *90CrSi* steel parts. The results showed that lower cutting temperature was observed and the surface roughness and cutting force were less. *Junankar* et al. [18] investigated the effect of vegetable oil-based nanofluid on *MQL* turning of bearing steel. The hybrid nanofluid reduced the surface roughness and cutting temperature by 65 and 11 %, respectively.

Ibrahim et al. [19] investigated the effect of rice bran oil on the machining performance of *AISI D3* steel turning. The experimental results showed that the cutting force was reduced by 18.48 %, the tool wear was reduced by 51.96 %, and the machined surface roughness was reduced by 12.84 %. *Ngol* [20] evaluated the machining performance of *90CrSi* steel under *MQL* by adding Al_2O_3 and MoS_2 nanoparticles into the base liquid soybean oil and emulsion. The results showed that *MQL* turning with the nanofluid made of MoS_2, emulsion and soybean could significantly reduce the total cutting force.

Pasam and *Neelam* [21] studied the machining performance of titanium alloys using hybrid cutting fluids based on vegetable oil. The developed cutting fluids reduced the cutting force and cutting temperature, increased the microhardness of the machined surface and favorable residual stresses. *Usca* [22] studied the machining performance of *Dillimax 690T* material using a cellulose nanocrystal-based nanofluid under *MQL*. According to the test results, significant cutting temperature, surface roughness, tool wear and energy consumption were observed.

Singh et al. [23] studied the effect of nanoparticle concentration on turning of Hastelloy *C-276* under *MQL*. The study found that higher nanoparticle concentration improved thermal conductivity by 12.28 %, surface roughness by 27.88 %, temperature by 16.8 % and tool wear by 22.5 %. *Das* et al. [24] evaluated the turning performance of *AISI 4340* steel using four different nanofluid compositions under *MQL*. The authors found that *CuO* nanofluid had superior effect on cutting force and tool wear. *Bai* et al. [25] evaluated the milling performance of Al_2O_3 and cottonseed oil based nanofluids under *MQL*. The results showed that the surface roughness was 1.63 µm at 0.5 wt. % Al_2O_3 in cottonseed oil.

Researchers have tried to investigate the machining performance using various vegetable oils such as sunflower, soybean and cottonseed ones. However, the machining performance using corn oil has not been studied. The aim of this study is to use copper oxide-aluminum oxide hybrid nanoparticles (CuO/Al_2O_3) in combination with corn oil. The work also investigated the thermal, antifriction and antiwear properties of the hybrid nanofluids in different concentrations and its effect on the machining of *SS 304* steel.

Methods

First, a cutting fluid was prepared using 30 nm diameter *CuO* and Al_2O_3 nanoparticles supplied by *Platonic Nanotech* in Jharkhand, India. The mixing ratio of corn oil with *CuO* and Al_2O_3 nanoparticles was 1:1.5. To improve stability, a surfactant, sodium dodecyl benzene sulfonate (10 % load of nanoparticles), was added to the base oil. A total of six hybrid cutting fluids of 100 ml (0.4 %, 0.8 %, 1.2 %, 1.6 %, 2 % and 2.4 %) were created by varying the weight concentration of the hybrid nanoparticles in the fluid. A homogeneous mixture was obtained by magnetic stirring for one hour and ultrasonic stirring for two hours. The stability of the hybrid nanofluid was evaluated using conventional sedimentation methods. All the hybrid nano cutting fluid (*HCF*) samples were collected in 10 ml measuring jars and kept frozen for 72 hours before being used. The specific heat capacity and thermal conductivity were measured using differential scanning calorimetry and a Pro thermal analyzer, respectively. A rheometer (manufacturer Anton Paar) was used to measure the viscosity of the developed nanofluid. Three independent tests were conducted, the results of which were averaged to determine the viscosity. To study the tribological properties of *HCF*, pin-and-disk tests were carried out.

Different weight concentrations of CuO/Al_2O_3 in corn oil were investigated tested using a pin-on-disc tester. Corn oil was preferred as the base for the preparation of nanofluids due to its availability, cost-effectiveness and desirable thermal properties. Corn oil is a common vegetable oil with good thermal stability and moderate viscosity, making it suitable for dispersing nanoparticles and improving the heat transfer properties of nanofluids. According to *ASTM G 99*, a maximum load of 200 N and a rotation speed of 2,000 rpm were allowed during the friction test. To determine the friction coefficient using the pin-on-disc setup, a pin is applied to a rotating disk under controlled conditions to measure the frictional resistance between the two surfaces. The approach used in this study is shown in Fig. 1.

The turning experiments were carried out using the center lathe machine (*Turn-master-35*) shown in Fig. 2 with the feed rate of the prepared cutting fluid (CuO/Al_2O_3) of 10 ml/s. The *SS 304* alloy workpiece with a length of 200 mm and a diameter of 50 mm was machined using the *SNMG120408 NSU* (coated carbide) tool. The cutting parameters were selected according to the manufacturer's recommendations for the tool and workpiece. The detailed information of the experimental setup is given in Table 1. The cutting speed, feed, and *depth of cut* were fixed at 1,000 rpm, 90 mm/rev, 0.15 mm, respectively. During the turning process, the cutting force, tool tip temperature, and machined workpiece's finish were measured using a piezoelectric dynamometer, digital pyrometer, and surface roughness tester, respectively. The tool flank wear was measured using an optical microscope. Table 2 shows the process parameters and *MQL* environment.

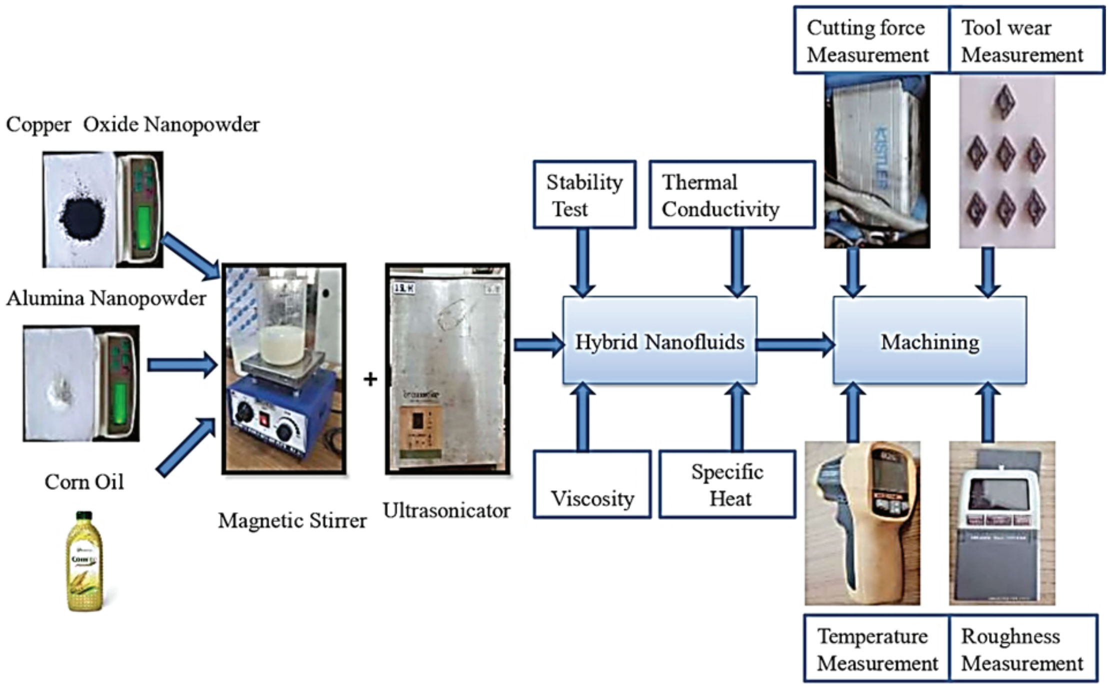


Fig. 1. Experimental methodology

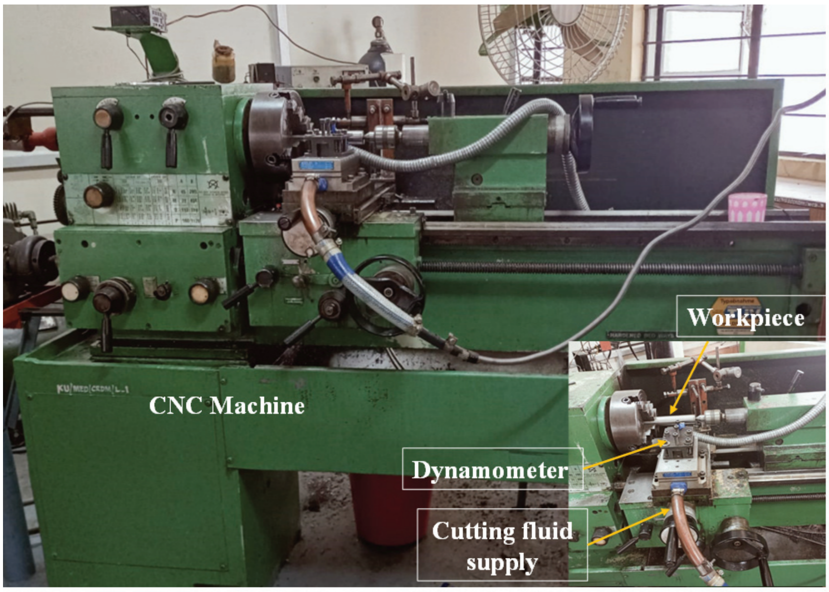


Fig. 2. Experimental setup for turning with *MQL*

Table 1

Details of experimental setup

Parameter	Description
Machine tool	Center lathe machine, *Turn-master-35*, (Make: *Kirloskar*)
Workpiece material	*SS 304* alloy
Workpiece size	Diameter 50 mm, length 200 mm
Tool holder	PSBNR 2525M-12
Cutting tool	*SNMG 120408 NSU* (Coated Carbide)

Table 2

Process Parameters and *MQL* Environment

Speed (rev/min)	1000
Feed (mm/min)	90
Depth of cut (mm)	0.3
Base oil	Corn oil
Surfactants	*SDBS*
Concentration of surfactants	10 (wt. % of np)
Nanoparticles	Copper oxide/alumina (CuO/Al_2O_3)
Hybrid ratio	1:1.5
Weight concentration	0.4,0.8,1.2,1.6, 2, 2.4
Lubrication	*MQL* flow rate of 10 mL/sec
Temperature measurement	Digital pyrometer
Cutting force measurement	Piezoelectric type, *Kistler 9257B*
Tool wear measurement	Optical Microscope

Results and Discussion

In this study, the stability of corn oil-based CuO/Al_2O_3 hybrid nanofluids was investigated by visual observation. After 96 hours of sample preparation, it was observed that the CuO/Al_2O_3 hybrid nanofluids in the ratio of 1:1.5 were most stable at the weight fraction of 0.4 and 1.6. Increasing the concentration led to increased aggregation and hence decreased stability. The stability test results of corn oil-based CuO/Al_2O_3 hybrid nanofluids for different weight concentrations are shown in Fig. 3.

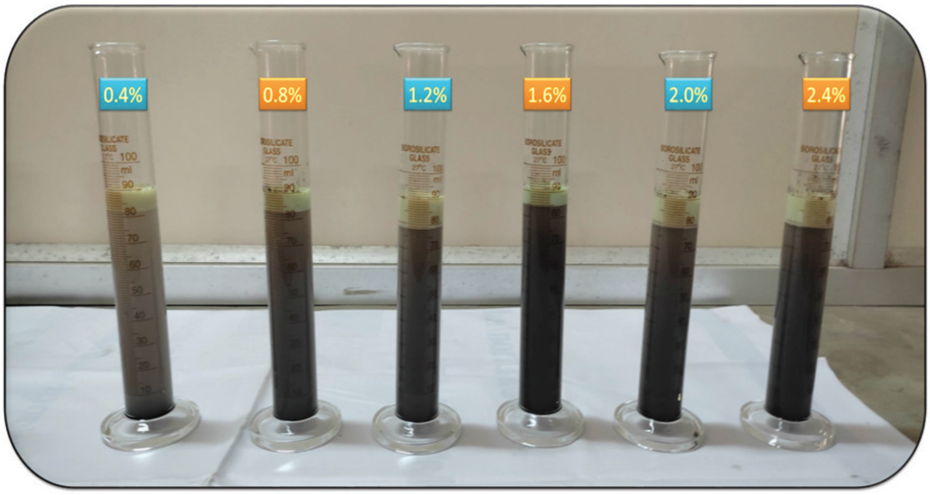


Fig. 3. Results of a 96-hour sedimentation test

Fig. 4, *a* shows the viscosity results using different concentrations of CuO/Al_2O_3 hybrid nanofluids. The viscosity can be increased by using hybrid nanoparticles in addition to the base oil with a particle concentration of 0.4–2.4 wt. %. The CuO/Al_2O_3 hybrid nanofluid becomes more viscous as a result of increasing the particle concentration in the liquid. The viscosity of the solution decreased with increasing temperature. As a result of the decrease in intermolecular cohesion between particles at higher temperatures, the viscosity becomes less significant.

Fig. 4, *b* shows the effect of temperature on thermal conductivity. This can be achieved by increasing the nanoparticle content (weight percent) in CuO/Al_2O_3 hybrid nanofluids and temperature. Fig. 4, *b* also shows that the thermal conductivity of the material was improved by adding nanoparticles due to *Brownian* motion and the huge surface area of nanofluids.

Fig. 4, *c* shows that the experimental values of specific heat capacity of CuO/Al_2O_3 HCF increase with the increase of particle concentration (in percent by weight). The specific heat capacity increases with the increase of nanoparticle concentration and temperature. At the nanoparticle concentration of 2.4 wt. %, the specific heat capacity of CuO/Al_2O_3 hybrid cutting fluid is 11.86 % higher than that of the base oil. This is probably due to the high stability of *HCF*. The thermal conductivity and specific heat capacity of *HCFs* were improved, which enables it to dissipate heat more efficiently. The tribological properties of hybrid nanofluids can be evaluated using the pin-on-disk friction test. By mixing copper oxide and aluminum oxide hybrid nanoparticles with corn oil, a thin tribofilm is formed between the pin and the disk. The film thickness and the obtained result become larger with the increase of the amount of nanoparticles to a certain ratio.

Fig. 4, *d* shows the decreasing pattern of the friction coefficient up to 1.6 wt. %, and then the increasing pattern of the friction coefficient after 1.6 wt. % is observed. After increasing to 1.6 wt. %, the friction coefficient is proportional to the content of nanoparticles, which indicates that the lubricating properties of the developed cutting fluid are eventually reduced. The reason is the agglomeration of nanoparticles observed as a result of sedimentation. The minimum friction coefficient of 0.124 is observed at a content of 1.6 wt. % of *CuO* and Al_2O_3 in hybrid nanofluids.

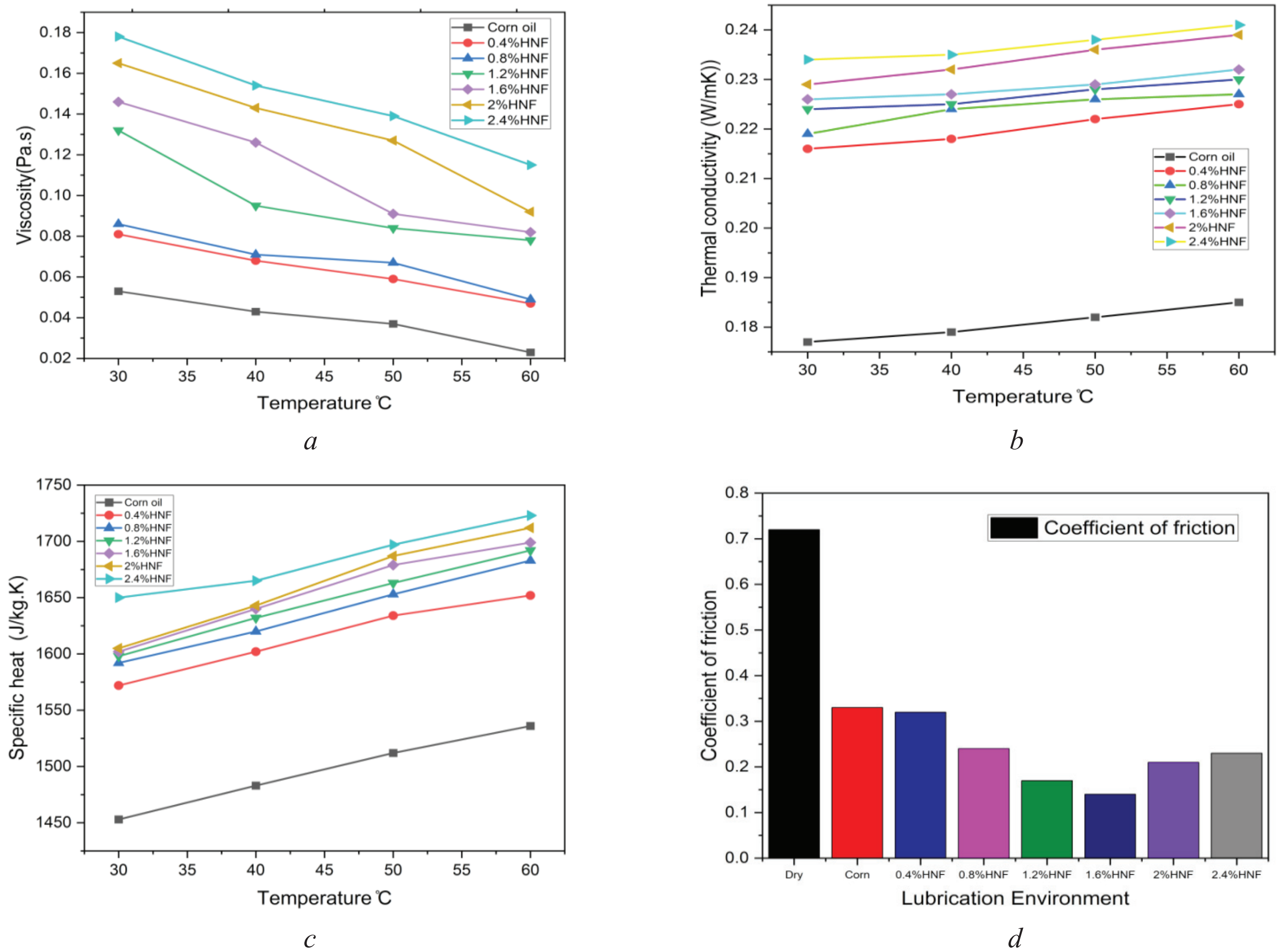


Fig. 4. Viscosity (*a*); thermal conductivity (*b*); specific heat (*c*); coefficient of friction (*d*)

Under continuous cutting conditions, an electric dynamometer with a piezo sensor mounted on the lathe measured the cutting forces in real time. The measured cutting forces are shown in Fig. 5, *a* for various lubrication conditions. Consistently low particle concentrations reduce all forces, while higher concentrations increase it only slightly.

As the concentration of nanoparticles increases, a dense or slurry layer is formed, which increases the cutting force. At a CuO/Al_2O_3 content of 1.6 wt. %, the cutting force decreases by 32 %. This is due to the formation of an adhesive coating between the sliding surfaces due to the layered nanoscale structure of Al_2O_3, which also makes the metal surfaces more easily absorbable. This can be seen from the friction coefficient in Fig. 4, *d*. CuO/Al_2O_3 *HCF* also has a higher viscosity than the base fluid. The thick film that forms during cutting eventually reduces the cutting pressure on the contacting surfaces.

The cutting temperature can be affected by the heat generated at the chip-tool interface. A digital pyrometer was used to determine the temperature of CuO/ Al_2O_3 *HCF*. Fig. 5, *b* shows different lubrication conditions affecting the cutting temperature. The cutting temperature was significantly reduced by using the CuO/Al_2O_3 hybrid nanofluid. The reduction in cutting temperature can be achieved when the copper and aluminum oxide concentration is as low as 2.4 %. Compared with other concentrations, the sample containing 1.6 wt. % CuO/Al_2O_3 has the lowest cutting temperature (67 °C). The hybrid nano cutting fluid containing 1.6 wt. % CuO/Al_2O_3 reduces the cutting temperature by 43.4 % compared with the traditional cutting fluid. By using this *HCF*, the thermal conductivity and heat transfer coefficient of the CuO/Al_2O_3 nano cutting fluid can be improved to reduce the temperature in the cutting zone.

The effectiveness of cutting fluids is determined by its ability to reduce the surface roughness of the workpiece. Fig. 5, *c* shows the measured surface roughness. With an increase in the concentration of

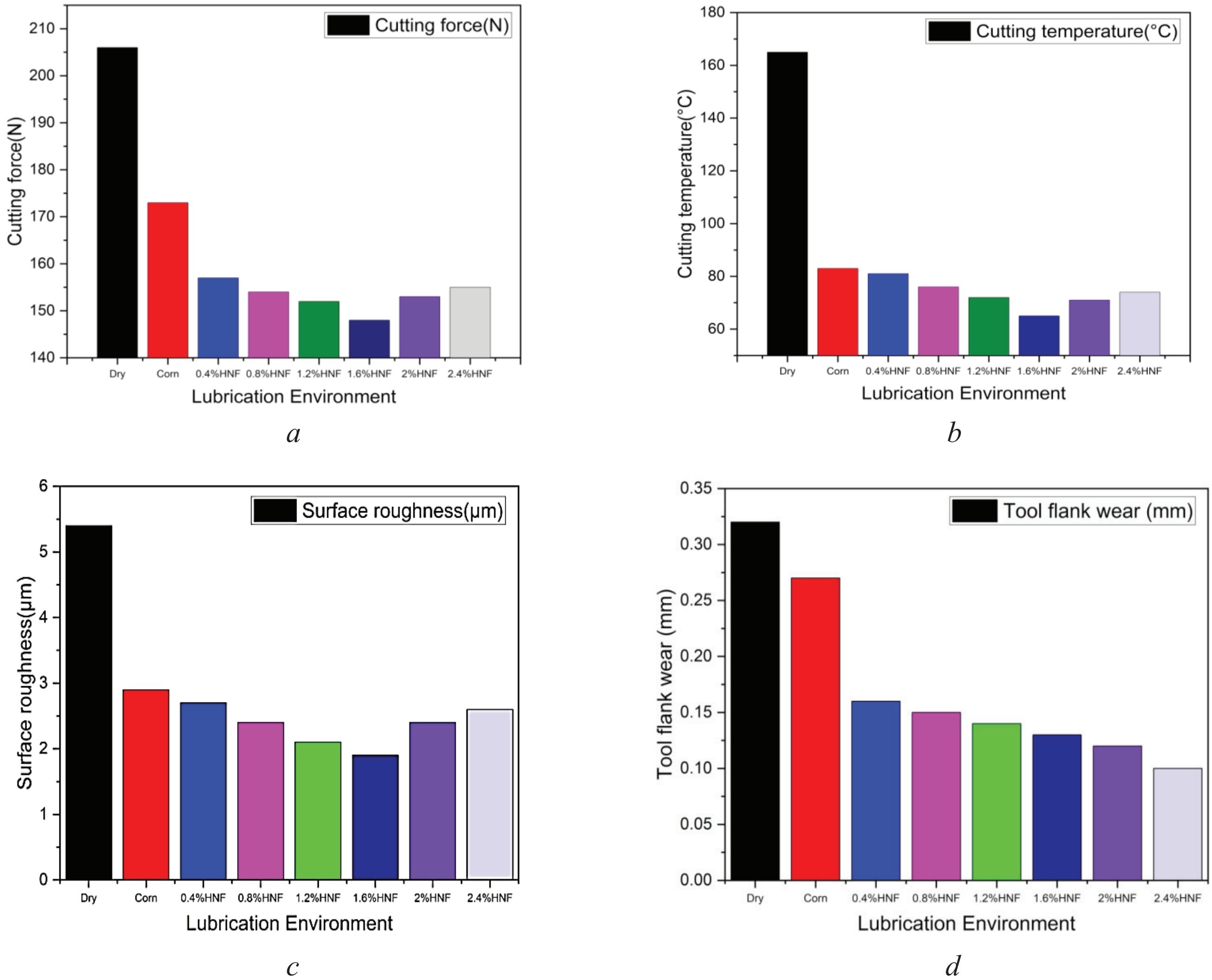


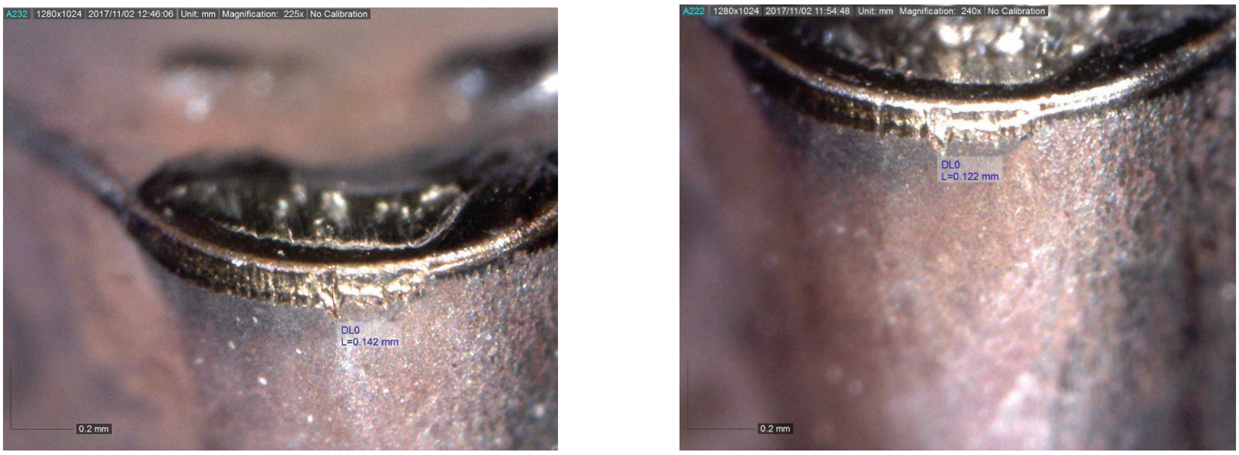
Fig. 5. The effect of the composition of the coating on: cutting force (*a*); cutting temperature (*b*); surface roughness (*c*); tool flank wear (*d*)

nanoparticles, the roughness value (*Ra*) decreases from 5.4 to 1.6 %, and then increases as the concentration increases. This may be due to the aggregation of nanoparticles. The surface roughness (*Ra*) when using *HCF* CuO/Al_2O_3 is reduced by 27.7 and 23.8 %, respectively, compared with dry cutting and cutting using base oil as a cutting fluid. Due to the minimal shear resistance between the tool and the workpiece, caused by the affinity of the tool to metal surfaces, the friction between the tool and the workpiece is minimized.

Measuring the flank wear helps to predict the remaining service life of the cutting tool. By measuring the flank wear, operators can monitor the tool condition in real time. It is possible to increase the service life of the tool by reducing its wear. Fig. 5, *b* shows the study of tool wear under various lubrication conditions. Fig. 6, *a*, *b* shows the tool wear with 2 % hybrid nanofluid and 0.8 % hybrid nanofluid, respectively. By using corn oil with a higher CuO/Al_2O_3 content than the base oil, the tool flank wear is significantly reduced. Reduced friction means less heating and less tool wear, which are both positive things. As a result, a very thin layer is formed between the workpiece and the tool. Alternatively, the reduction in tool flank wear may be due to the synergistic combination of the ball bearing properties of *CuO* and Al_2O_3 nanoparticles.

Conclusions

In this study, corn oil-based nanofluids with different concentrations of $CuO + Al_2O_3$ are prepared and tested for turning performance. The cutting force, surface roughness and tool are investigated. The results show that the use of hybrid nanofluids under *MQL* can improve the machining performance of *SS 304*. In all



a *b*

Fig. 6. Tool wear when using 2 % hybrid nanofluid (*a*); tool wear when using 0.8 % hybrid nanofluid (*b*)

tests, *HCF* with 0.4 and 1.6 wt. % of CuO/Al_2O_3 showed little sedimentation. The properties of CuO/Al_2O_3 cutting fluid such as specific heat, viscosity and thermal conductivity are improved by increasing the particle concentration and temperature. The developed cutting fluid reduces the friction coefficient compared with dry turning and turning using 1.6 wt. % base oil as cutting fluid. The highest tool wear is observed in dry turning, followed by turning using corn oil. The developed hybrid nano cutting fluid reduces cutting force, temperature, and improves surface quality at a concentration of 1.6 wt.% CuO/Al_2O_3. When using a hybrid nanofluid with a concentration of 2.4 wt. % CuO/Al_2O_3, low tool wear is observed.

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Conflicts of Interest

The authors declare no conflict of interest.