



An attempt towards green machining of Ni-based Hastelloy C4 alloy: Effect of vegetable oils and their combination with TiO₂ and SiO₂ nanoparticles on outputs

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ABSTRACT

The importance of nickel-based superalloys has increased day by day due to their use in special applications. However, the difficulties in the machinability of these alloys bring some concerns about parts quality and efficiency. Although researchers have tried ways (such as the use of high-performance cutting fluids) to overcome these challenges, their sustainability is still controversial. Therefore, this experimental research aims to contribute to the sustainable machining of nickel-based superalloys. In this regard, the present study investigates the effectiveness of vegetable-based fluids (sunflower, olive, hazelnut, and corn oils) and nanofluids (SiO₂ + sunflower oil, SiO₂ + olive oil, SiO₂ + hazelnut oil, SiO₂ + corn oil, TiO₂ + sunflower oil, TiO₂ + olive oil, TiO₂ + hazelnut oil, and TiO₂ + corn oil) during the machining of Ni-based Hastelloy C4 alloy. The study was carried out in three stages. In the first stage, all cutting fluids' pH and thermal conductivity values were measured. In the second stage, machinability tests were conducted under the prepared cutting fluids. Later, friction-wear tests of the cutting fluids that offered the best performance in the previous stage were done. As a result, the pH change was significantly increased with the addition of nanoparticles (TiO₂ and SiO₂) to corn oil. TiO₂ nanoparticles allowed further improvement of thermal conductivity. Compared to dry machining, improvements of 58.57%, 34.88%, 53.18%, and 36.1% in surface roughness, cutting temperature, tool wear, and power consumption were achieved with corn oil+TiO₂ nanofluid, respectively. It was determined that adhesion, BUE, BUL, and chipping were dominant damage types. Also, an adhesive is the dominant wear mechanism.

1. Introduction

Nickel-based superalloys are indispensable alloys for aircraft engines due to their excellent stability at elevated temperatures [1]. They make up about 50% of the weight of a gas turbine aircraft engine [2]. The high temperature stability, high corrosion resistance, tensile and creep properties of superalloys, even under extreme conditions, make these materials attractive for harsh conditions [3]. However, the high strain hardening tendency of these alloys, the presence of hard abrasive carbides, the desire to adhere to the cutting tool materials, and the hot-hardness severely limit their machinability levels [4]. Moreover, the difficulties encountered in machining nickel-based superalloys have led

them to be included in the hard-to-machine materials in the literature [5].

It was determined that the use of cutting fluid is a practical way to avoid difficulties caused by high temperatures and friction-wear in the cutting zone [6]. Cutting fluids carry out various tasks such as removing the chip from the cutting zone and cooling/lubricating the contact surfaces during chip removal. However, conventional petroleum-based cutting fluids are not sustainable due to their negative effects on the environment and employee health and production costs [7]. For this reason, researchers have been making intense efforts recently to reduce the amount of coolant without reducing the machining efficiency and to introduce a sustainable metal removal concept. Although several different solutions have been devised to address this issue, the minimal

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Nomenclature

SiO ₂	Silicon dioxide
TiO ₂	Titanium dioxide
SiC	Silicon carbide
Al ₂ O ₃	Aluminum oxide
Nps	Nanoparticles
STs	Surfactants
PVD	Physical vapor deposition
TiAlN	Titanium aluminum nitride
TiN	Titanium nitride
f	Feed rate
Vc	Cutting speed
ap	Depth of cut
CoF	Coefficient of friction
MQL	Minimal quantity lubrication
EDX	Energy-dispersive X-ray spectroscopy
SEM	Scanning electron microscope
PVP	Polyvinylpyrrolidone
BUE	Built-up edge
BUL	Built-up layer
Ra	Average surface roughness

quantity lubrication (MQL) method is one of the most popular ones. In the MQL system, where very little cutting fluid is transported to the cutting zone with the help of compressed air, many problems arising from the use of petroleum-based cutting fluid can be eliminated, especially thanks to the use of vegetable-based oils. For example, the use of vegetable-based cutting fluid up to a maximum of 500 mL/h not only significantly reduced production costs but also eliminated concerns about the environment and employee health [8]. Biodegradable vegetable-based oils evaporate immediately after fulfilling their functions in the cutting area and do not reflect a serious impact on the environment and employee health [9]. Various studies on this subject are available in the literature. Some of these are summarized as follows: Ozcelik et al. [10] aimed to find the effectiveness of vegetable-based oils in terms of machining efficiency by comparing canola oil, sunflower oil, semi-synthetic cutting fluids, and mineral cutting fluids during metal cutting operations. Researchers have reported that canola-based cutting fluid containing EP gives better results.

However, while the rapid evaporation of a small amount of cutting oil gives positive results in light and medium machining conditions, it was reported that it does not provide sufficient efficiency in terms of cooling in heavy machining conditions [11]. In this case, the use of nanofluids has emerged as a good solution to improve its properties without increasing the amount of cutting fluid [12]. Kumar and Gopal [13] compared Cu-Zn-based hybrid nanofluids' performance with base cutting fluids. During the comparison, thermal conductivity and rheological properties were considered rather than cutting performance. As a result, it has been claimed that nanofluids exhibit more effective properties than base fluids. Li et al. [14] aimed to contribute to sustainability by adding SiC/TiO₂ particles into waste cooking oil. In order to evaluate the performance of the nanofluids, the researchers looked at thermal conductivity, viscosity, and dielectric constant. According to the researchers, the nanoparticles improved the thermo-physical characteristics of used cooking oil. Sujith et al. [15] added nano-sized Al₂O₃ at rates ranging from 0.2% to 1.2% in pure coconut oil and investigated the viscosity change of nanofluid with a concentration ratio. As a result, it was highlighted that the viscosity of the nanofluids increased with an increase in nanoparticle concentration and reduced with an increase in temperature.

Thanks to their improved tribological properties and high thermal conductivity, nanofluids can both evacuate heat in the cutting zone

more efficiently and reduce friction on the contact surfaces [16]. Venkatesan et al. [17] added different proportions of Al₂O₃ nanoparticles into coconut oil and they investigated the effect of the concentration ratio on the outputs during the turning of Inconel 617. According to the experimental results, the combination of 0.25% concentration ratio gave the best results. Danish et al. [18] compared a number of conditions, such as dry, wet, sunflower oil with MQL and nanographene based nanofluid during cutting of Inconel 718. Based on their experimental findings, the researchers claimed that nanofluid offers the best results for surface roughness, cutting force, temperature, and tool wear. Sen et al. [19] added 0.5%, 1%, and 1.5% nano-silica powders into palm oil and compared the performance of these mixtures with dry and pure MQL conditions during the machining of Inconel 690. For the evaluations, the researchers took into account the tool life, surface roughness, cutting force, and cutting temperature. They concluded that an additive ratio of 1% to the base fluid provides the highest performance.

According to the literature review, there are investigations in machining of nickel-based superalloys under various conditions. However, to the best of the authors' knowledge, there is no comprehensive research examining the behavior of various vegetable oils and vegetable-based nanofluids in terms of both tribological and machinability. In this regard, the current investigation intends to conduct comprehensive research on the effectiveness of nanoparticles incorporated into vegetable cutting fluids under heavy machining conditions during the machining of Hastelloy C4 alloy. For this aim, in the first part of the study, eight different nanofluids were created by adding two different oxide-based nanoparticles (TiO₂ and SiO₂) into four different vegetable cutting fluids, and their performance in the turning process was compared with pure cutting oils and a dry environment. Then, the friction-wear behaviors of different conditions were investigated. The results of the study will contribute to the existing literature for establishing a sustainable metal cutting process.

2. Methodology

2.1. Nanofluid preparation and MQL system

In this study, nanofluid mixtures were prepared by adding 0.55 vol% SiO₂ and TiO₂ nanoparticles separately to different vegetable oils (i.e., sunflower oil, olive oil, hazelnut oil, and corn oil). Technical properties of SiO₂ and TiO₂ nanoparticles are provided in Table 1, and EDX and SEM outputs are given in Fig. 1. In nanofluids, sedimentation and/or agglomeration formations can often be encountered. In order to prevent these undesirable situations in nanofluids, surfactants with different properties can be added to the mixtures. The added surfactants adhere to the outer surface of the nanoparticles, reducing the tendency of the particles to approach each other, and a relatively homogeneous mixture is obtained as the same polar particles repel each other. In the current study, by considering the weight of nanoparticles, 0.25 wt% Polyvinylpyrrolidone (PVP) surfactant was added to increase the homogeneity of the nanofluid mixtures. A Kern PCB (made in Germany) precision balance was used to determine the surfactant and nanoparticle weights.

The nanofluid mixing process was done in 4 different steps. In the first step, PVP surfactant was added to the vegetable oils, and the mixture was started at 800 rpm for 10 min with the help of a Daihan HD3200 (made in Korea) mechanical mixer. The second phase involved

Table 1

Technical properties of SiO₂ and TiO₂ nanoparticles (supplied by Nanografi, Turkey).

Nanoparticle	Purity (%)	Size (nm)	Color	True density (g/cm ³)	Morphology
SiO ₂	99.50	15–35	white	2.2	near spherical
TiO ₂	99.99	40–50	white	4.5	near spherical

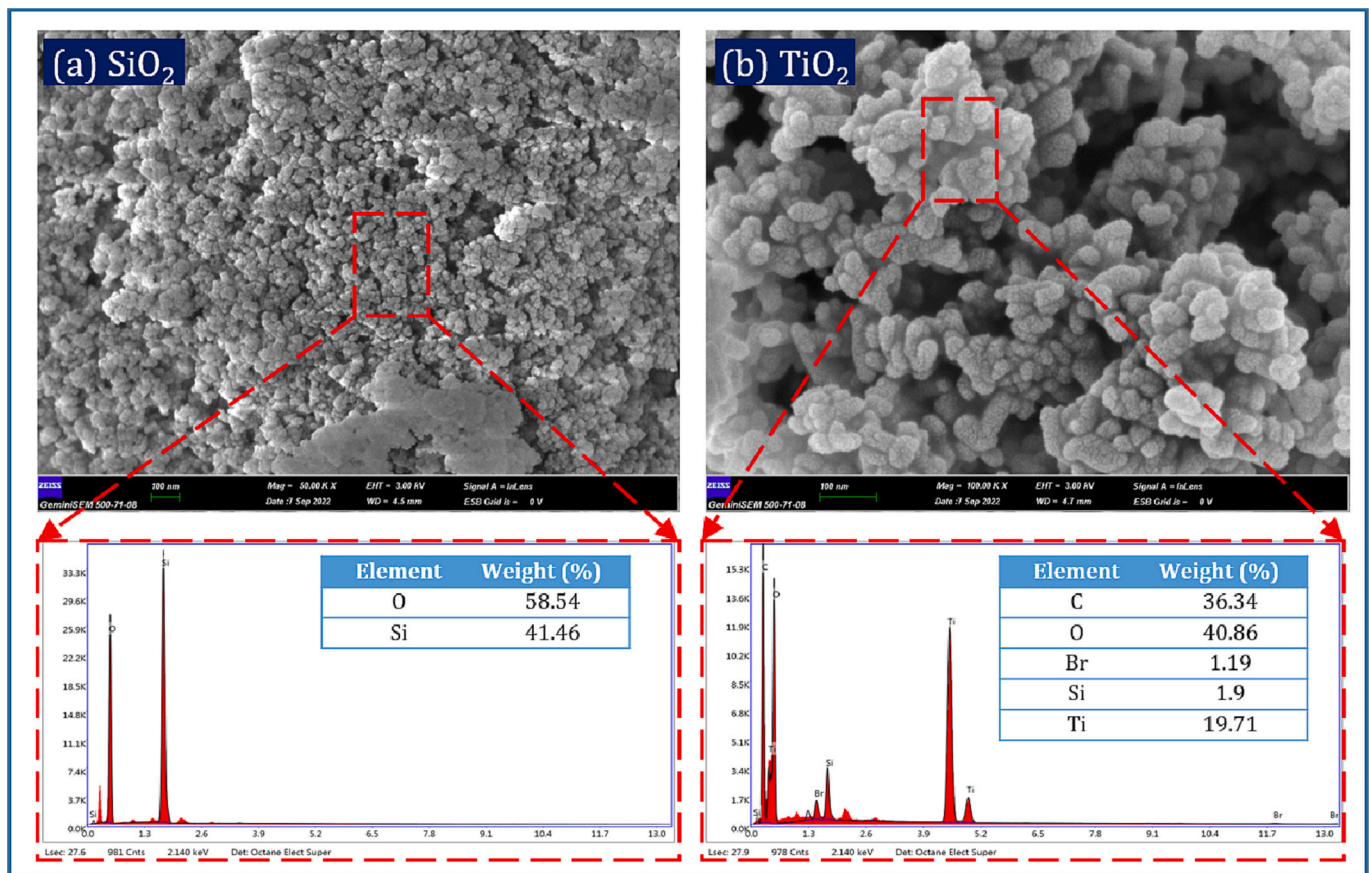


Fig. 1. SEM images and EDX analyzes of (a) SiO₂ and (b) TiO₂ nanoparticles.

adding nanoparticles to the slurry and mechanically mixing it for 50 min at 800 rpm. In the third step, mixing was carried out for a further 30 min at 20 kHz and 200 W parameters using a Bandelin Sonopuls HD3200 ultrasonic homogenizer (manufactured in Germany). In the last stage, a Termal N11151M magnetic stirrer (made in Turkey) was employed at 1500 rpm for 2 h. The nanofluid mixture preparation process steps can

also be seen in Fig. 2.

The prepared nanofluids were added freshly to the fluid reservoir of the SKF Vario (made in Germany) MQL device. The air-oil mixture, which was pulverized in the specially designed MQL device chamber, was transferred to a nozzle which has a 2 mm diameter, through 12 mm diameter hoses.

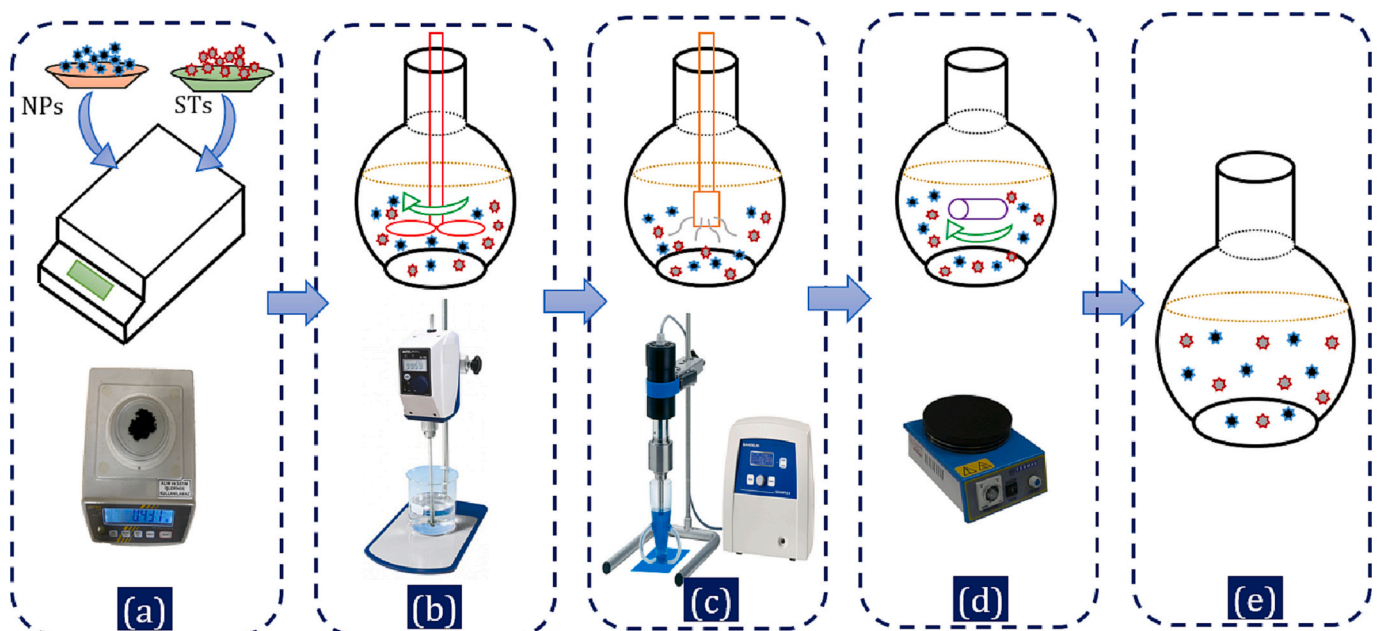


Fig. 2. Preparation of nanofluid (a) precision balance, (b) mechanical stirrer, (c) ultrasonication, (d) magnetic stirrer, and (e) nanofluid mixtures.

2.2. Experimental tools and workpiece material

The tests were carried out at the Accuway JT-150 (made in Taiwan) CNC turning center. Its technical specifications are provided in Table 2. DCMT 11 T304 MT TT5080 Taegutec (made in Korea) with a 7° clearance angle and positive 55° rhombic cutting insert were used in turning tests. An AKKO SDJR 2020 K11 (made in Turkey) holder was utilized for rigidly connecting the insert tools to the machine. Nickel-chromium-molybdenum alloy Hastelloy C4 was employed as a workpiece in all tests. The chemical components of Hastelloy C4 are given in Table 3, and the physical and mechanical properties are illustrated in Table 4.

2.3. Design of tests and parameters

The experimental study was done in three processes, i.e., (1) preparation of nanofluids, (2) turning tests, and (3) friction tests. First, nanofluids prepared in four different steps were freshly used in turning and friction tests. In the second process, turning tests were conducted at constant parameters, i.e., cutting speed (75 m/min), feed (0.1 mm/rev), and depth of cut (0.5 mm). The parameters used in the turning tests were marked considering the preliminary test results. Turning experiments were carried out in thirteen different ecological cooling/lubrication conditions. The parameters used in the turning tests are given in Table 5.

In order to compare the best results obtained after turning tests, the coefficient of friction (CoF) tests were carried out in the third process. The tests were conducted using a Turkyus ball-on-disc device, which is made in Turkey. Prior to friction tests, Hastelloy C4 workpiece surfaces were abraded using 400, 800, and 1200-grit abrasive papers, respectively. Metkon Diapat 6 µm, 3 µm, and 1 µm diamond solutions were used, respectively, to obtain a mirror image on the workpiece surfaces. CoF tests were carried out according to the ASTM G99–05 standard, and in all tests, distance (452,376 m), sampling frequency (1 Hz), and time (1200 s) were taken. The parameters used in the CoF tests are given in Table 6.

Before each CoF test, ball-on-disc tester calibration was performed to ensure the accuracy of the data obtained. A load of 18 N is fixed on the ball-on-disc tester arm, and the load data obtained through the load-cell are recorded with a software. A specially designed oil reservoir was used in CoF tests, and fluids were added in a volume of 100 mL in all tests. The schematic representation of the turning and friction experiments is provided in Fig. 3 (a) and Fig. 3 (b), respectively.

2.4. Responses measurements

The processes and measurements followed throughout the study are provided in Fig. 4. Accordingly, thermal conductivity, and pH measurements were applied after the preparation of the nanofluid process. The thermal properties of the prepared fluids were determined by Decagon KD2 pro thermal analyzer (made in USA). First, all fluids were brought to a constant temperature (40 °C), and then, thermal conductivity coefficients were measured. Measurements were repeated three times and recorded. The pH values measured were utilized by a digital portable pH meter pH -2004 device. Before pH measurements, the device was also calibrated with special solutions.

In the second process, the temperature, power, tool wear, and surface

roughness (Ra) measurements were carried out. Optris PI 450 (manufactured in Germany) thermal imager for maximum cutting temperature measurements was employed. In cutting temperature measurements, the emissivity value was marked as 0.5, considering the device manufacturer's recommendation. In order to prevent the thermal imager from being affected by the chips, it is fixed at an angle of 30° and a distance of 300 mm to that cutting area. Fluke 1732 three-phase electrical energy logger (made in USA) was used to determine the total power consumed during the cutting process. Before the measurements, electrical cable connections were made to the transformer of the turning center, and online calibration was carried out on the device. Power consumption data was recorded during the measurements, and a power trend graph was obtained with the Energy Analyze software. DinoLite AM73915MZT4 (made in Taiwan) digital microscope was utilized to determine the wear size of cutting tools in turning tests and to measure wear track width in CoF tests. After each test, the oil and dirt in the samples were carefully cleaned, and the wear sizes and wear track width were marked via the microscope at the same resolution and scale. In order to observe the tool damages and wear mechanisms, a German-made Zeiss LEO 44 scanning electron microscope (SEM) was employed. At the same time, a BUE and/or BUL formation on the cutting tool was searched for using an Energy-dispersive X-ray spectroscopy (EDX) module. The portable Mahr Marsurf PS 10 instrument (manufactured in Germany) was utilized for determining of the average surface roughness, Ra. In the last process, namely friction-wear tests, measurements of CoF were carried out.

3. Results and discussion

3.1. pH and thermal conductivity

In order to assess the impact on fluid friction connected to the viscosity and rheological behavior of nanofluids, it is required to understand their pH values [21]. In general, the pH value gives a clue about the homogeneity of the nanofluid, and it is accepted that the homogeneity of the fluids with higher pH values is higher [22]. Zhu et al. [23] claimed that effective thermal conductivity and stability can be significantly increased by manipulating the pH level. In another study, Said et al. [24] highlighted that nanofluids' stability, dynamic viscosity, and thermal conductivity can be made more efficient by changing the pH level. In this sub-section of the study, the pH values of nanofluids and base liquids are presented in Fig. 5. From this figure, it is seen that the pH values increased significantly with the addition of additives. In the nanofluids, the pH level of almost all fluids rose above 7. Because in cases where the pH value is below 7, agglomerated structures may form, and this may cause rapid sedimentation [25]. The pH change increased dramatically, especially through corn oil based nanofluids. Compared to the base corn oil, the pH increase was 10.6% with the addition of SiO₂ and 17.16% with the addition of TiO₂.

The heat produced by friction and plastic deformation at the tool-workpiece interface is crucial for metal cutting operations. The high heat generated during the operation negatively affects the machining output parameters, especially the shortening of the tool life [26]. It is very critical to remove the heat generated in the cutting zone, and most cutting fluids are used for this. However, as compared to the majority of solids, typical heat transfer fluids exhibit weak thermal conductivity [27]. Therefore, in order to speed up lowering the cutting temperature, it is imperative to increase the thermal conductivity of these fluids. It is quite common to use nanosolid lubricants for such purposes. One of the most important advantages of nano lubricants is that they can increase the thermal conductivity properties of the base fluids [28].

The basic oils' and nanofluids' thermal conductivities are shown in Fig. 6. When base fluids are considered in Fig. 6; corn oil had the highest thermal conductivity value, followed by hazelnut oil, olive oil, and then sunflower oil. The thermal conductivity value rose in almost all fluids when nanosolid lubricants were added to the basic fluid. The addition of

Table 2
Technical specifications of the Accuway JT-150 CNC lathe.

Item	Capacity
Spindle speed	4500 rpm
Spindle motor power	11 kW
Chuck diameter	6 in.
Guideway type	Linear
Controller system	FANUC Oi-T

Table 3

Chemical components of Hastelloy C4 [20].

Material	Ni	Co	Cr	Mo	Ti	Fe	Si	Mn	C
Alloy C4 2.4610 UNS06455	65	2	14–18	14–17	0.7	3	0.08	1	0.01

Table 4

Physical and mechanical properties of Hastelloy C4 [20].

Specification	Value
Density (g/cm ³)	8.64
Melting point (°C)	1399
Resistivity (microhm-m)	1.25
Coefficient of thermal expansion (m/m-K)	10.8×10^{-6}
Thermal conductivity (W/m-K)	10.1
Specific heat (J/kg-K)	406
Hardness (HRc)	37
Tensile strength (ksi)	115
Yield strength (ksi)	60.3
Elongation (%)	52

Table 5

Parameters for turning tests.

Parameters	Descriptions
Workpiece	Hastelloy C4 Ø85 × 250 mm
Turning parameters	f: 0.1 mm/rev; ap: 0.5 mm; Vc: 75 m/min
Cutting tool	Taegutec DCMT 11 T304 MT TT5080 cemented carbide PVD TiAlN-TiN coated
Tool holder	AKKO SDJR 2020 K11
Conditions	¹ sunflower oil, ² olive oil, ³ hazelnut oil, ⁴ corn oil, ⁵ sunflower oil+TiO ₂ , ⁶ olive oil+TiO ₂ , ⁷ hazelnut oil+TiO ₂ , ⁸ corn oil+TiO ₂ , ⁹ sunflower oil+SiO ₂ , ¹⁰ olive oil+SiO ₂ , ¹¹ hazelnut oil+SiO ₂ , ¹² corn oil+SiO ₂ , and ¹³ dry
MQL parameters	Flow rate: 75 mL/h; Pressure: 8 bar
MQL nozzle	Diameter: 2 mm; Angle to cutting zone: 30°; Distance to cutting zone: 20 mm

Table 6

Parameters for used in CoF tests.

Parameters	Descriptions
Time	1200 s
Load	16 N
Total distance	452,376 m
Sample frequency	1 Hz
Ball	Ø6 mm spherical AISI 52100
Disc	Ø55 × 8 mm Hastelloy C4
Track diameter	36 mm
Test Temperature	At room temperature (25 °C)

solid into the liquid clearly improved thermal conductivity since the thermal conductivity of solid materials is significantly higher than that of liquids [29]. Both the rate of heat transmission and the physical size of the heat transfer system are increased by utilizing nanoparticles to boost the thermal conductivity of the base fluid [30]. There was no change with the addition of SiO₂ into sunflower oil; however, an increase of 3.95% occurred with the addition of TiO₂. When SiO₂ was added to olive oil, the thermal conductivity level increased by 1.30%, while when TiO₂ was added, it increased by 3.27%. Likewise, when SiO₂ was added to hazelnut oil, the thermal conductivity level increased by 2.60%, while when TiO₂ was added, it increased by 3.25%. And finally, when SiO₂ was added to corn oil, the thermal conductivity level increased by 1.92%, while when TiO₂ was added, it increased by 3.21%. As can be

seen from the change rates, the TiO₂ additive performed better in increasing the thermal conductivity. It is thought that the better performance of TiO₂ in increasing the thermal conductivity is related to the crystalline nature, morphology, and particle size. Additionally, a significant contributor to the rise in heat conductivity may be the huge surface area [31,32].

3.2. Cutting temperature

When cutting temperatures cannot be controlled and become too high, various problems, i.e., short tool life, workpiece surface/sub-surface damages, high dimensional deviations, poor efficiency, etc., are most likely to occur [33]. From this perspective, the impact of prepared fluids on cutting temperature are provided in Fig. 7. From Fig. 7, the highest cutting temperature was seen as 281 °C under dry cutting; however, a drop in cutting temperature was observed when employing vegetable-based fluids. In addition to their cooling properties, cutting fluids form a thin film layer at the tool-chip-workpiece interface, reducing friction and reducing the formation of temperature [34]. Compared to dry turning, sunflower oil, olive oil, hazelnut oil, and corn oil helped to reduce by 14.23%, 14.94%, 17.79%, and 18.50%, respectively. Among the pure vegetable-based oils, corn oil gave the best results. According to section 3.1, this can be attributed to the oil's tribological and thermal conductivity specifications. The decrease in temperature continued with the addition of nanoparticles into pure vegetable-based oils. That is, sunflower oil+SiO₂ and sunflower oil+TiO₂ improved by 11.62% and 18.26% compared to pure sunflower oil, respectively. In comparison with pure olive oil, olive oil+SiO₂, and olive oil+TiO₂ provided 9.20% and 15.06% improvement. Compared to pure hazelnut oil, hazelnut oil+SiO₂ provided 11.26% improvement, while hazelnut oil+TiO₂ improved 18.61%. Finally, corn oil+SiO₂ provided an improvement of 11.79%, while corn oil+TiO₂ showed an improvement of 20.08%, compared to pure corn oil. As can be seen from the percentages, significant decreases in temperatures were observed with the addition of nanoparticles. This was associated with nano-additives improving the tribological, rheological, and thermal conductivity of base cutting oils. Nanoparticles suspended in base fluid reduce friction by showing a ball effect at interfaces in contact, thus reducing heat generation. Moreover, depending on the nanoparticle's features, the thermal conductivity of the base cutting fluid may increase and so faster heat evacuation in the cutting zone occurs [35]. In summary, corn oil+TiO₂ nanofluid gave the lowest temperature; that is, it provided a 34.88% improvement in cutting temperature compared to dry machining. Compared to SiO₂, TiO₂ is more adept at reducing the cutting temperature. Outstanding chemical stability, resistance to acid and caustic corrosion, and high temperature resistance are all characteristics of TiO₂ nanoparticles [36]. In addition, both polar and non-polar base solutions exhibit good dispersibility of TiO₂ nanoparticles [37].

3.3. Tool wear

In order to quantify the magnitude of tool wear, worn tools were examined under a microscope, and flank wear was found to be the predominant type of wear. Therefore, the maximum flank wear (VB_{max}) of each worn tool was observed. Flank wear has a strong correlation with the type of cooling/lubrication agency employed during cutting, as previously reported in the literature [38]. As provided in Fig. 8, the

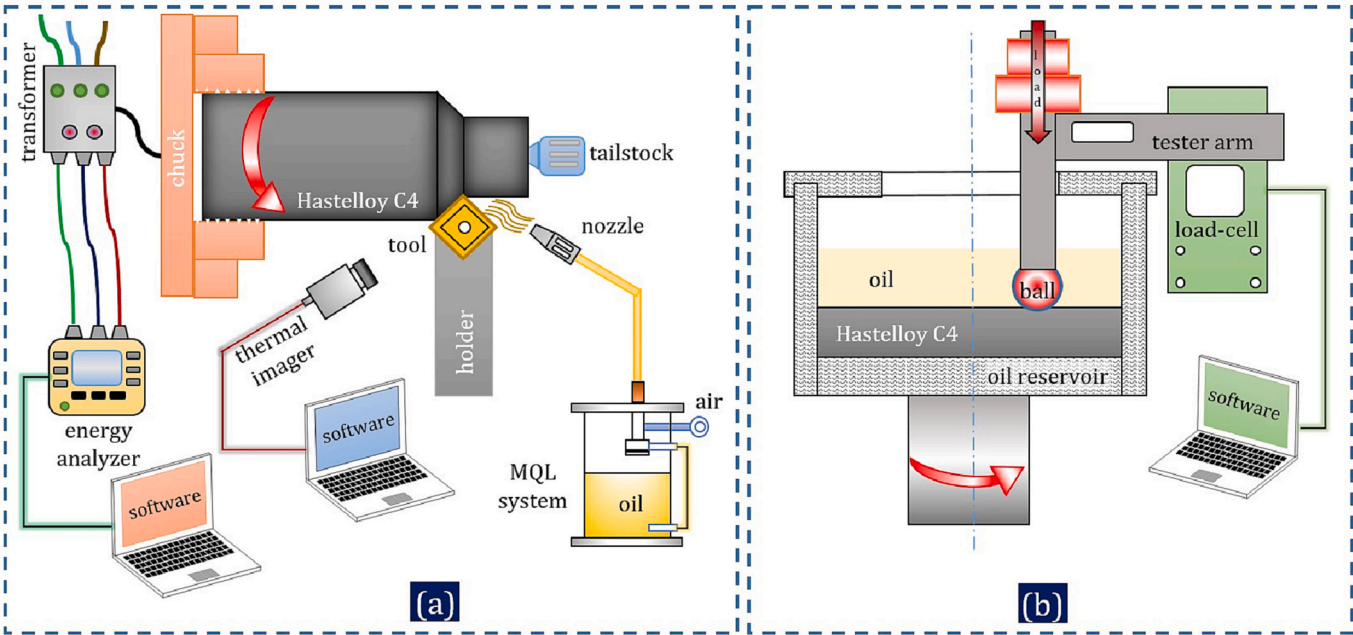


Fig. 3. Experimental setup for (a) turning and (b) friction tests.

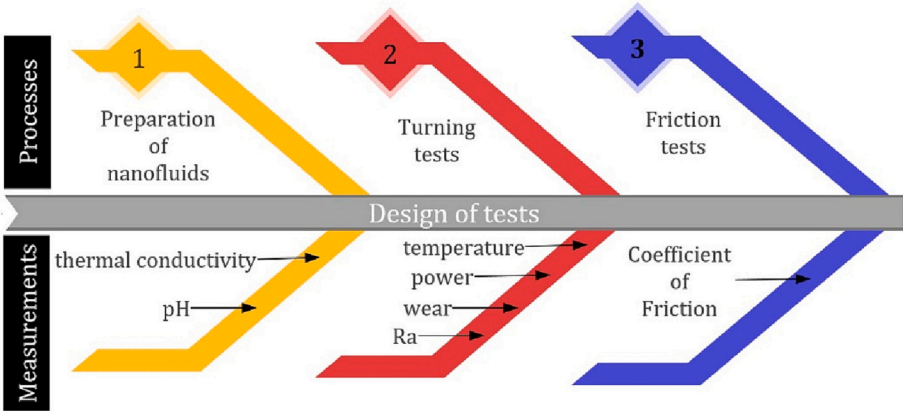


Fig. 4. Design of tests and steps for measurement.

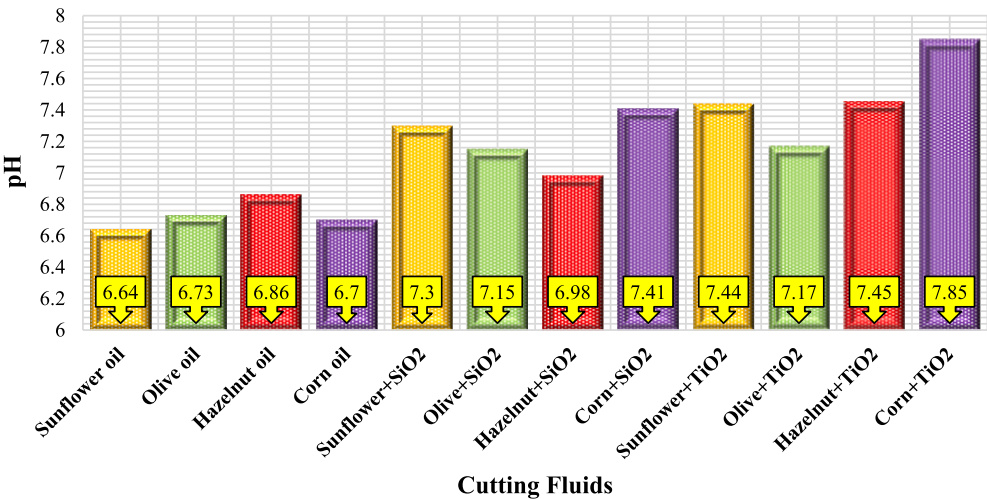


Fig. 5. Change of pH against cutting fluids.

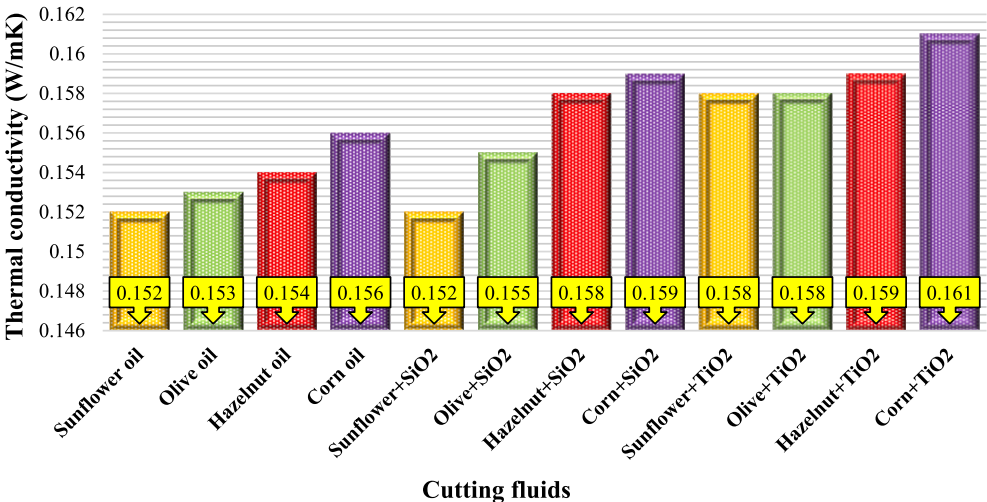


Fig. 6. Change of thermal conductivity against cutting fluids.

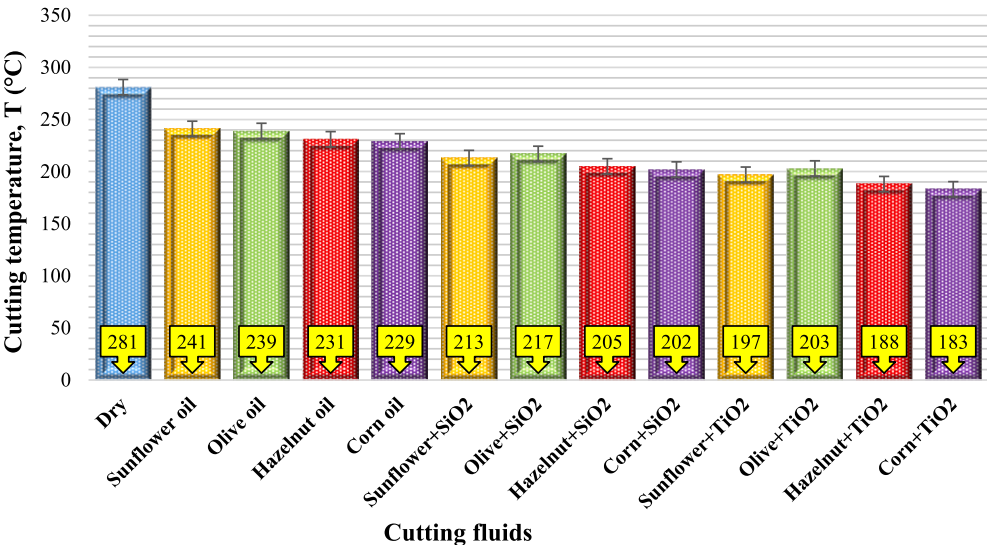


Fig. 7. Change of cutting temperature against cutting fluids.

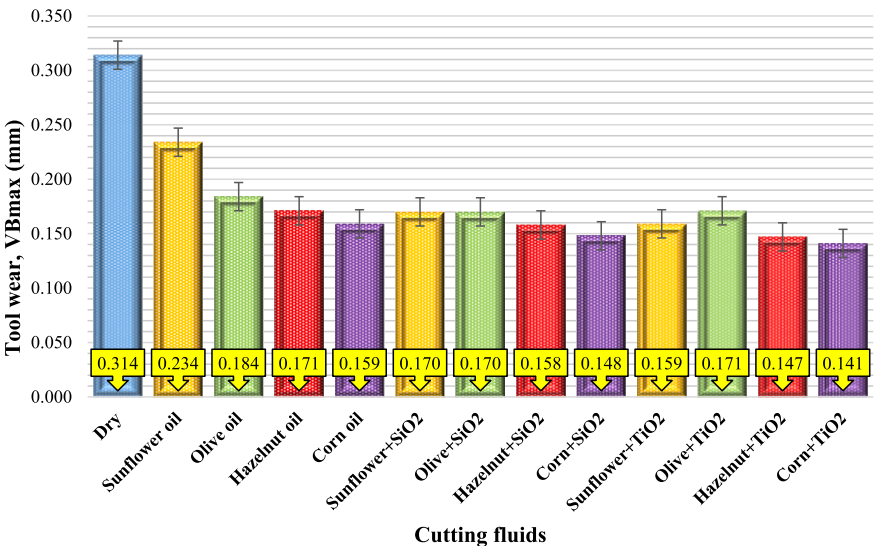


Fig. 8. Change of tool wear against cutting fluids.

positive effect of the various vegetable-based oils on tool wear compared to dry cutting is admirable, both in terms of productivity and environmentally friendly machining. Moreover, the nanoparticles added to these vegetable oils increased machining efficiency by reducing tool wear. Approximately 25.5% of tool wear got reduced when sunflower oil base fluid was used as the cutting fluid. The maximum reduction of 55.1% in tool wear compared to dry cutting was achieved with the corn oil+TiO₂ vegetable-based nanofluid. In addition, under the employment of other base and nanofluid cutting fluids, improvements in tool wear have occurred between 41.4% and 53.18% compared to dry cutting. High heat generation during cutting due to plastic deformation and friction between the tool-chip and tool-workpiece are the main causes of tool wear [39]. Therefore, it is of great importance to decrease both the temperature and the friction coefficient. It is known that nanoparticles are in an advantageous position in terms of heat evacuation by increasing the thermal conductivity of the base cutting fluids [40]. The unique properties of both the base liquid and the nanoparticles play a role in determining the degree of its effectiveness. On the other hand, the properties of the nanofluids that are created when base liquid and nanoparticles combine can be special. The efficiency and heat release capabilities of nanofluids are among the characteristics that are influenced by stability and thermal conductivity. In general, the pH value gives a clue about the homogeneity of the nanofluid, and it is accepted that the homogeneity of the fluids with higher pH values is higher [22].

As given in section 3.1, the rich pH value of corn oil+TiO₂ increased the homogeneity of the nanofluid compared to its competitors. Moreover, corn oil+TiO₂ offered maximum thermal conductivity among prepared nanofluids. It is thought that the better performance of TiO₂ in increasing the thermal conductivity is related to the crystalline nature, morphology, and particle size. In addition, the large surface volume may be one of the main factors in increasing the thermal conductivity [31,32]. As mentioned above, another factor that triggers tool wear is friction. The friction coefficient results given in Section 3.7, and the tool wear results are in agreement. In other words, it is not a coincidence that

the lowest friction coefficient and wear occur under corn+TiO₂ cutting fluid. It is believed that a more stable tribo-film layer developed on the disc-ball surfaces under the corn oil+TiO₂ condition since it had a more uniform distribution than other nanofluids.

3.4. Tool damage mechanisms

Detailed analysis of wear mechanisms is required to understand the factors that lead to tool damage and/or tool wear. In this section, the damage mechanisms on the tool are revealed by performing SEM and EDX analyzes on the worn cutting tools. SEM images and EDX outputs of the tools are given in Figs. 9-15. Accordingly, when the image of worn tools is examined, abrasive tracks, BUE, BUL, attached chips, and chipping stand out as common damage types. Among these, the dominant damage type was BUE and BUL, and therefore adhesive was the dominant wear mechanism. In the present study, EDX analyzes performed on each cutting tool revealed the presence of workpiece material elements on the tool surface. Adhesion of the workpiece to the tool surfaces in a certain temperature range and at high stresses causes adhesive wear of the tool. It leads to the formation of BUL on the rake face and BUE on the tool edge responsible for tool failure [41]. When machining nickel-based superalloys, adhesive wear is the most prevalent type of tool wear mechanism, it is frequently brought on by excessive cutting pressures and the cutting environment when the tool penetrates the workpiece, and it can happen at both high and low cutting temperatures [42]. When the worn tools under cooling lubrication conditions are examined on the SEM images, it can be said that the other dominant damage type is chipping. BUE and unstable adhesion material were produced as a result of workpiece material adhering to the tool surface. While the cutting process is in progress, the BUE and the unstable adhesive workpiece material break off from the tool surface at the end of a certain cycle. The accompanying of the tool material to the separated workpiece material revealed the chipping damage mechanism [43]. That is, the main reason for this type of damage is also the adhesive

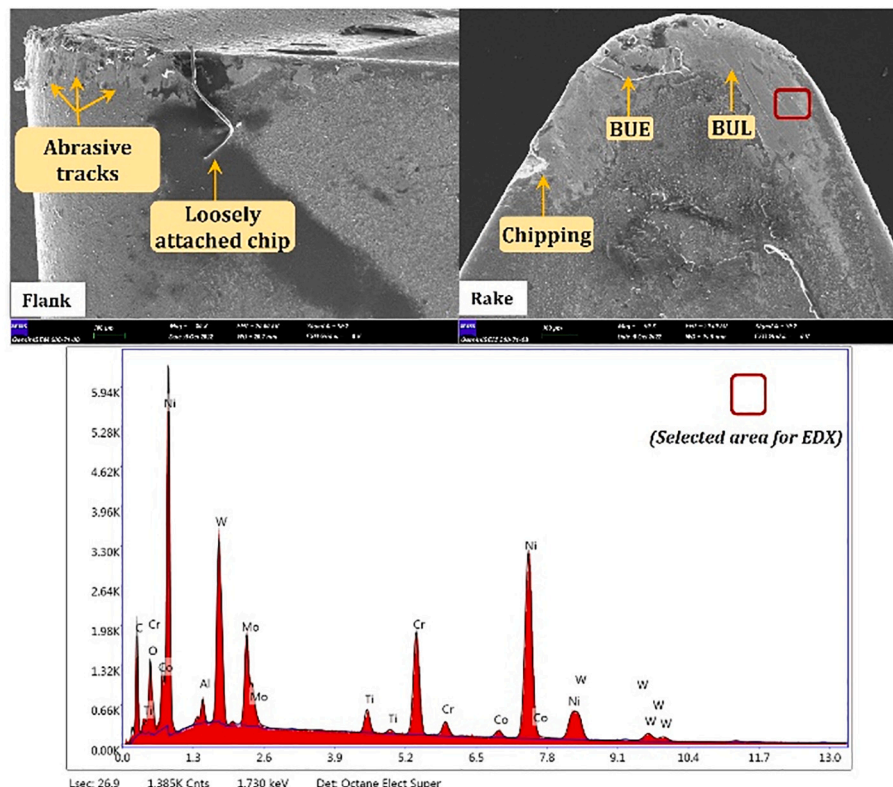


Fig. 9. SEM and EDX images of tools used under dry conditions.

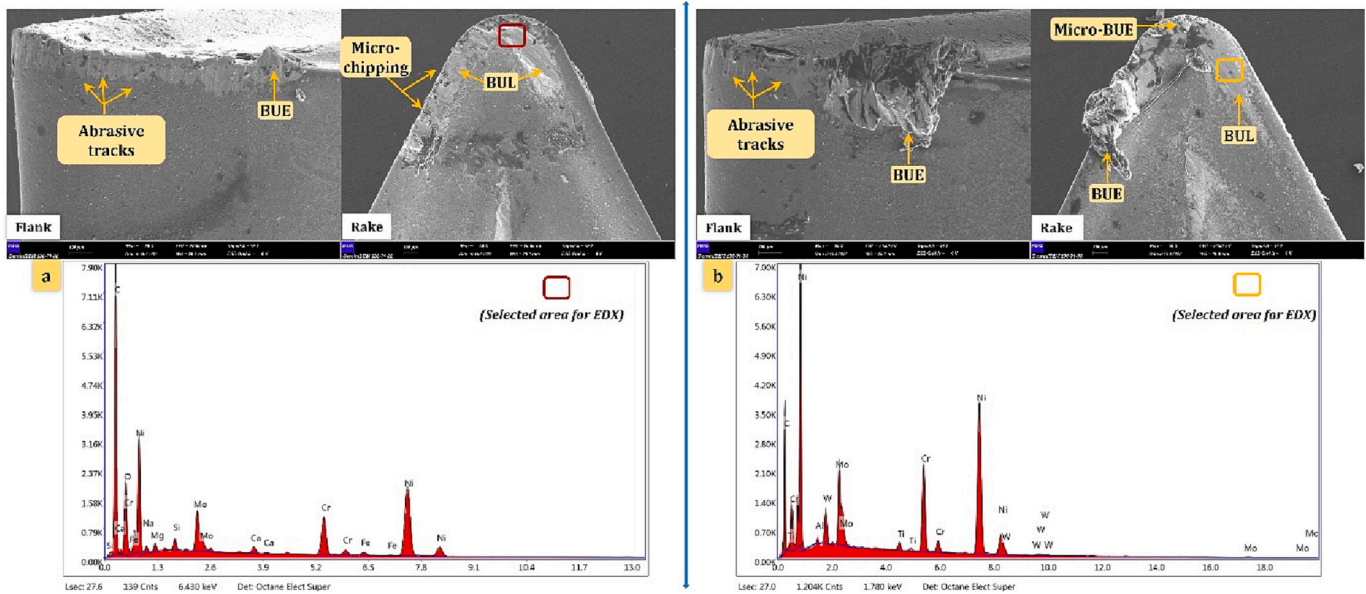


Fig. 10. SEM and EDX images of tools used under a) Sunflower oil, b) Olive oil.

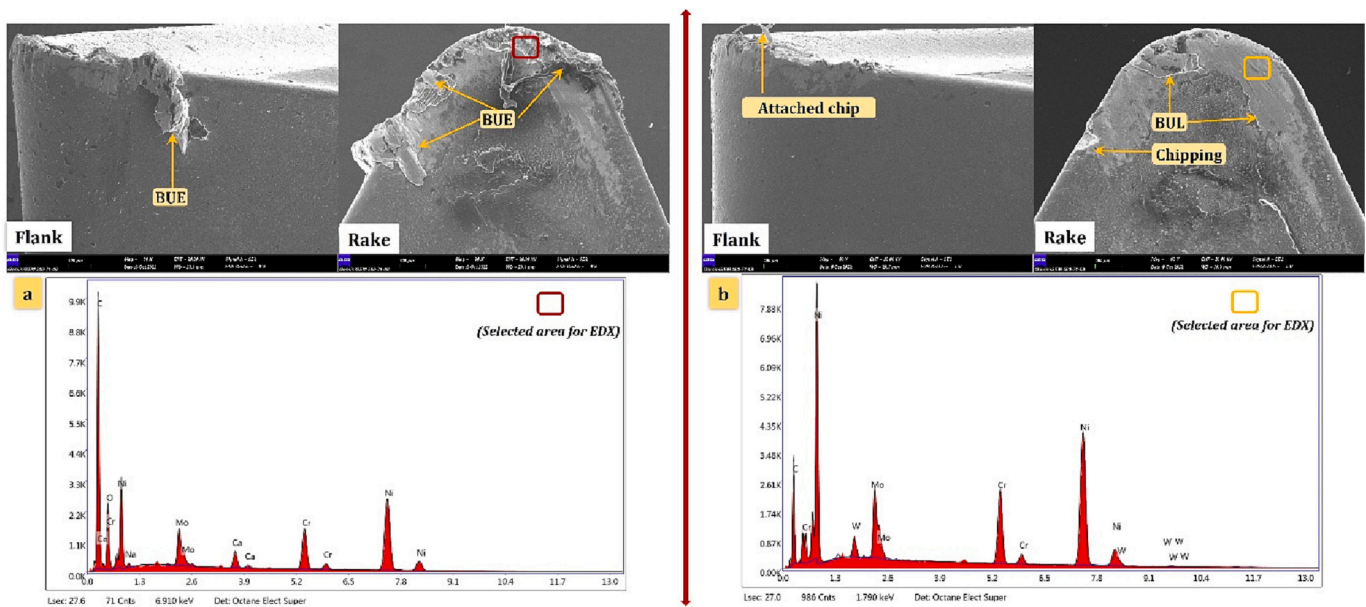


Fig. 11. SEM and EDX images of tools used under a) Hazelnut oil, b) Corn oil.

wear mechanism. When cutting nickel-based superalloys, it appears that friction between the hard carbides in the workpiece and the carbide particles that have been separated from the tool material is the primary contributor to abrasive wear. In addition, burrs that have hardened on the surface of the workpiece might wear out the tool and cause harm [41]. When the effect of the various cutting fluids used on tool damage is evaluated, it can be said that they do not completely eliminate tool damage but contribute to a slight reduction.

3.5. Surface roughness

Mechanical, thermal, topological, and metallurgical changes occur during the machining of nickel-based superalloys. Thermal fluctuations due to high temperatures lead to undesirable conditions in the surface morphology. The microstructural change is impacted by metallurgical alteration, which includes phase transition, surface, and sub-surface

recrystallization. As a result, it directly affects the behavior of the machined surface and the near-surface region [44]. For this reason, evaluating the surface quality in machining nickel-based superalloys is considered important from more than one point of view. Fig. 16 shows the average surface roughness values after the chip removal process with different cooling methods. For a clear comparison, the surface roughness outputs under dry machining are also added to the graph. Thus, in the first stage, it is aimed to make a general evaluation between dry machining and cooling methods. According to Fig. 16, the average surface roughness value decreases significantly with the employment of cutting fluids. It is seen that even in the use of olive oil, which gives the highest value, a significant improvement has occurred. While $R_a = 2.199 \mu\text{m}$ was obtained with dry machining, this value was $1.505 \mu\text{m}$ in olive oil-based machining. In other words, a 31.55% improvement was achieved using olive oil based-cutting fluid compared to dry machining. The main reason for this situation is closely related to cutting fluids'

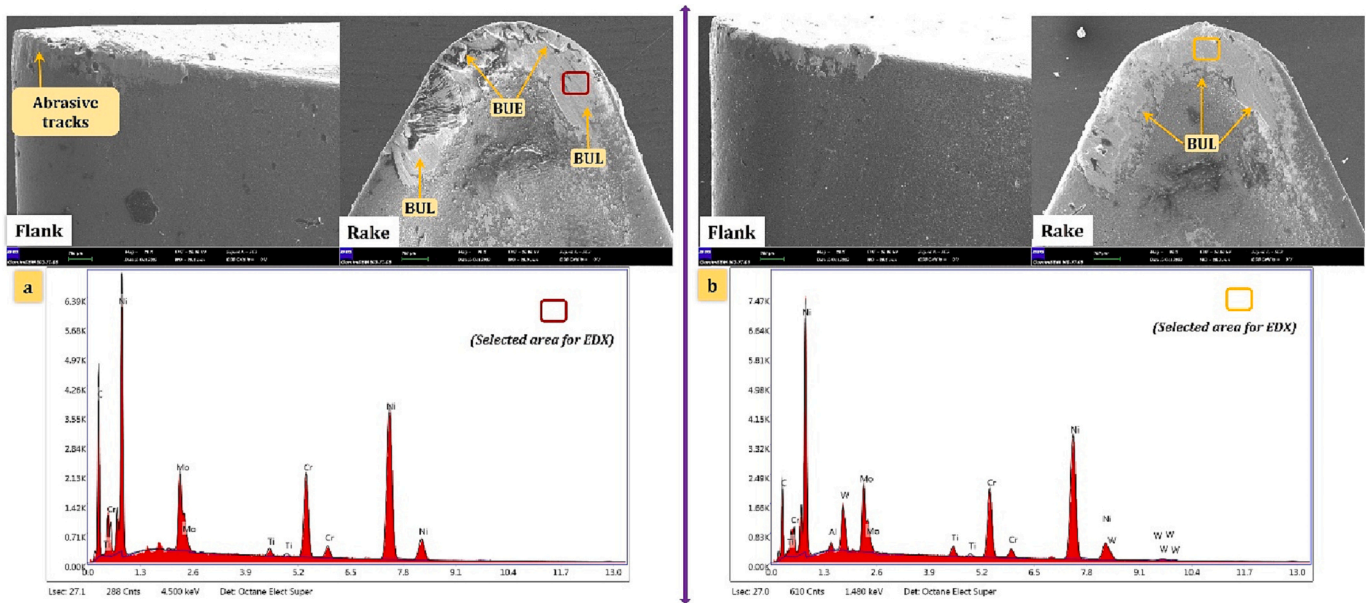


Fig. 12. SEM and EDX images of tools used under a) Sunflower oil+SiO₂, b) Olive oil+SiO₂.

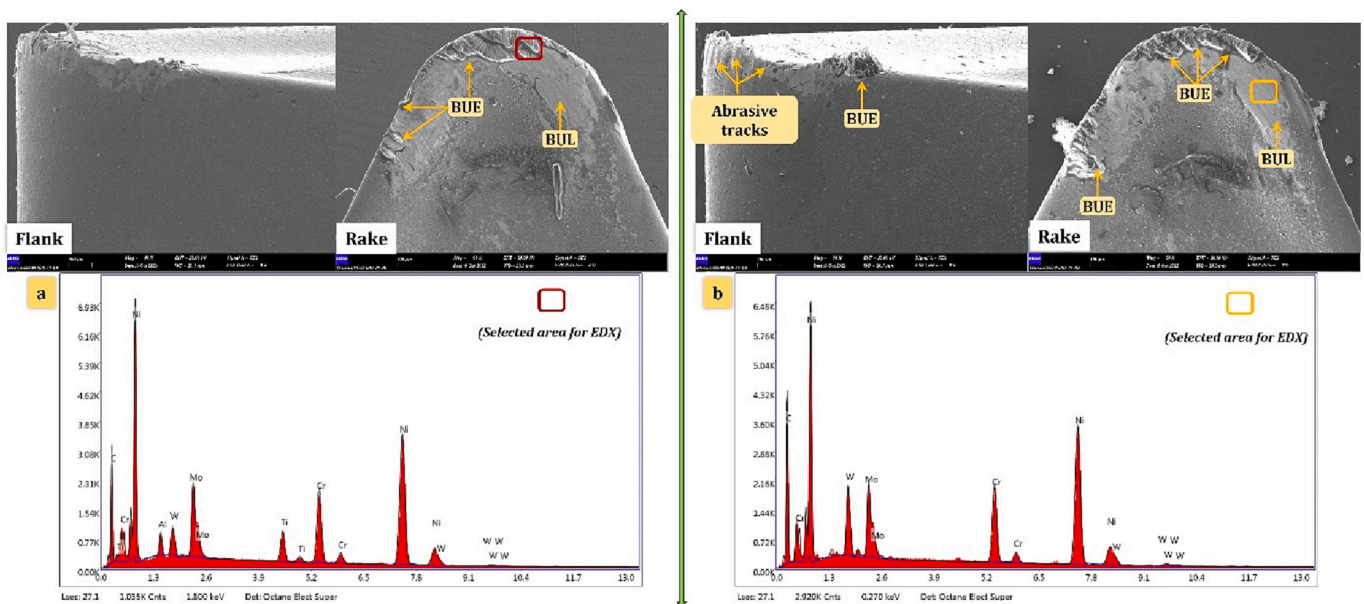


Fig. 13. SEM and EDX images of tools used under a) Hazelnut oil+SiO₂, b) Corn oil+SiO₂.

tribological and thermal properties. Cutting fluids form a lubricating film at the workpiece-tool-chip interfaces. Also, other crucial functions of the cutting fluid, i.e., cooling and chip removal from the cutting zone, can help the cutting process [45]. Fig. 16 shows that corn oil with $R_a = 1.343 \mu\text{m}$ gives the best results among base vegetable oils. This was followed by hazelnut oil ($1.408 \mu\text{m}$), sunflower oil ($1.498 \mu\text{m}$), and olive oil ($1.505 \mu\text{m}$). Compared to dry machining, corn oil provided a 38.92% improvement in surface roughness. Saturated fatty acids are more abundant in corn oil than in sunflower oil [46]. Cutting oils made from vegetables are regarded to work better thanks to the aforementioned qualities. However, using oils with additional nanoparticles has led to a remarkable reduction in surface roughness (see Fig. 16). This is connected to the fact that the tribological, rheological, and conductivity properties of the cutting fluid are enhanced by the nano-additives in the fluid. Nano-additives show a ball effect by settling at the tool-chip-workpiece interface. Hence, it reduces the coefficient of friction and

cutting forces and, thus, better surface quality. In addition, the fluid's thermal conductivity increases with adding additives (section 3.1). Because of its excellent thermal conductivity, the cutting zone's heat is swiftly dissipated, improving process effectiveness [47]. In previous studies carried out by Jiang et al. [48] and Babu et al. [49], it has been emphasized that the properties of the fluid increase with nanoadditives and offer improvements in surface roughness. However, the improvement in nanofluid is directly related to the characteristic properties of the nanoadditives [50]. In this study, it was seen that TiO₂ doped nanofluid gave better results in comparison to SiO₂. The cooling condition that gave the best R_a value under all conditions was corn oil with TiO₂. Compared to dry machining, an improvement of 58.57% was achieved with TiO₂ based corn oil. TiO₂ nanoparticles improve the pH and thermal conductivity properties of the base oil (section 3.1). TiO₂-doped nanofluid, which has better thermal conductivity than SiO₂-doped nanofluid, can quickly evacuate the temperature in the cutting

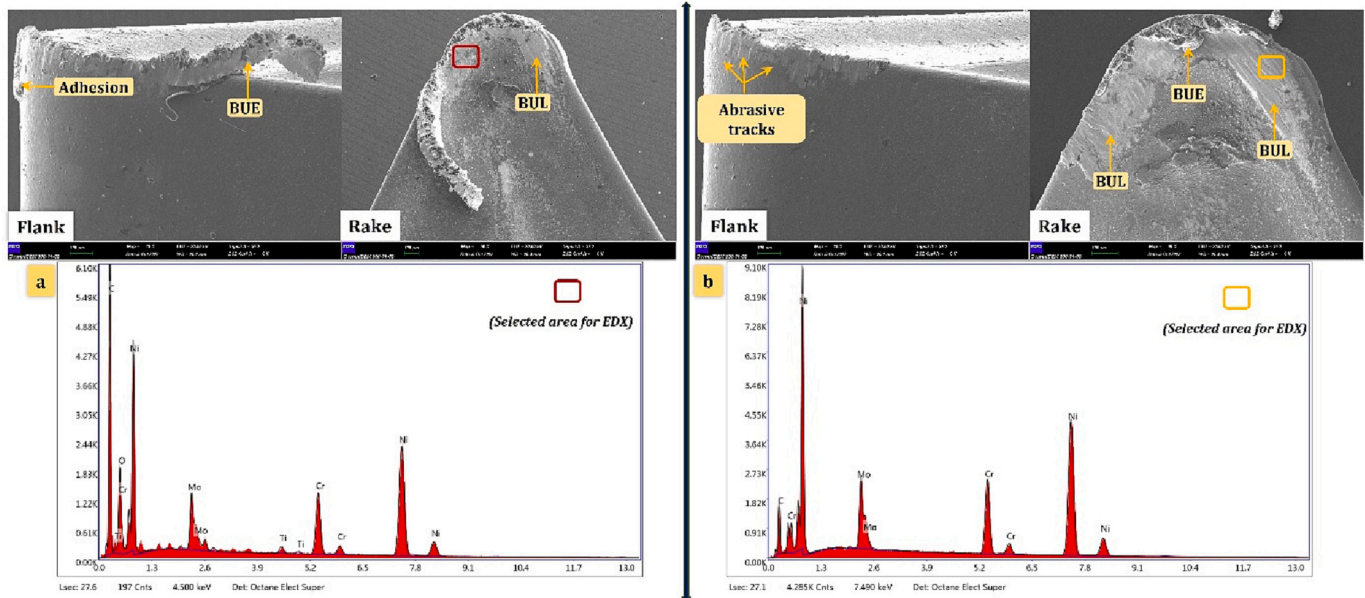


Fig. 14. SEM and EDX images of tools used under a) Sunflower oil+TiO₂, b) Olive oil+TiO₂.

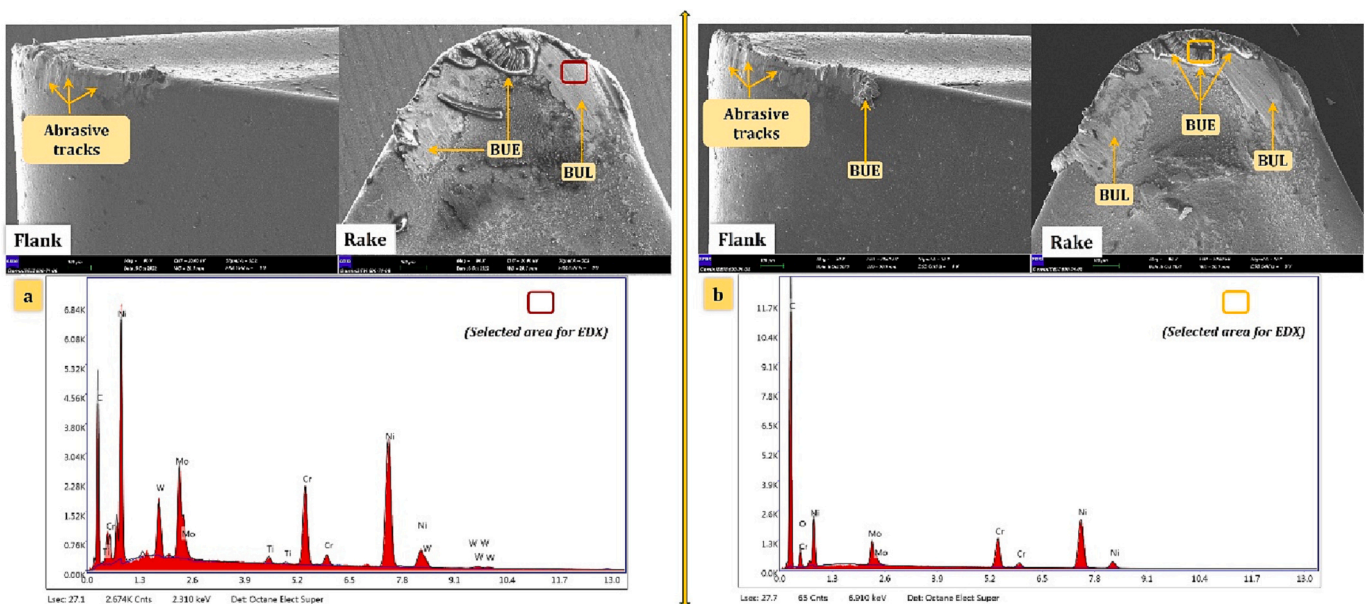


Fig. 15. SEM and EDX images of tools used under a) Hazelnut oil+TiO₂, b) Corn oil+TiO₂.

zone. Moreover, it can also offer improvements in tool wear. This situation affects the surface roughness directly/indirectly.

3.6. Power consumption

In recent years, the increase in energy consumption and prices and the progress in environmental awareness have led to more interest in energy efficiency in the manufacturing industry [51,52]. One of the main ways to contribute to energy efficiency and sustainability in machining is to minimize power consumption in machine tools which affected by various such as tool/material pair, machining parameters, cooling/lubrication methods, etc., [53]. This study focuses on the impact of cooling-lubrication techniques while holding other variables constant on power usage. For this purpose, the power consumption performance of the machine during machining was measured under the vegetable pure-MQL and vegetable oil+nanoparticles-MQL. The

responses were compared with dry cutting responses as presented in Fig. 17. The highest power consumption value among the tested conditions was 360 W, which was obtained in dry cutting conditions. This can be considered as a result of high friction due to the absence of any lubricating agent in the tool/chip contact area. The fact that the highest friction coefficient (0.252) was obtained in the dry friction condition (refer to CoF test results in Fig. 19) confirms this situation. The use of vegetable-based pure oils provided an effective lubrication feature in the tool/chip contact area, resulting in significant reductions in power consumption values. To put it more clearly, improvements through base fluids in energy consumption between 5.6% and 19.4% were recorded when compared to dry cutting. Among pure oils, hazelnut oil showed the best performance, with a power consumption of 290 W. Moreover, the improvement in power consumption of pure oils compared to dry cutting was further enhanced by the addition of nanoparticles. This can be explained by the fact that nanoparticles significantly increase the

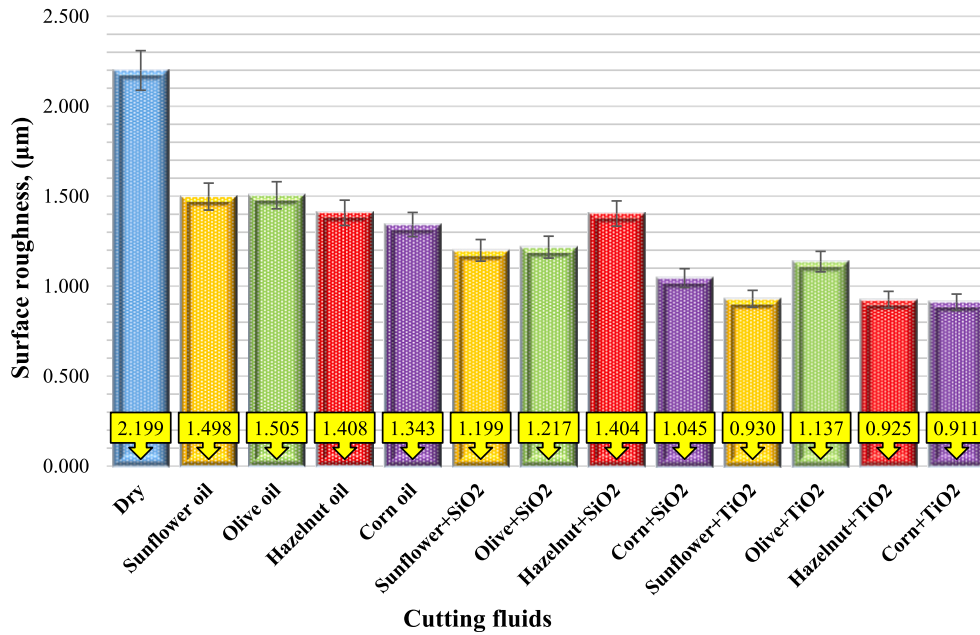


Fig. 16. Change of surface roughness against cutting fluids.

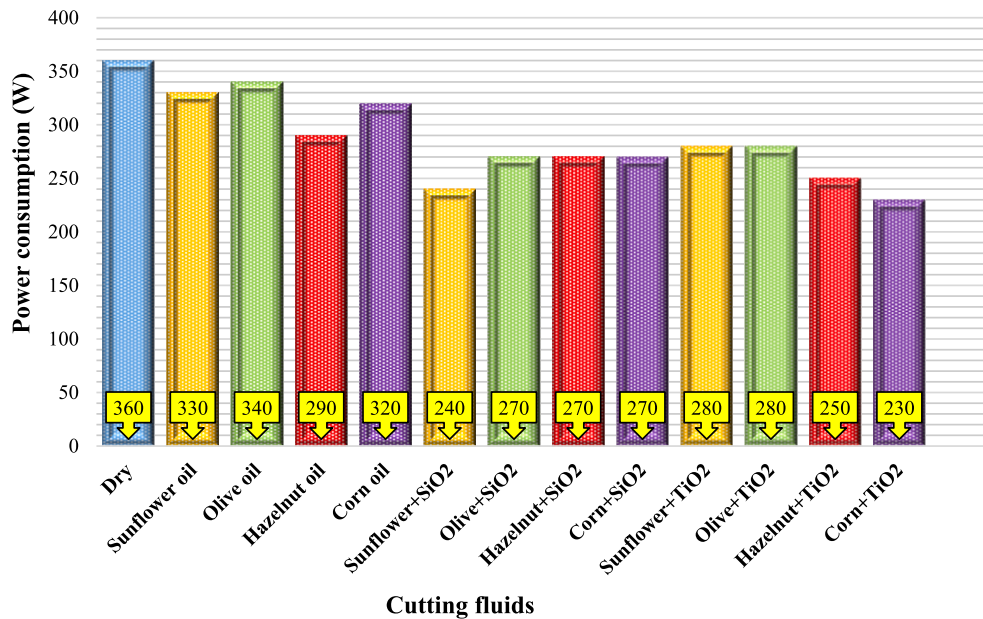


Fig. 17. Change of power consumption against cutting fluids.

tribological and rheological properties of the cutting oil [54], providing effective lubrication between the tool/chip and thus significantly reducing friction. The spherical form of SiO₂ and TiO₂ nanoparticles used in the study created a rolling effect on the contact surfaces, providing a barrier against friction. It has been observed that the pure performance ranking of cutting oils changes with the addition of nanoparticles. So, while hazelnut oil showed the best performance in pure form, sunflower oil provided the best performance in SiO₂ addition. On the other hand, corn oil offered the best performance engaged with TiO₂ addition. This indicates the importance of the synergistic effect of the interaction of the cutting oil with the nanoparticles. Although the addition of SiO₂ and TiO₂ had similar effects on power consumption, especially corn oil+TiO₂ condition provided the lowest power consumption with 230 W among all cutting conditions. While this value provided a decrease of 36.1% compared to dry cutting, it provided an

improvement of 20.7% compared to hazelnut oil, which showed the best performance among pure oils. The reason for this is thought to be due to the excellent chemical stability of TiO₂ nanoparticles and the synergistic effect of corn oil with dispersibility in base liquids [36,37]. With this effect, it can be said that it exhibits a more effective lubrication feature than other mixtures and reduces friction and, thus, power consumption. The fact that the lowest CoF from the friction test results (See Fig. 19) was obtained via corn oil+TiO₂ confirms this situation. As a result, dry cutting increases the power consumption during the machining of materials with excellent mechanical properties, which affects energy efficiency negatively. So, the obtained results revealed the importance of the use of a lubricating agent in terms of reducing friction and consequently power consumption during the machining of superalloys. It can be said that nanofluids, with their superior tribological properties, have an undeniable contribution to energy consumption as well as to all

processing outputs.

3.7. Coefficient of friction tests

CoF tests were conducted using AISI 52100 ball against Hastelloy C4 disc material under dry, corn oil, corn oil+SiO₂, and corn oil+TiO₂ conditions. As stated in the previous sections, corn oil proved to perform relatively better when compared to other vegetable oils. For this reason, in CoF tests, corn oil, and nanofluid types were considered to be compared among themselves. The CoF trend obtained under dry, corn oil, corn oil+SiO₂, and corn oil+TiO₂ conditions is given in Fig. 18. Herewith, it was seen that there is a non-uniform trend during the test in dry condition. The reason why this CoF trend was higher at the beginning of the test is thought to be due to the running-in or break-in region. Running-in is inevitable under dry or oil conditions due to relative slip [55]; however, there is still insufficient clarity about running-in [56]. In dry condition, ball and disc materials created a relatively more uniform CoF curve after the running-in stage. Towards the end of the test, the CoF curve again entered an upward trend due to the wear on the disc-ball interfaces. Corn oil, corn oil+SiO₂, and corn oil+TiO₂ followed the curve trend obtained under dry conditions, respectively. Especially corn oil+TiO₂ conditions created a more uniform curve when compared to other conditions. The graph created by the average of the CoF values obtained during the tests is provided in Fig. 19. According to Fig. 19, the highest CoF mean value (0.252) was found under dry condition. The absence of any lubricating or cooling substance in the dry condition led to the greatest CoF value.

The Stribeck curve graph given in Fig. 20 is a basic approach that helps us to understand the tribological behaviors between regimes of lubrication and surfaces. As can be seen from Fig. 20, lubrication is divided into three regions: i.e., boundary, mixed, and hydrodynamic lubrication [57]. In the boundary lubrication region (at the dry regime), high CoF values are expected as the metal-metal surfaces are in friction. In tests conducted under corn oil conditions, the average CoF value decreased by 42.9% compared to the dry condition. As expected, CoF showed a downward trend with adding oil, which acts as a barrier and reduces metal-to-metal friction. It has also been stated in the literature that the oil decreases the CoF values by increasing the friction performance [58]. With the addition of nanoparticles to liquids, their viscosity and density increase [59]. This nanofluid contributes to the formation of a tribological thin film layer on the surfaces in contact. Compared to the dry and corn oil conditions, the SiO₂ nanofluid condition resulted in the formation of a relatively thin tribo-film layer in the boundary and mixed lubrication intermediate region. With the addition of SiO₂ nanoparticles to the oil, the mean CoF values decreased by 43.3% and 0.7%,

respectively, compared to dry and corn oil conditions. SiO₂ nanoparticles added to the oil are thought to reduce wear by creating different mechanisms (rolling, mending, polishing, etc.) between the disc and the ball. In previous studies, it was stated that adding nanoparticles to oils as additives reduces wear, acts as a barrier, and improves surface quality [60,61]. The surface roughness Ra values (refer to section 3.5) that decreased with the addition of nanoparticles showed the same trend as the CoF results. Uniform CoF trend and lowest CoF mean values were obtained in the corn oil+TiO₂ regime. It was stated in the previous sections that the corn oil+TiO₂ nanofluid condition showed the best performance in the outputs of surface roughness, cutting temperature, power consumption, and tool wear. Uniform CoF trend and lowest CoF mean values were obtained in the corn oil+TiO₂ condition. This proves the importance of a low coefficient of friction in machining. Compared to dry, corn oil, and corn oil+SiO₂ conditions, the corn+TiO₂ regime reduced CoF values by 47.6%, 8.3%, and 7.7%, respectively. One of the most important limitations of nanofluids is the formation of sedimentation and/or agglomeration [62]. It is well known that the distribution of nanofluids with high pH values is comparatively more homogeneous [63]. Among the lubrication conditions, the highest pH value was obtained in the corn oil+TiO₂ condition. Since the corn oil+TiO₂ condition showed a more homogeneous distribution compared to other nanofluid conditions, a more stable tribo-film layer was formed on the disc-ball surfaces. In summary, it can be said that the corn oil+TiO₂ condition exhibits a property close to the mixed lubrication region on the Stribeck curve compared to other conditions, and this allows CoF values to be lower.

4. Conclusions

Vegetable oils provided better cooling and lubrication during machining compared to dry cutting. The minimal social, environmental, and economic impacts of vegetable oil-based cutting fluids have attracted the attention of industries seeking to achieve sustainability. However, it has had an important place in studies to improve the performance of these oils while maintaining sustainability. In this respect, the present study has served as a guide, and its main conclusions are summarized below.

- I. Thanks to nanoparticles dispersed into corn oil, the pH change increased dramatically. Compared to the base corn oil, the pH increase was 10.6% and 17.16% with the addition of SiO₂ and TiO₂, respectively. Maximum thermal conductivity was obtained with corn oil+TiO₂ nanofluids. The TiO₂ additive performed

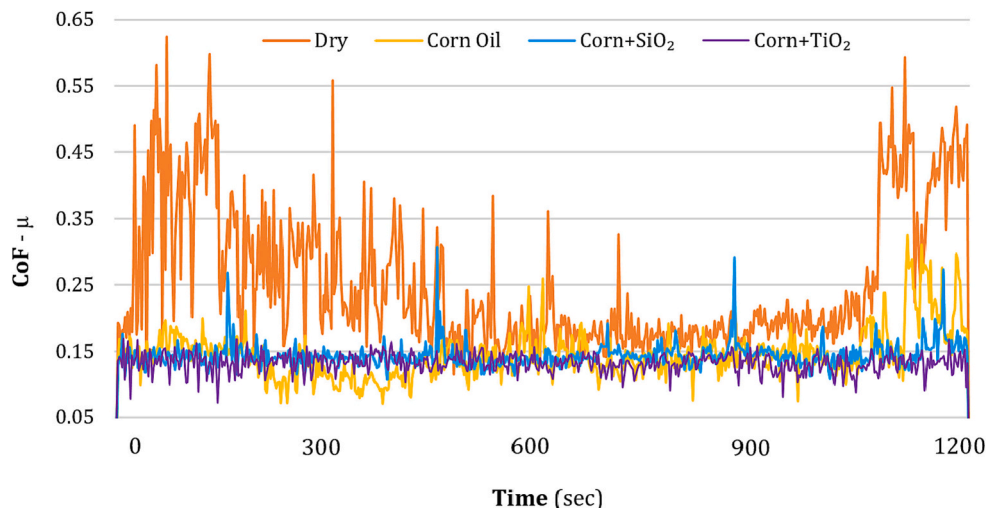


Fig. 18. Coefficient of friction trend against time (time sec).

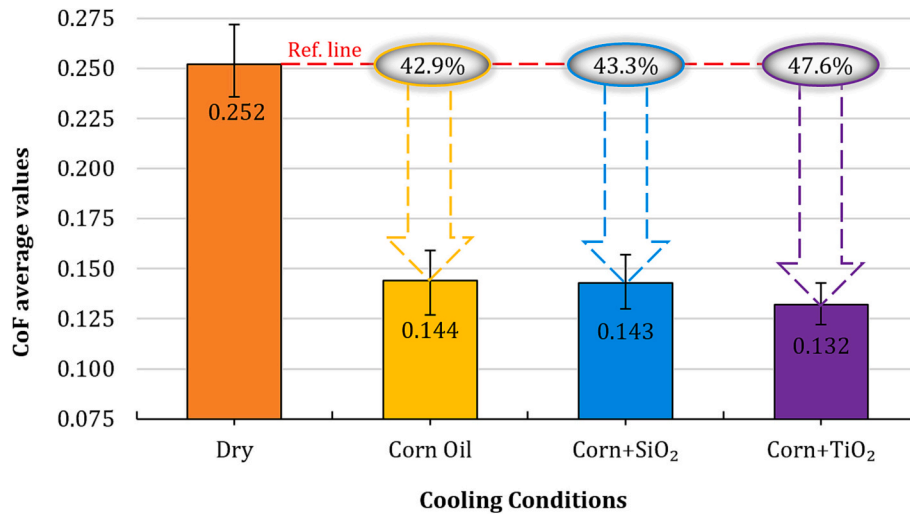


Fig. 19. CoF average values of cooling conditions.

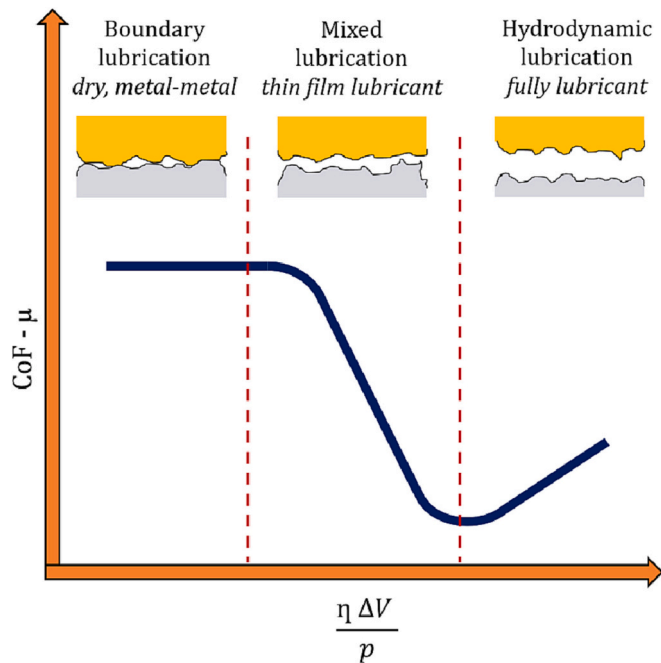


Fig. 20. Stribeck curve with three lubrication agents.

better than SiO₂ in increasing the thermal conductivity of vegetable fluids.

- II. Compared to dry cutting, sunflower oil, olive oil, hazelnut oil, and corn oil helped to reduce the temperature by 14.23%, 14.94%, 17.79%, and 18.50%, respectively. Among the base vegetable-based oils, corn oil offered good results. Moreover, corn oil+TiO₂ nanofluid gave the lowest temperature.
- III. The maximum reduction of 55.1% in tool wear compared to dry cutting was achieved with the corn oil+TiO₂ vegetable-based nanofluid. In addition, under the employment of other base and nanofluid cutting fluids, improvements in tool wear have occurred between 25.48% and 53.18%.
- IV. Abrasive tracks, BUE, BUL, adhesion, and chipping stand out as common damage types. Among these, the dominant damage type was BUE and BUL. Also, chipping is another dominant damage type. The adhesive was found as the main wear mechanism.

V. The use of vegetable oils provided an effective lubrication feature in the tool/chip contact area, resulting in significant reductions in power consumption values. Improvements in energy consumption between 5.6% and 19.4% were recorded when compared to dry cutting.

VI. Corn oil with respect to surface roughness gives the fine results with Ra = 1.343 μm among base vegetable oils. Compared to dry machining, the corn oil provided a 38.92% improvement in surface roughness. The best Ra value under all conditions was corn oil+TiO₂. Compared to dry machining, an improvement of 58.57% was achieved with TiO₂ based corn oil.

VII. Although the addition of SiO₂ and TiO₂ had similar effects on power consumption, especially corn oil+TiO₂ condition provided the lowest power consumption with 230 W. While this value provided a decrease of 36.1% compared to dry cutting.

VIII. In the friction-wear tests, the corn oil+TiO₂ conditions created a more uniform CoF curve and the lowest CoF mean values when compared to other conditions. Compared to dry, corn oil, and corn oil+SiO₂ conditions, the corn oil+TiO₂ condition reduced CoF values by 47.6%, 8.3%, and 7.7%, respectively.

CRedit authorship contribution statement

Çağrı Vakkas Yıldırım: Conceptualization, Investigation, Resources, Funding acquisition. **Şenol Şirin:** Methodology, Formal analysis, Validation, Writing – original draft. **Turgay Kıvak:** Formal analysis, Data curation, Supervision, Project administration. **Hamdi Ercan:** Conceptualization, Software, Formal analysis. **Murat Sarıkaya:** Writing – original draft, Writing – review & editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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