Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2025 vol. 27 no. 1 pp. 20–33
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2025-27.1-20-33

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Investigation of vegetable oil-based cutting fluids enhanced with nanoparticle additions in turning operations

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ARTICLE INFO

Article history:
Received: 11 November 2024
Revised: 25 November 2024
Accepted: 17 December 2024
Available online: 15 March 2025

Keywords:
Vegetable oils
Nanofluids
High-Speed machining
Environmental sustainability

ABSTRACT

Introduction. Currently, the use of vegetable oil-based cutting fluids with nanoparticles is being implemented in turning operations. These fluids provide a sustainable and high-performance solution by improving lubrication, cooling, and surface quality. The use of vegetable oil-based cutting fluids with nanoparticles also promotes an eco-friendly approach in the manufacturing industry. These fluids serve as an alternative to conventional cutting fluids, which are hazardous chemical mixtures that pose a risk to both the environment and the operator. **The purpose of the work.** The present study focuses on the use of cutting fluids based on environmentally friendly vegetable oils in the turning process. This work investigates the performance of turning *AISI 1014* steel with various nanoparticle combinations and ratios. **The methods of investigation.** In this study, five different vegetable oils — corn oil, coconut oil, sunflower oil, palm oil, and neem oil — were used as base fluid. *CuO*, Al_2O_3, graphene, and powdered multi-walled carbon nanotubes were added to the base fluid to create nanofluids. Cutting fluids were developed with varying weight concentrations of 0.20 %, 0.40 %, 0.60 %, 0.80 %, and 1 %, and its performance when machining *AISI 1014* steel was investigated. **Results and Discussion.** The results indicated that, among the vegetable oils, corn oil had the greatest effect on viscosity and thermal conductivity. Graphene nanoparticles showed promising results in reducing cutting force, temperature, and surface roughness. When using corn oil containing 0.8 wt. % graphene nanoparticles, a 104 N reduction in cutting force was observed, this is 29.8 % less than that achieved with pure corn oil. At a high concentration (1 wt. %), the reduction in load decreases due to significant agglomeration of nanoparticles. The optimal nanoparticle concentration in the base fluid (corn oil) is 0.8 wt. %.

For citation: Manikanta J.E., Ambhore N., Thellaputta G.R. Investigation of vegetable oil-based cutting fluids enhanced with nanoparticle additions in turning operations. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2025, vol. 27, no. 1, pp. 20–33. DOI: 10.17212/1994-6309-2025-27.1-20-33. (In Russian).

Introduction

Cutting fluids play a crucial role in metal cutting operations by lubricating the tool-workpiece interface, removing chips from the cutting zone, and cooling the workpiece and cutting tool [1]. However, improper use and disposal of cutting fluids can negatively impact the environment and human health. Turning, a widely used machining process in industries such as marine, energy, construction, and automotive manufacturing, involves removing material from a rotating workpiece using a single-point cutting tool [2]. Turning processes face challenges such as high cutting pressures, friction, tool wear, elevated temperatures at the tool-workpiece interface, and significant energy consumption [3–4]. Improving the sustainability and efficiency of turning requires reducing cutting forces and energy consumption, for which the use of effective cutting fluids is essential [5–6].

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Conventional mineral oil-based cutting fluids often contain hazardous components such as bactericides, wetting agents, preservatives, and extreme pressure additives, posing risks to the environment and worker health [7]. Furthermore, the recycling and disposal of used cutting fluids contribute to environmental pollution [8]. This has led to increasing interest in alternative lubrication methods for turning operations [9]. Vegetable oil-based lubricants offer an attractive alternative due to their lubricating properties, cost-effectiveness, and biodegradability, particularly when used under minimum quantity lubrication (*MQL*) conditions [10]. *MQL* can serve as a substitute for flood cooling in terms of tool performance, cost, environmental impact, health, and safety. The use of eco-friendly lubricants and lubrication techniques can significantly reduce the environmental impact of the turning industry while improving machining efficiency and product quality [11].

Several lubricating fluids, including mineral, natural, synthetic, and semi-synthetic oils, are commonly used in turning operations. Researchers have extensively investigated the performance of these fluids. For example, *Manikanta* et al. [12] found that using maize oil under *MQL* conditions in turning *SS 304* steel improved cutting force, temperature, and tool life compared to dry cutting. *Wang* et al. [13] investigated the impact of various vegetable oils (soybean, peanut, maize, rapeseed, palm, castor, and sunflower) on the grinding of nickel alloy under *MQL*. Their findings indicated that coconut oil was readily absorbed into the tools and workpieces and exhibited excellent lubricating effect, while castor oil outperformed other grinding fluids in terms of lubrication and workpiece surface quality. *Shaikh* and *Siddhu* [14] reported favorable results when machining *D2* steel with a non-edible vegetable oil-based cutting fluid, observing comparable surface finishes for mineral oil, soybean oil, and cottonseed oil (variations less than 10 %).

Puttaswamy and *Ramachandra* [15] explored the feasibility of using Mahua oil and Neem oil as drilling fluids for *AISI 304L* under *MQL* at 2 bar pressure, concluding that neem and mahua oil performed better than traditional cutting fluids in all aspects. *Li* et al. [16] investigated *MQL* grinding experiments with pure vegetable oil, finding that palm oil was the most suitable base oil for *MQL* grinding of high-temperature nickel alloy based on energy ratio coefficient and grinding temperature. Similarly, *Babu* et al. [17] found that olive oil reduced surface roughness and tool wear during milling of *AISI 304* steel with *MQL*, and *Radhika* et al. [18] observed improved surface quality and reduced cutting force when using sesame oil as a cutting fluid during turning of *AISI 1014* steel. *Guo* et al. [19] investigated six different oils combined with castor oil for *MQL* grinding, revealing that nanoparticles exhibit excellent tribological properties and thermal conductivity.

The addition of nanoparticles can significantly enhance the thermal conductivity and lubricating properties of vegetable oils, improving machining performance [20–21]. Research has focused on the effects of adding nanoparticles to eco-friendly vegetable oils to improve cutting efficiency under *MQL*. *Nam* et al. [22] investigated the use of nanofluid *MQL* in micro-drilling, finding that it led to a significant decrease in drilling torques and thrust forces, as well as an increase in the number of drilled holes, and effectively eliminated remaining chips and burrs, thereby improving the overall quality of drilled holes. *Shen* et al. [23] dispersed MoS_2, diamond, and Al_2O_3 nanoparticles in vegetable oil to examine forces and tool abrasion in near-dry grinding, finding that *MQL* using 100 nm diamond nanoparticles at a 1.5 % volume fraction resulted in the greatest force reduction.

Vasu et al. [24] investigated the effect of *MQL* with nano-Al_2O_3 on the surface quality of *Inconel 600*, finding that a higher volume fraction of nano-Al_2O3 in vegetable oil correlated with improved surface quality. *Ni* et al. [25] added graphene to castor, corn, and rapeseed oil at varying mass fractions to enhance *MQL* tapping of *ADC12* aluminum alloy, discovering that a 0.5 wt % concentration of graphene yielded the lowest average torque, regardless of the base oil used. High-quality thread surfaces were also achieved with a suspension *MQL* based on 0.5 wt% castor oil. *Zhang* et al. [26] created Al_2O_3 nanofluids by milling *Ti-6Al-4V* under *MQL* conditions with cryogenic air, finding that the combination of nanofluids and cryogenic air demonstrated superior grinding performance compared to either cryogenic air or Al_2O_3 nanofluids alone. *Manojkumar* and *Ghosh* [27] added multi-walled carbon nanotubes to sunflower oil to grind *AISI 52100* steel using small-quantity cooling lubrication (*SQCL*), showing that the developed liquid improved the workpiece's surface quality and the wheel's service life [28].

Sustainable practices are crucial in the machining industry, and selecting appropriate cutting fluids is essential for minimizing environmental impact. While previous studies have largely focused on the use of green cutting fluids in various machining operations (turning, milling, drilling, reaming, and grinding), investigations on various vegetable oils with nanoparticle additions and varying ratios are limited.

This study aims to address this research gap by employing both pure vegetable oil and vegetable oil-based nanofluids in *MQL*-assisted machining. The goal of the present study is to determine the optimal vegetable oil for use as a green cutting fluid and evaluate different nanoparticle combinations and ratios to improve machining performance, thus offering a novel perspective on cutting fluid formulations for enhanced machining results.

Methods

AISI 1014 steel was used as the workpiece material in the turning operation. Corn oil, coconut oil, sunflower oil, palm oil, and neem oil served as the base fluids. Copper oxide nanoparticles (*CuO*, 99.5 % purity, 30-50 nm size range), aluminium oxide nanoparticles (Al_2O_3, 99.5 % purity, 30-50 nm size range) were supplied by *Platonic Nanotech Private Limited Laboratory*, India. Multi-walled carbon nanotubes (*MWCNTs*, 99.9 % purity, 5-20 nm size range, powdered), and graphene nanoparticles (99.5 % purity, 5-10 nm size range) were supplied by the same laboratory.

Pure corn oil was used as the base fluid, to which nanoparticles were subsequently added to create the nano cutting fluids. The concentrations of mixed powder particles in the base fluid were calculated as follows: 0.20 wt. %, 0.40 wt. %, 0.60 wt. %, 0.80 wt. %, and 1 wt. %. The nanofluids were blended using a magnetic stirrer for three hours followed by ultrasonication for six hours to achieve a uniform and stable suspension. A fresh sample of the stable nanofluid dispersion was used for each test to prevent agglomeration or sedimentation.

MQL was implemented on a lathe machine for turning *AISI 1014* steel. The schematic diagram of the experimental setup and details of the turning zone are shown in Fig. 1 and Fig. 2, respectively. A coated carbide insert (*SNMG120408 NSU*) was mechanically clamped onto a rigid tool holder (*PSBNR2525M-12*). An *MQL* system consisting of a compressor, flow controller, air dryer, and spray nozzle was used in the machining zone for lubrication. The air supply pressure was 5 bar, and the nanofluid flow rate was 20 ml/min. The spray nozzle was positioned 4 cm above the tool rake face.

Machining parameters (cutting force, cutting temperature, and surface roughness) were examined during turning using a *Turn Master 35 Center* lathe machine (*KIRLOSKAR*) in a mist of different concentration nano cutting fluids. Tests were repeated at least three times, and the average results were recorded. Cutting

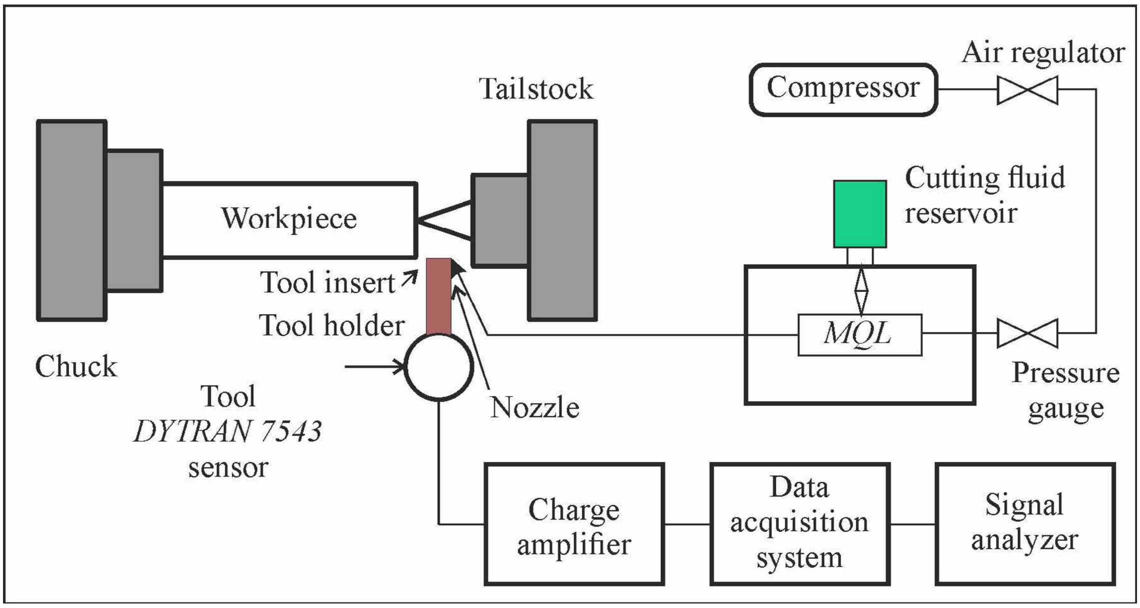

Fig. 1. Experimental methodology

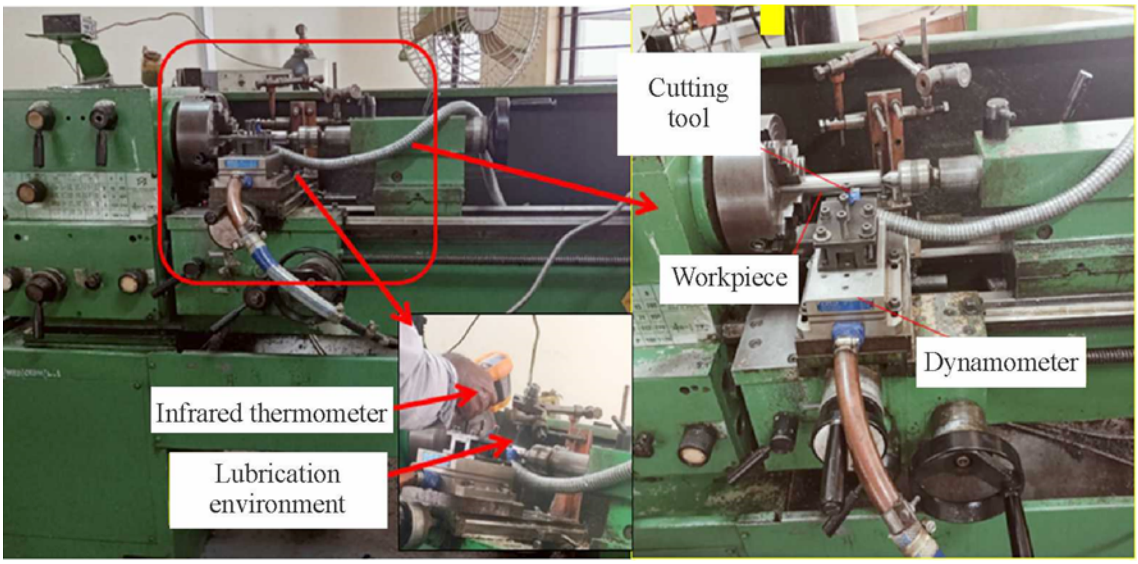

Fig. 2. Experimental setup with *MQL*

force was measured using a *Kistler* dynamometer (Type *9275B*) employing three-component piezoelectric crystals. Over a regular period, the cutting forces' average values were stopped. A digital pyrometer was used to measure the cutting temperature. The average surface roughness (***Ra***) of the workpiece was determined using a contact-type measurement device (*Surftest SJ-210*). Data were recorded for each turning operation under varied machining conditions.

Results and Discussion

This study focuses on the thermal conductivity and viscosity of various vegetable oils at 25 °C, properties that are crucial for determining their suitability in manufacturing applications. Among the tested oils, corn oil exhibited the highest thermal conductivity (0.154 W/mK), indicating its effectiveness in heat transfer, which is vital for maintaining optimal operating temperatures. The thermal conductivity of the different vegetable oils is compared in Fig. 3.

Viscosity, which characterizes a fluid's resistance to flow, is affected by factors such as temperature and molecular structure. Corn oil also exhibited a viscosity of 61 cP (centipoise) at 25 °C, reflecting its

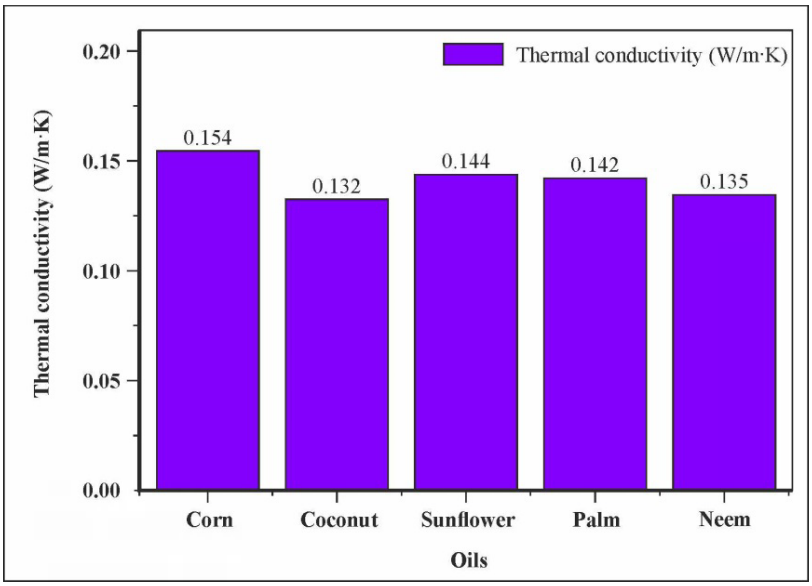

Fig. 3. Thermal conductivity of different vegetable oils

resistance to flow at that temperature. The viscosity of various vegetable oils is shown in Fig. 4. Viscosity plays a crucial role in applications where oils are used to reduce friction and wear between moving components. Oils with higher viscosity generally provide better lubrication and film formation, thereby protecting mechanical components from damage. In metal processing operations, such as machining, where heat generation is unavoidable, the use of corn oil as a cutting fluid can effectively dissipate heat, preventing tool wear and extending tool life.

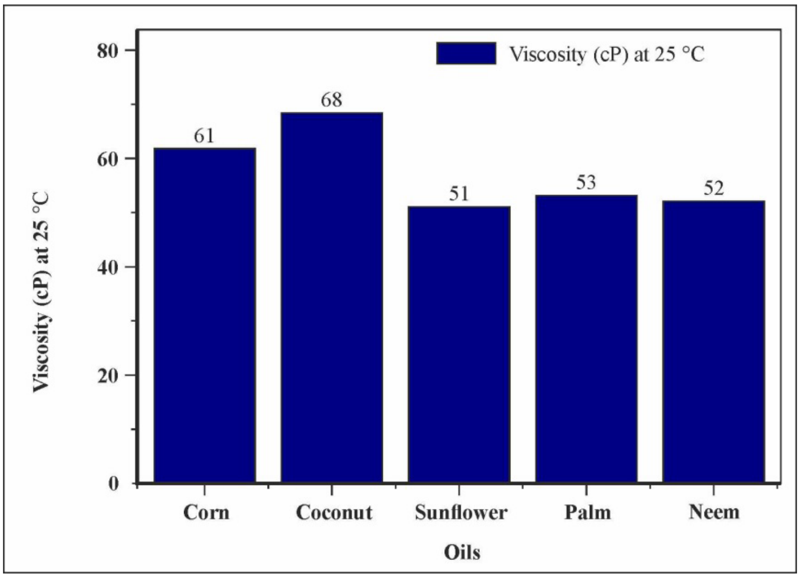

Fig. 4. Viscosity of different vegetable oils

The integration of nanoparticles into corn oil is an effective strategy for minimizing friction due to their superior tribological and thermo-physical characteristics compared to corn oil alone. Nano-lubricants have been shown to exhibit exceptional efficacy, forming a rolling, protective film and promoting mending and polishing effects. Fig. 5 shows the thermal conductivity behavior of nanofluids.

Across all nanofluids, the thermal conductivity increases by up to 0.8 % with the incorporation of nanoparticles. However, when the nanoparticle concentration reaches 1 %, a decline occurs because

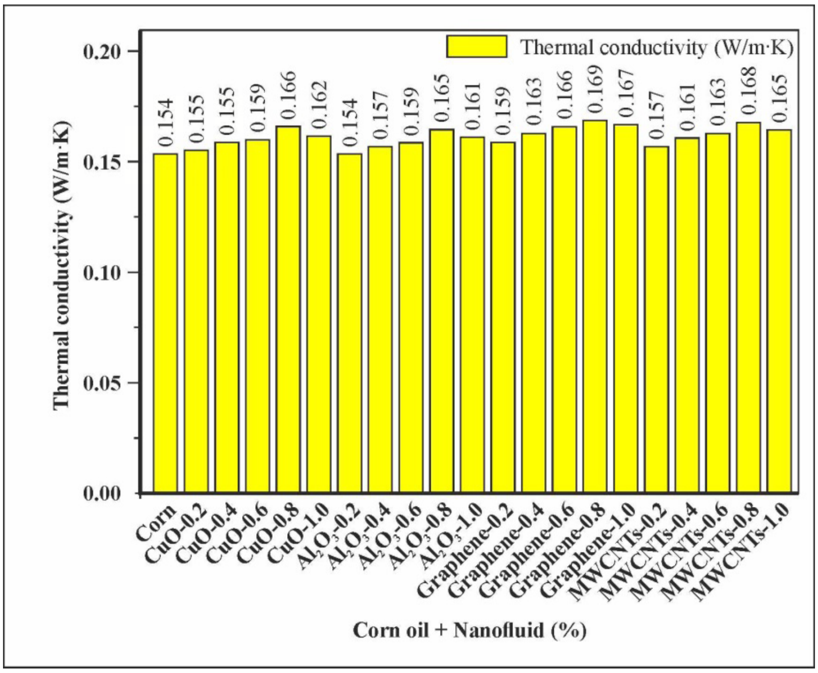

Fig. 5. Thermal conductivity of different nanofluids

of sedimentation or agglomeration phenomena. Different nanopowders such as *CuO*, Al_2O_3, graphene, and multi-walled carbon nanotubes were evaluated across different nanofluids. Among these, graphene nanofluids exhibited the most promising thermal conductivity performance. Compared to corn oil's thermal conductivity of 0.154 W/mK, graphene oil with a 0.8 % nanoparticle concentration demonstrated an improvement of 9.74 %, reaching 0.169 W/mK.

Remarkable fact is that graphene nanofluids exhibited the most promising thermal conductivity performance. In particular, graphene nanofluids consistently outperformed other types, with multi-walled carbon nanotubes following closely, next by copper oxide and aluminum oxide. These findings underscore the remarkable potential of graphene-based nanofluids in enhancing thermal conductivity compared to conventional base fluids. Graphene's exceptional thermal conductivity is attributed to its unique atomic structure. Graphene consists of a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, enabling efficient heat transfer due to its high phonon mean free path and ballistic transport of heat carriers. Furthermore, graphene exhibits superior mechanical strength and stability, preventing structural deformations that could impede heat transfer. Its immense surface area allows for easier interaction with neighboring molecules, enhancing heat transfer efficiency.

Fig. 6 illustrates the change in viscosity of different nanofluids with the incorporation of different nanoparticles. Across all nanofluids, there is a noticeable increase in viscosity of up to 0.8 % upon the addition of nanoparticles. However, once the nanoparticle concentration reaches 1 %, a decrease in viscosity occurs due to sedimentation or agglomeration phenomena. Various nanopowders, including *CuO*, Al_2O_3, graphene, and multi-walled carbon nanotubes, underwent evaluation in different nanofluid formulations. Graphene nanofluids demonstrated the most favorable viscosity performance. In comparison to corn oil's viscosity of 61 cP, the viscosity of graphene oil with a 0.8 % nanoparticle concentration saw a notable increase of 21.3 %, reaching 74 cP. Remarkably, graphene nanofluids consistently surpassed other types in terms of viscosity enhancement. These results highlight the potential of graphene-based nanofluids in improving viscosity characteristics compared to conventional base fluids because graphene's inherent robustness minimizes structural deformations within the fluid, thus contributing to enhanced viscosity.

High cutting forces lead to rapid tool wear, shortening tool lifespan and increasing the frequency of tool changes, and result in poor surface finish due to vibration and chatter during machining. Various nanopowders, such as *CuO*, Al_2O_3, graphene, and multi-walled carbon nanotubes, were evaluated in

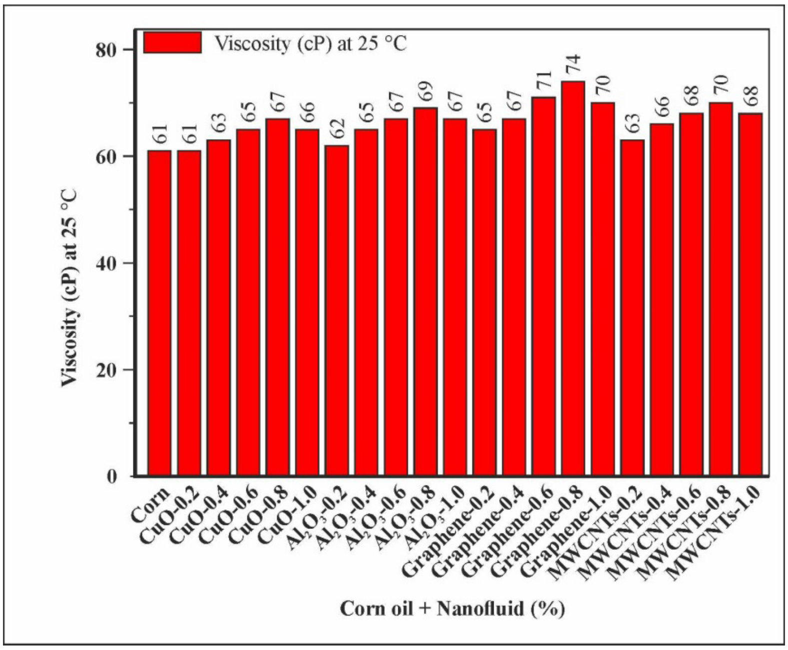

Fig. 6. Viscosity of different nanofluids

nanofluids of different compositions. Fig. 7 illustrates the measured cutting force with varying nanoparticle concentrations (0.2 wt. %, 0.4 wt. %, 0.8 wt. %, and 1 wt. %). Graphene nanofluids provided the most significant reduction in cutting force. Using the base cutting fluid resulted in a cutting force of 135 N; however, with 0.8 wt. % graphene nanofluid, the cutting force decreased to 104 N, i.e. by 29.8 %. This is attributed to improved lubrication; nanoparticles on the metal surface formed a robust lubricant film, leading to better heat dispersion. The higher thermal conductivity and improved lubrication from increased graphene concentration reduced friction and heat generation. At 1 wt. % graphene concentration, the cutting force increased to 108 N compared to 0.8 wt. %, primarily because of nanoparticle agglomeration, which impaired the nanofluid's performance.

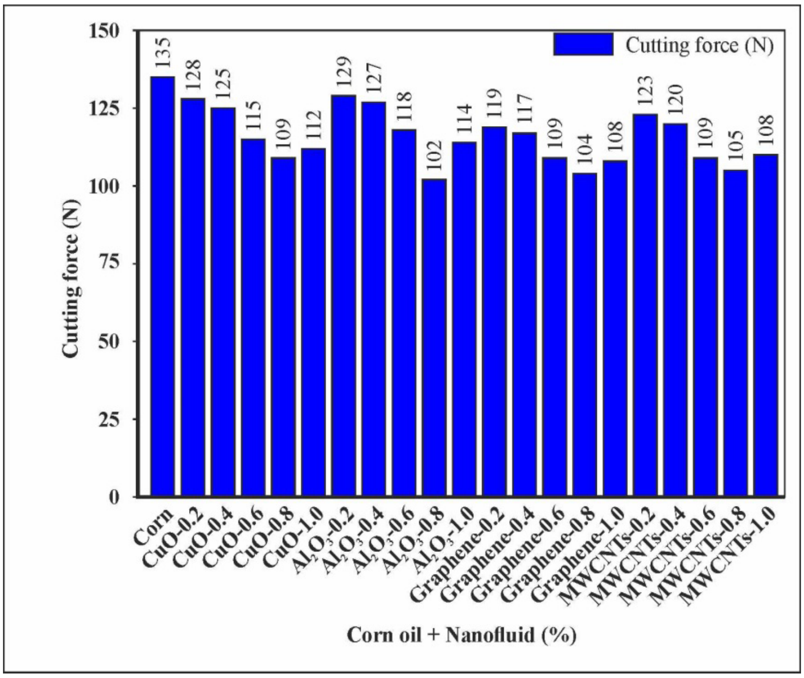

Fig. 7. Cutting forces when using different nanofluids

The tribological properties of a component determine its ability to effectively and long-term perform its intended function in the intended application area. Surface quality is a key factor influencing tribological characteristics, and low surface roughness is generally preferred. This study investigated the effects of several nanofluids (*CuO*, Al_2O_3, graphene, and multi-walled carbon nanotubes) on average surface roughness. Fig. 8 illustrates the measured surface roughness with varying nanoparticle concentrations (0.2 wt. %, 0.4 wt. %, 0.8 wt. %, and 1 wt.%). Graphene nanofluids provided the most significant reduction in surface roughness. Using the base cutting fluid resulted in a surface roughness of 1.18 µm; however, with 0.8 wt. % of graphene nanofluid, the surface roughness decreased to 0.78 µm, i.e. by 51.3 %. This is attributed to improved lubrication; nanoparticles on the metal surface formed a robust lubricant film, leading to better heat dispersion. The higher thermal conductivity and improved lubrication from increased graphene concentration reduced friction and heat generation. However, at 1 wt. % graphene concentration, the surface roughness increased to 0.8 µm compared to 0.8 wt.%, primarily because of nanoparticle agglomeration, which impaired the nanofluid's performance.

Higher cutting temperatures expedite the deterioration of the cutting tool, causing tool materials to soften and wear down, leading to reduced tool life, and can negatively affect surface finish. Extreme cutting temperatures can cause changes in the workpiece material microstructure because of heat generated in the cutting process, affecting properties such as hardness, tensile strength, and residual stresses. This study investigated how different nanofluids affect the average cutting temperature. Fig. 9 illustrates the measured cutting temperature with varying nanoparticle concentrations in nano cutting fluids (0.2 wt. %, 0.4 wt. %, 0.6 wt. %, 0.8 wt. %, and 1 wt. %). Graphene nanofluids provided the most significant reduction in cutting temperature. Using the base cutting fluid resulted in a cutting temperature of 48 °C; however, with

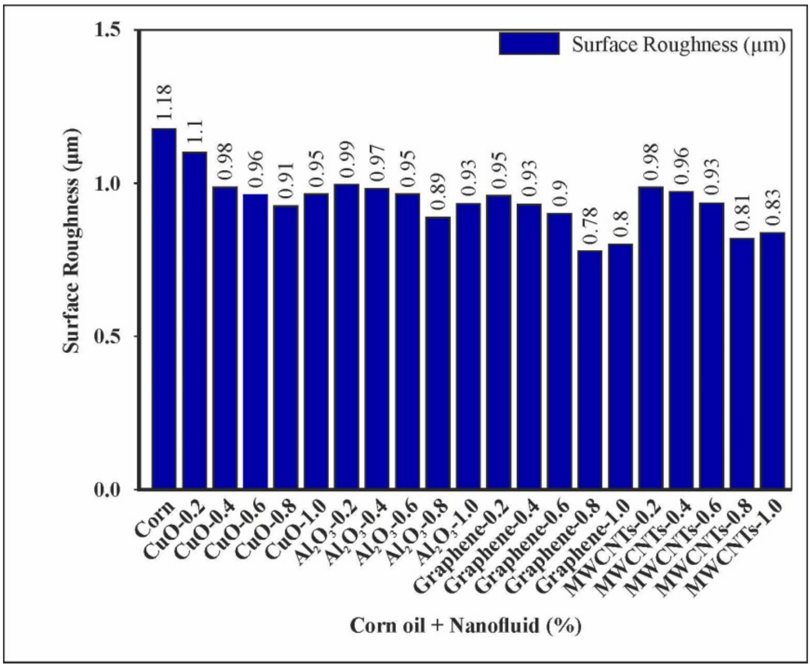

Fig. 8. Surface roughness when using different nanofluids

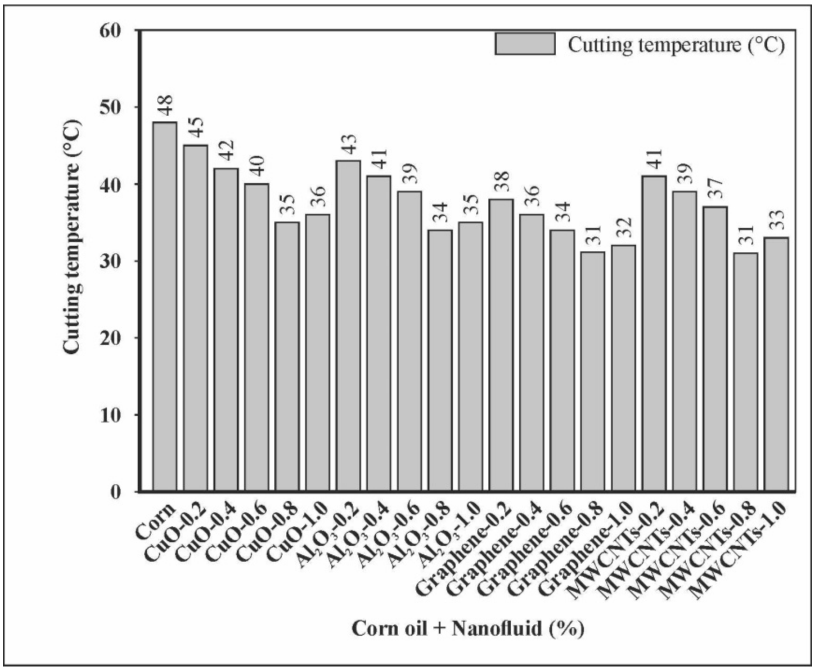

Fig. 9. Cutting temperature when using different nanofluids

0.8 wt. % of graphene nanofluid, the cutting temperature decreased to 31 °C, i.e. by 54.2%. This is attributed to improved lubrication; nanoparticles on the metal surface formed a robust lubricant film, leading to better heat dispersion. The higher thermal conductivity and improved lubrication from increased graphene concentration reduced friction and heat generation. However, at 1 wt. % graphene concentration, the cutting temperature increased to 32 °C compared to 0.8 wt.%, primarily because of nanoparticle agglomeration, which impaired the nanofluid's performance.

Conclusion

This study reports on turning experiments on *AISI 1014* steel under *MQL* condition, using five vegetable oils. Corn oil was selected as the base oil, and nanofluids were created by adding *CuO*, Al_2O_3, graphene, and multi-walled carbon nanotubes to the base oil. The optimal concentration and nanoparticle type were identified. The main findings are summarized below:

- Corn oil significantly affects the thermophysical characteristics such as viscosity and thermal conductivity compared to other vegetable oils.
- Of the four nanoparticle types investigated, graphene nanoparticles provided the greatest reduction in cutting force, temperature, and surface roughness during the turning process. Experimentally, the use of corn oil containing 0.8 wt. % graphene nanoparticles resulted in a cutting force of 104 N, which is 29.8 % less than that of pure corn oil.
- The nanofluid's effectiveness in reducing cutting force, cutting temperature, and surface roughness decreases at given nanoparticle concentrations (1 wt. %). However, at a high concentration (1 wt. %), the load reduction decreases because of a significant agglomeration of nanoparticles. The optimal nanoparticle concentration in corn oil is 0.8 wt. %.

The potential for future research in sustainable machining processes is significant. Means to mitigate environmental damage compared to traditional lubrication methods and lubricants are proposed, and promising developments in economic and social aspects are demonstrated. Expanding the exploration of green nano-cutting fluids (*NCF*) under *MQL*, future research could investigate di- and tri-hybrid nanoparticles to enhance the functional properties of cutting fluids, including the development of biosynthesis plant extract routes for nanoparticle preparation, and assess the impact of developed *NCF* on the performance characteristics of various metals, alloys, and composites during turning.

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Conflicts of Interest

The authors declare no conflict of interest.