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Development and Characterization of Novel Green Cutting Fluids with Nano-additives

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Abstract

In this current investigation, novel cutting fluids developed through a unique combination of food grade emulsifiers, plant based additives (EA) and nano particles (NP) as cutting fluid additives in corn oil (CO) based vegetable oil. Five dissimilar corn-based green cutting fluids (CBGC1, CBGC2, CBGC3, CBGC4, CBGC5) were prepared by varying the weight percentages (wt.%) of EAs (5, 10, 15, 20, 25) with CO, and their thermo-physical properties were meticulously analyzed. Among these formulations, CBGC2 demonstrated superior lubrication performance, making it the most promising oil for further investigation. Subsequently, the effect of different NP was investigated by adding alumina (Al_2O_3), graphene (Gr) and multi walled carbon nanotubes (MWCNT) NPs in the CBGC2 solution in the ratio of 0.4, 0.8 and 1.2 in weight percent (wt.%) and the experimental results reveal substantial enhancements in thermophysical properties. Among various samples, the nanofluid containing 0.8 wt.% concentration of Al_2O_3 nanoparticles in CBGC2 exhibited the highest viscosity. Additionally, the thermal conductivity of the nanofluid enhanced by 24.82% when 1.2 wt.% of Gr nanoparticles added oil compared to CBGC2. Furthermore, in tribological tests, CBGC2 with 0.4% Al_2O_3 exhibited the lowest frictional force among the prepared cutting fluids. The contact angle reduced to a maximum extent by 11.14% for cutting fluids containing 1.2% alumina nanoparticles. These findings suggest that these innovative green cutting fluid formulations with nano-additives hold great potential for improving machining processes in various industrial applications towards sustainability.

Keywords

green cutting fluid, nano-additives, thermo-physical properties, thermal conductivity, frictional force, contact angle, machining processes, industrial applications

1 Introduction

Machining techniques play a pivotal function in the production sector, facilitating the refinement and shaping of materials to achieve desired geometries. However, the inherent friction between the workpiece and cutting tool generates substantial heat during machining, resulting in elevated temperatures within the machining area [1]. This elevated temperature contributes to extreme tool wear, thereby falling tool longevity and compromising surface finish quality [2, 3]. To mitigate these issues, it is imperative to minimize heat generation during machining operations. Metal Cutting Fluids (MCFs) have long been employed throughout the machining process to address these challenges by providing cooling and lubrication. Essentially, MCFs act as a barrier between the contacting surfaces, preventing direct surface-to-surface contact and thereby reducing wear and friction, which subsequently minimizes heat generation. Additionally, MCFs aid in the removal of chips from the work area, preventing damage to finished surfaces [4]. Nevertheless, traditional MCFs, primarily petroleum-based, pose significant environmental and health concerns. Their improper disposal is a major issue, and they have been linked to occupational disorders among industrial workers involved in machining [5]. To address both ecological footprint

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and worker safety considerations, there is a growing need for sustainable alternatives in the form of green lubricants [6]. Vegetable oils emerge as a promising candidate in this regard, offering a range of advantages. These oils comprised of triglycerides, exhibit excellent lubricating properties [7]. They are environmentally benign, biodegradable, possess superior lubricity compared to traditional MCFs, boast high flash and fire points, and have a high viscosity index [8]. Additionally, vegetable-based oils such as groundnut, palm, sunflower, canola, jojoba, almond, soybean, among others, have been explored as lubricants in machining in numerous studies [9]. Notably, these oils have demonstrated enhanced machining performance, extended tool life, and improved surface finish compared to their conventional fluids. Innovative formulations have also been explored to create environmentally safe metalworking soluble oils [10]. For instance, Singh and Gupta [10] used non-edible oils like neem, karanja, and rice bran, which are readily available, to develop sustainable formulations. Extensive testing in accordance with ASTM standards confirmed the stability of these formulations at varying temperatures, their corrosion resistance, and minimal deposit formation. Furthermore, these formulations exhibited reduced wear scar diameters and proved biodegradable, with no toxicity to bacteria. Among the oils tested, neem-based formulations stood out as particularly effective [11]. Abdalla et al. [11] delved into the formulation of long-lasting neat-oil metal removal fluids, exploring a range of oils, from commercial and natural vegetable oils to fatty acid esters and polyols derived from chemically modified vegetable oils [12]. Tribological tests revealed that naturally derived cutting oils exhibited significantly lower friction values compared to commercial oils, and micro tap tests showed reduced cutting force and torque when machining stainless steel. Furthermore, rheological characteristics of various bio-edible oils, including coconut, sunflower, canola, corn, and palm oil, were examined by Nik et al. [12]. Their study found the impact of temperature on viscosity and employed empirical models to understand fluid flow characteristics. To propose an extensive insight into the machining applications of vegetable oils [13]. Kazeem et al. [13] conducted a study on jatropha oil-based cutting fluids, assessing their impact on machining performance. The results indicated that jatropha oil outperformed mineral oil-based alternatives [14]. Despite their numerous advantages, vegetable oils face challenges due to poor tribological behavior, low pour points, and inferior oxidative stability. Enhancing their performance as lubricants can be achieved through the incorporation of lubricating additives or chemical modifications. Ionic liquids, a novel class of substances with organic cations and inorganic anions, have gained attention as effective lubricant additives [15]. Additionally, researchers have explored the integration of various nanoparticles (NPs) into base fluids to enhance lubrication in various various metal cutting processes [16]. Loredana Pop et al.'s study focused on mixtures of corn oil and synthetic additives, demonstrating that eco friendly vegetable oils and their derivatives present viable alternatives to conventional cutting fluids [17]. Sah et al. [18] prepared novel cutting fluid by incorporating a blend of ionic liquids and nano-particles as lubricant additives for Jatropha oil. The effect of several nanoparticles was investigated by adding Al_2O_3, ZrO_2. In this the outcomes demonstrate enhancements in the thermo-physical characteristics [18]. Singh and Sharma [19] investigated the impact of ionic liquids with varying alkyl chain lengths on cutting fluid properties. Results shown that in five different ionic liquids longer alkyl chain lengths yielded better results than shorter ones. Ionic liquid-based cutting fluid showed significant improvements compared to pure rice bran oil [19]. The study demonstrated the effectiveness of a novel MoS_2/SiC nanoparticle-enhanced cutting fluid in milling CFRP using minimal lubrication techniques, showing reduced forces, temperatures, surface roughness, and tool wear. The nanofluid caused only a 3.85% reduction in interlaminar shear strength while mitigating surface defects like fiber pull-out. These findings suggest that nanoparticle-based fluids can significantly improve the efficiency and quality of CFRP machining [20]. The research evaluated the effectiveness of water-based solutions enriched with cellulose nanocrystals at different concentrations (0.25%, 0.5%, and 1%) compared to conventional methods like MQL, flood, and dry cooling. Results showed that these nanofluids significantly reduced tool wear and cutting temperatures, though further research is needed to optimize water-particle concentrations for improved surface quality [21]. The motivation for this study is driven by the need for sustainable alternatives to traditional petroleum-based cutting fluids, which are harmful to the environment and pose health risks to workers. Vegetable oils, such as corn oil, have shown promise as eco-friendly lubricants due to their biodegradability and superior lubricity. However, they suffer from limitations like poor tribological performance and low oxidative stability. To address these issues, incorporated additives like nanoparticles to enhance their properties. Despite previous studies on vegetable oils, there is a significant research gap regarding corn oil-based cutting fluids formulated with a combination of non-toxic emulsifiers, plant-based additives, and nanoparticles. This study aims to bridge that gap by developing and characterizing novel green cutting fluids with improved thermo-physical properties.

2 Materials and methods

In the current research, corn oil served as the primary cutting fluid due to its favorable lubricating properties and environmentally friendly characteristics. Added emulsifiers are polysorbate 80, polysorbate 85, triethanolamine and additives are oil extracted from *Azadirachta indica*, *Cymbopogon citrates*, *Centella asiatic* stem and leaf, jaggery syrup, turmeric powder [22]. Various cutting fluid materials were combined at ambient temperature using a magnetic stirrer. Five different CBGC oils prepared by adding 5, 10, 15, 20, 25 wt.% of additives and emulsifiers (EA) with CO to investigate the influence of wt.% EAs on the thermo-physical properties of CO. Further, Al_2O_3, graphene and multi walled carbon nanotubes (MWCNT) were added to best one of CBGC oil to investigate nanoparticles influence on their thermophysical characteristics. Table 1 presents the prepared corn based green cutting fluids with % of emulsifiers &additives.

2.1 Preparation of samples

In this research, examined the impact of emulsifiers, additives and nanoparticles on the thermophysical characteristics of corn oil in a two-stage investigation. Initially, investigated the influence of EAs on CO thermophysical properties, leading to the identification of the most suitable CBGC oil based on the analysis of sample properties. In the first step, with the selected CBGC oil, nanofluids are prepared by adding 0.4, 0.8, 1.2 wt.% Al_2O_3, graphene and MWCNT. For proper mixing of nanoparticles, magnetic stirring was carried out for 90 min followed by 1 h ultrasonication using ultrasonicator.

Table 1 Corn based green cutting fluids

S.No.	Oil sample	% of emulsifiers &additives
1	CO	0
2	CBGC1	5
3	CBGC2	10
4	CBGC3	15
5	CBGC4	20
6	CBGC5	25

2.2 Characterization of oil samples

The morphology of the nanoparticles was examined using a field emission scanning electron microscope. Figs. 1, 2 and 3 shows the Al_2O_3, graphene and MWCNT nanoparticles scanning electron microscopy images, respectively. Prepared oil samples characterized with viscosity, thermal conductivity, wettability and coefficient of friction testing. The viscosity property plays a vital role in assessing lubrication qualities. Hence, dynamic viscosity measured using a Redwood viscometer. Additionally, evaluated the thermal behavior of the liquid samples to understand their heat transfer capacity by conducting thermal conductivity tests at a standard room temperature of 30 °C, utilizing a KD 2 pro thermal analyzer. Furthermore, assessed wettability,

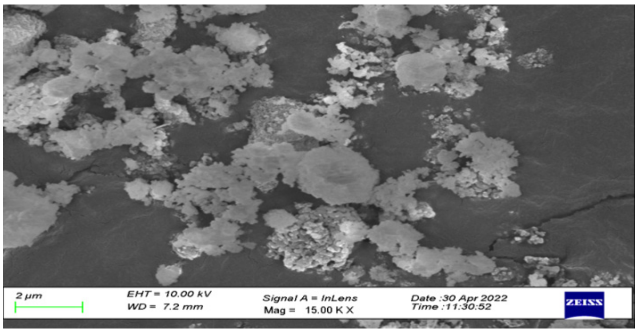

Fig. 1 Al_2O_3 scanning electron microscopy image

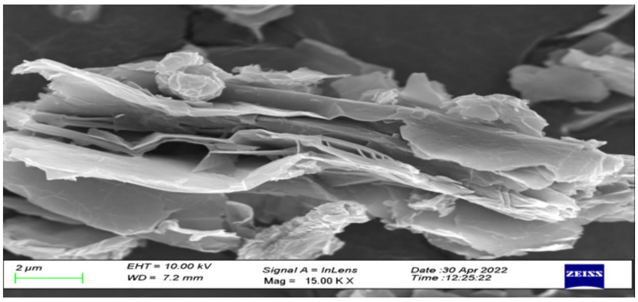

Fig. 2 Graphene scanning electron microscopy image

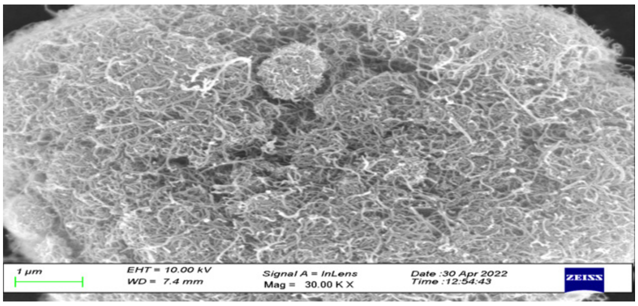

Fig. 3 MWCNT scanning electron microscopy image

which is the propensity of a liquid to maintain contact with the surface it lands on, by examining the contact angle. A lower contact angle indicates improved fluid spreading over the surface and, consequently, enhanced wettability. The contact angle measurements for all liquid samples were conducted at 30 °C using a Contact Angle Meter. In the context of this study, also focused on the tribological properties, which are crucial for characterizing cutting fluids. To analyze these properties, conducted pin-on-disc tests, with experiments running at 600 rpm and a track radius of 60 mm. Throughout the experiments, the flow rate of the cutting fluid remained constant at 0.75 mL/min.

3 Results and discussion

3.1 Effect of EAs on the lubrication properties

In the subsequent section, experimental investigations were performed to assess the thermo-physical properties of all the samples, findings are elaborated as follows.

3.1.1 Viscosity measurement

Viscosity is a fundamental property that describes a fluid resistance to flow. Highly viscous fluids play a crucial role in reducing friction and exhibit effective lubrication when applied to interacting surfaces. In current study, a Redwood Viscometer employed to measure the kinematic viscosity (measured in Pa s) of both corn oil (CO) and corn-based green cutting oil (CBGC) over a range of temperatures spanning from 30 to 60 °C. At 30 °C, the kinematic viscosity of corn oil was determined to be 0.047 Pa s. Notably, when a minor quantity (5 wt.%) of EAs was introduced into CO, it caused a discernible increase in viscosity. The increase in viscosity with the addition of EAs is due to stronger intermolecular forces while the decrease in viscosity with rising temperature is caused by enhanced molecular motion that weakens these forces. Specifically, among the samples, sample 3 (CBGC2) exhibited the highest viscosity, recording at 0.057 Pa s. Consequently, the inclusion of 10% EA resulted in a substantial 21.27% enhancement in CO viscosity at a temperature of 30 °C. Investigations revealed a consistent trend where the viscosity of the liquid samples (samples No. 1 to 6) decreased as the temperature rose. This behavior can be elucidated by recognizing that elevated temperatures trigger increased molecular motion within the liquids. This heightened motion, in turn, diminishes the intermolecular forces between the molecules, ultimately leading to a reduction in viscosity. These findings are visually depicted in Fig. 4, which illustrates the impact of EAs on viscosity.

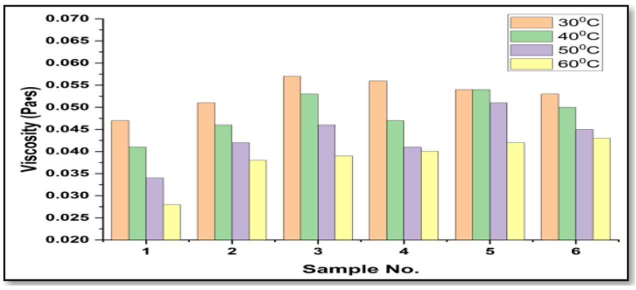

Fig. 4 Effect of EAs on viscosity

3.1.2 Thermal conductivity measurement

High heat transfer capacity in cutting fluids is essential to mitigate the heat generated during metal cutting processes. To assess the heat transfer capabilities of lubricants, conducted thermal conductivity measurements for all samples using a KD2 Pro thermal analyzer. The results illustrating the impact of EAs on thermal properties are presented in Fig. 5. The thermal conductivity of CO was determined to be 0.154 W/mK. Interestingly, the addition of EAs resulted in a reduction in the thermal conductivity of CO. The reduction in thermal conductivity after adding EAs is a result of the formation of nonconductive molecular layers that inhibit electron flow, thus decreasing the fluid's heat transfer capacity. This, in turn, hinders the flow of electrons, leading to a decreased heat transfer capacity of the fluid. Among the tested CBGO oils, CBGO2 exhibited the highest thermal conductivity. Specifically, the introduction of EA2 into CO yielded thermal conductivity of 0.141 W/mK.

3.1.3 Wettability measurement

The contact angle results are indicative of the wettability characteristics of the lubricants, measured by the angles formed by liquid droplets on the substrate. The contact angle for pure CO was measured at 14.908°. As shown in Fig. 6, the addition of EAs to CO leads to a decrease in the contact angle. This effect can be attributed to the formation

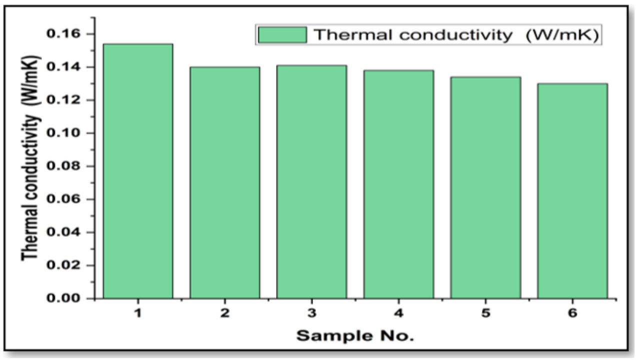

Fig. 5 Effect of EAs on thermal conductivity

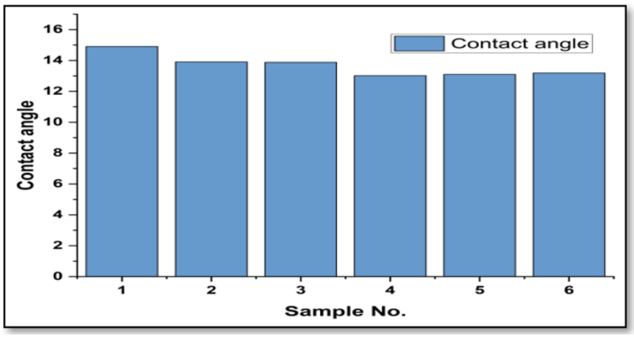

Fig. 6 Effect of EAs on contact angle

of a uniform layer that spreads effectively across the surface, consequently reducing the contact angle between the liquid and the substrate. Notably, Fig. 6 highlights the efficacy of EA3 as an additive, as it exhibits the lowest average contact angle compared to other oils. The introduction of 15% EA into CO results in a contact angle of 13.018°, representing a 12.67% improvement in wettability compared to pure CO. Improved wettability of a lubricant indicates enhanced interactions between the lubricant and solid surfaces, facilitating the formation of a protective layer between sliding surfaces. This, in turn, contributes to the reduction of friction and wear.

3.1.4 Study of friction coefficient

The outcomes from the pin-on-disc test, as illustrated in Fig. 7, demonstrate the impact of cutting fluids on the coefficient of friction. The introduction of cutting fluid results in a notable reduction in frictional force and the coefficient of friction. This phenomenon is attributed to the formation of a lubricating fluid film between the contact pairs of the pin and disc. Specifically, under 10 N loads, the frictional force is measured at 0.33 N in the presence of CO oil, while it decreases to 0.24 N when CGGC2 cutting fluid is employed. This reduction is attributed to the improved lubricating properties of vegetable oil stemming from its superior thermo-physical characteristics.

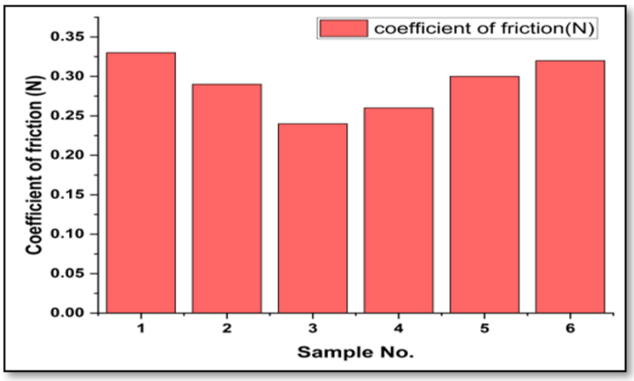

Fig. 7 Effect of EAs on coefficient of friction

3.2 Effect of NP on the lubrication properties

In Section 3.2, a variety of nanofluids were created by blending 0.4, 0.8, 1.2 wt.% Al_2O_3, MWCNTs and Gr in the CBGC2 solution and their thermophysical and the examination of tribological properties is conducted in the following manner. The prepared nanofluids samples are given in Table 2.

3.2.1 Viscosity measurement

As depicted in Fig. 8, the introduction of NPs into the CBGC2 solution leads to a notable enhancement in viscosity. This enhancement can be attributed to the increased intermolecular forces among the fluid molecule, which introduces additional internal flow resistance and consequently elevates the viscosity. Due to collisions with molecules of the fluid lead to an increase in fluid viscosity as they disrupt the flow of the fluid. The addition of Al_2O_3 NPs has been found to perform better than MWCNTs and Gr NPs. Noteworthy progress in viscosity of CBGC2 by 42.1% was observed by the addition of 0.8% of Al_2O_3 NPs at a temperature of 30 °C.

3.2.2 Thermal conductivity measurement

The influence of NPs on the thermal characteristics of CGGC2 solution is depicted in Fig. 9. It is evident from

Table 2 Nanofluids with corn based green cutting fluids

S.No	Nanofluids
1	CBGC
2	CBGC2+ 0.4% Al_2O_3
3	CBGC2+ 0.4% MWCNT
4	CBGC2+ 0.4% Gr
5	CBGC2+ 0.8% Al_2O_3
6	CBGC2+ 0.8% MWCNT
7	CBGC2+ 0.8% Gr
8	CBGC2+ 1.2% Al_2O_3
9	CBGC2+ 1.2% MWCNT
10	CBGC2+ 1.2% Gr

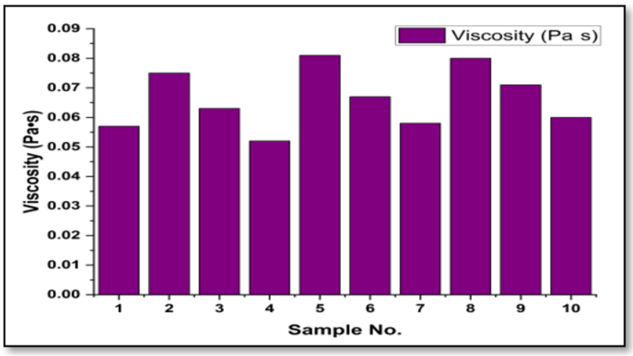

Fig. 8 Effect of NPs on viscosity

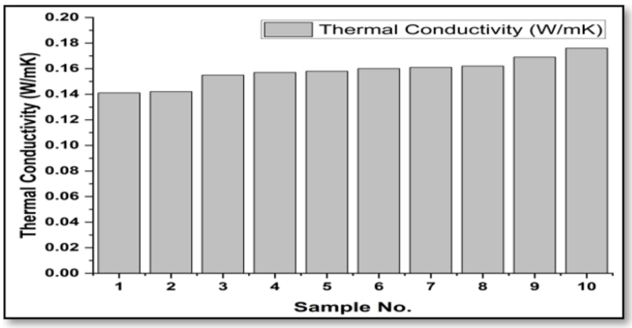

Fig. 9 Effect of NPs on thermal conductivity

Fig. 9 that the thermal conductivity increases as NPs are incorporated into CGGC2. This augmentation in thermal conductivity can be attributed to the NPs ability to induce molecular vibrations through their Brownian motion within the liquid solution. Consequently, the movement of free electrons and the large surface area contribute to an enhanced heat transfer capacity. Notably, among the NPs investigated, Graphene (Gr) NPs exhibit the most pronounced improvement in the thermal conductivity of the CGGC2 solution, surpassing other NPs. Graphene has exceptionally high thermal conductivity along their basal planes. When these nanoparticles are incorporated into a fluid, they act as heat highways due to their superior heat-conductive properties.

3.2.3 Wettability measurement

Fig. 10 illustrates the impact of various NPs on the contact angle. The contact angle of CGGC2 diminishes upon the inclusion of NPs. This is attributed to the nearly spherical shape of the NPs, which facilitates their rolling on solid surfaces. Consequently, this reduces the surface tension at the liquid-solid interface, causing the liquid to spread more extensively on the surface and as a result decreasing the contact angle. Among the various NPs examined, Al_2O_3 NPs exhibit superior wettability compared to others. Specifically, the contact angle for nanofluid containing 1.2% Al_2O_3 is measured at 13.249°, signifying an 11.14% reduction in comparison to CGGC2.

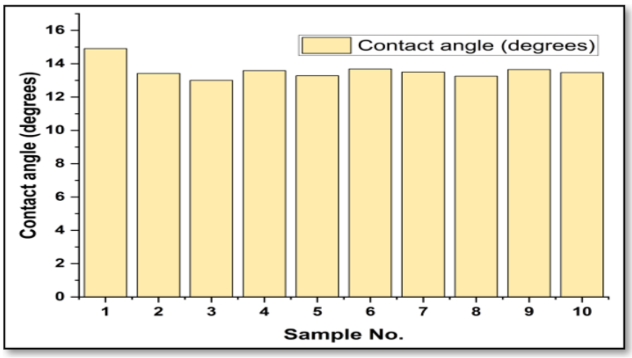

Fig. 10 Effect of NPs on contact angle

3.2.4 Study of friction coefficient

Nano cutting fluids exhibit a notable reduction in the coefficient of friction. This effect can be attributed to the formation of a robust fluid film between the contacting pin and disc surfaces, which differs significantly from CO lubrication. Under a 10 N load, CO yielded a friction force of 0.24 N. In contrast, the introduction of a mere 0.4% alumina into CO cutting fluid reduced this friction force to 0.14 N shown in Fig. 11. This enhancement in lubrication performance can be attributed to the superior thermo-physical properties of nanofluids. The incorporation of nanoparticles introduces a transformative element to the lubrication process by promoting rolling motion between contact pairs, a result of the spherical shape of the nanoparticles. This rolling mechanism in turn contributes to a further reduction in the frictional force. Overall, the experimental results conclusively demonstrate that the utilization of nanofluids in cutting processes leads to a substantial decrease in friction, thereby enhancing the efficiency and effectiveness of machining operations.

4 Conclusions

In the present experimental study, vegetable based nanofluids were successfully prepared by adding Al_2O_3, MWCNTs and graphene nanoparticles in CBGC2 oil. The investigation involved the thermophysical and tribological analysis of a newly developed environmentally friendly cutting fluid. The noteworthy discoveries from this research are as follows:

1. CBGC2 oil significantly enhances the viscosity of the base oil, with a 21.27% improvement at 30 °C. The addition of 0.8% Al_2O_3 nanoparticles outperforms other nanoparticles, increasing viscosity by 42.1%.

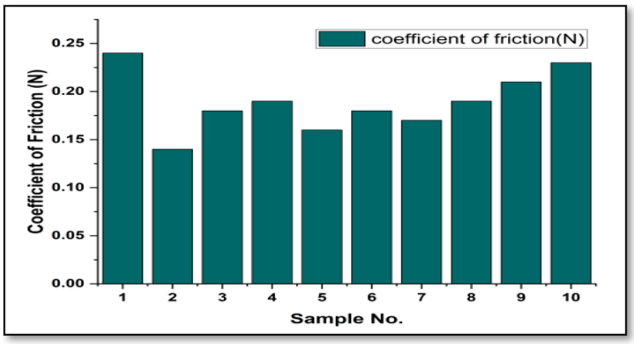

Fig. 11 Effect of NPs on coefficient of friction

2. Incorporating nanoparticles into CBGC2 improves thermal conductivity, with 1.2% graphene nanoparticles enhancing it by 24.82%.
3. The addition of nanoparticles reduces the contact angle of CBGC2 oil, enhancing wetting properties. CBGC2 with 1.2% alumina nanoparticles achieves the greatest reduction, surpassing CBGC2 alone by 11.14%.
4. Tribological testing demonstrates that these nanofluids effectively reduce the coefficient of friction, CBGC2 with 0.4% Al_2O_3 nanoparticles exhibits the best lubrication properties, reducing friction by 34.33% compared to CBGC2 oil.

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