

Article

A Holistic Perspective on Sustainable Machining of Al6082: Synergistic Effects of Nano-Enhanced Bio-Lubricants

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Abstract: This study investigates the performance of biobased and nano-additive lubricants for the sustainable machining of Al6082 alloy. The experiments were conducted in five different cutting environments: dry cutting, olive oil-based minimum quantity lubrication (MQL), sunflower oil-based MQL, olive oil-based MQL with nano-SiO₂ additives, and sunflower oil-based MQL with nano-SiO₂ additives. The machining performance was evaluated in terms of key parameters such as surface roughness, cutting forces, tool wear, cutting temperature, and chip morphology. The results show that nano-additive lubricants reduce friction, reduce tool wear, and reduce cutting forces, thus providing lower surface roughness. The nano-SiO₂-additive olive oil-based MQL method showed the optimum performance by providing the lowest cutting force and temperature values. It was also determined that nano-additive lubricants contributed to more regular chip formation. The study reveals that the use of biobased nano-lubricants in sustainable machining processes offers environmental and economic advantages. In the future, it is recommended to examine different types and concentrations of nanoparticles, conduct long-term tool wear analyses, and evaluate the effects on other machining methods.

Keywords: sustainable machining; Al6082 alloy; MQL; nanoparticles; machining characteristics



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1. Introduction

In order to carry out precise and high-volume mass production processes, the parts produced must be subjected to high-speed cutting [1]. High-speed cutting brings with it a number of problems. These problems can be listed as reduced tool life, deterioration of the workpiece surface quality, and excessive load on the machine [2]. The principal factor contributing to reduced tool longevity and worse workpiece surface quality is the excessive heat generated between the cutting tool and the workpiece during chip removal processes [3]. To resolve this issue, the heat generated must be promptly eliminated from the cutting region [4]. Cooling–lubricating fluids are sent to the cutting site to dissipate the generated heat [5,6].

Minimum Quantity Lubrication (MQL) applications have supplanted conventional cooling fluids in machining processes [7] due to the detrimental effects of traditional cooling fluids on the environment and human health [8]. The escalating costs of conventional cooling fluids exacerbate this scenario significantly [9]. MQL is a cooling and lubrication system that offers technological, economic, and environmental advantages for machining engineering materials at standard and elevated rates [10]. In MQL, a minimal quantity of biodegradable (recyclable) oil droplets is combined with compressed air and atomized

across the cutting zone [11]. This reduces the temperature of the cutting tool, diminishes wear on the cutting tool, and enhances the quality of the surface [12]. A novel MQL processing approach utilizing nanofluids has been recently developed [13]. A nanofluid is a fluid that incorporates nanoparticles, which may consist of materials such as carbon nanotubes [14], copper oxide [15], silicon dioxide [16], titanium dioxide [17], aluminum oxide [18], molybdenum disulfide [19], diamonds [20], and analogous compounds. The addition of a small quantity of nanoparticles to the base fluid significantly enhances thermal conductivity [21]. For mechanical processing applications, it is essential to improve tribological characteristics by the use of nanoparticles [22]. Nanofluids promote heat conductivity and lubrication, as well as improve cutting performance when applied to the cutting area during machining [23]. Figure 1 presents a short review of the improvement of nano lubrication in the cutting process.

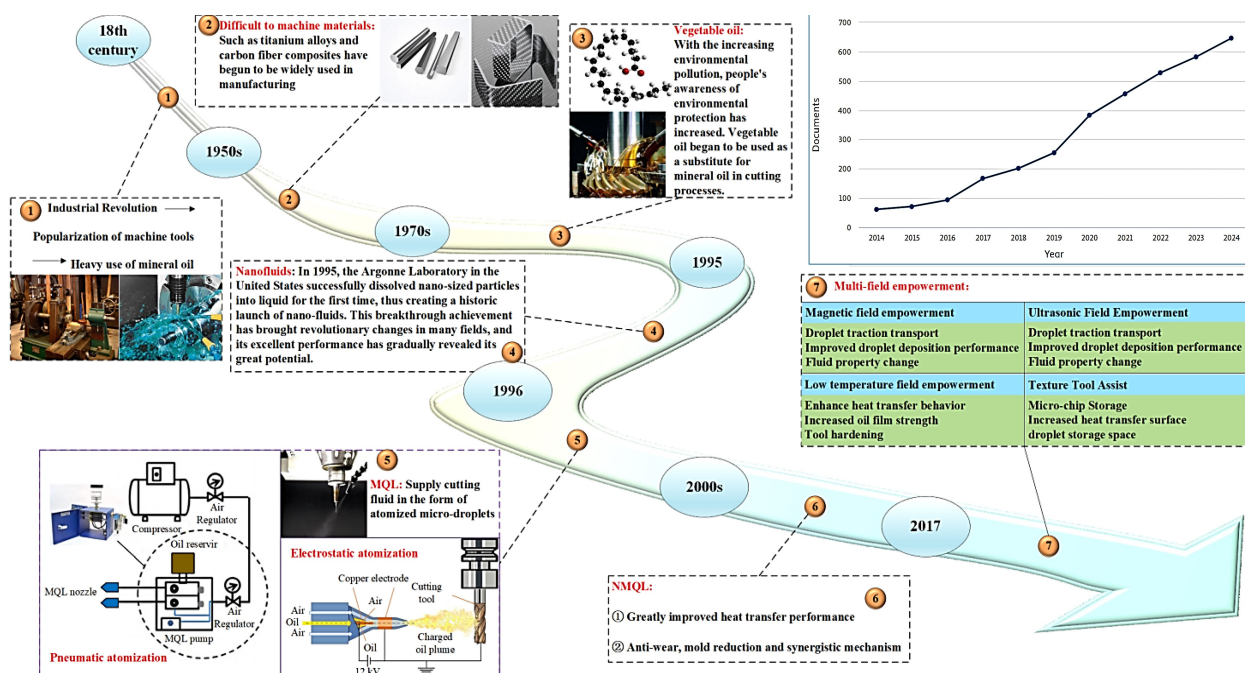


Figure 1. A short review of the improvement of nano lubrication in the cutting process (Adopted from Ref. [24] and Copyright Reserved).

1.1. Literature

Kulkarni et al. [25] applied the milling process to AA 7075-T6 alloy with three different cooling techniques and different cutting parameters and investigated their effects on surface roughness. Experiments were performed under dry conditions, with MQL, and with MQL with nanoparticle addition under cooling conditions. As a result of the experiments, it was observed that the best surface roughness, in general, occurred under the same cutting parameters with MQL machining conditions. The speed had the greatest effect on the surface roughness, and the surface roughness value decreased with the increase in the speed. Furthermore, the effect of the increase in feed and depth of cut on the surface roughness showed differences. The authors found that the surface roughness gave the worst result in dry conditions. When the temperatures formed on the workpiece were examined, they observed that the MQL coolant with nanoparticle addition gave the best result, and the dry machining conditions gave the worst result. Kishore Joshi et al. [26] machined Inconel 600 material with dry, MQL, and nano Al_2O_3 additive MQL methods in their studies. The nano-additive MQL method gave better surface quality values than other cooling methods. They stated that the effect of MQL decreased when they processed

at high cutting speeds, passes, and feeds, and they attributed this to the fact that the air–oil mixture aerosol could not reach the cutting zone effectively. Pasam et al. [27] investigated the differences in the additives added to the oil in nano or micro size to increase performance in the MQL method. They used MQL methods with MoS₂ and boric acid (H₃BO₃) additives in nano and micro scales in turning 1040 steel. The MoS₂ additive MQL method resulted in lower tool wear, surface roughness, cutting force, and temperature values at high cutting speeds. Gutnichenko et al. [28] machined cold work tool steel under dry, MQL, and GnP-added MQL conditions. They stated that GnP added to the vegetable oil used significantly reduced friction. Lv et al. [29] applied the GnP-added electrostatic MQL method and the traditional MQL method in the milling process of AISI 304 steel and compared these two methods. They stated that the GnP-added method penetrated better into the friction zone, reduced friction, increased lubrication performance, and extended tool life. L. Samylingam et al. [30] used nanocellulose as a nano-additive in the MQL method. In their experimental studies, where they used stainless material, they stated that the addition of nanocellulose to the oil in the MQL method significantly increased tool life. Sekhar et al. [31] compared the MQL method with nano MoS₂ additives, which we also used in our thesis study, in the turning of AISI 1040 steel; dry machining with MQL and the machining performance of oils using nano MoS₂ additives in canola, sunflower, and commercial oils. They obtained the best surface quality when the nano-additive ratio in the oil was 0.5% by weight. They obtained the best surface quality when the nano MoS₂ powders were 70–80 nm in size. Sharma et al. [32] performed the turning process of AISI 1040 material under the conditions of dry, liquid cooling, MQL, and SiO₂-added MQL methods. According to the results they obtained, the MQL method with added nano SiO₂ provided better values in surface roughness, tool wear, and cutting forces compared to MQL and liquid cooling methods. While the increase in thermal conductivity has a positive effect in reducing the temperature at the tool–workpiece interface, the increased viscosity has a negative effect as it causes a decrease in spray pressure. For this reason, they decided on a 1% nano-added ratio by weight as the optimum value in their study. In their distinct study, the authors used dry, liquid, MQL, and nano TiO₂ additive MQL methods in the turning process of the same material and stated that tool wear decreased by 35.85% in the nano TiO₂ additive MQL method compared to the nano-additive-free MQL method [33]. In another study, Sharma et al. [34] tried the Al₂O₃ additive MQL method on the same material and processing method and stated that the cutting forces decreased by 29.2% compared to the nano-additive-free MQL method. Maruda et al. [35] used dry, MQL, and phosphate ester-added MQL methods in the turning process of AISI 1045 material. They stated that the phosphate ester-added significantly affected the tool wear and chip formation. They stated that the tool wear at different cutting speeds decreased by up to 27% in the phosphate ester-added MQL method compared to dry machining and by 2–20% compared to the MQL method. Vegetable cutting oils stand out because they are biodegradable in nature, do not pollute the environment, and are harmless to human health. Guo et al. [36] added six different vegetable oils separately to vegetable castor oil in the processing of Inconel 718 material that they ground using the MQL method and compared the performances of the resulting oil mixtures. Castor oil has good lubricating properties, but its use is restricted due to its high viscosity and low fluidity. They tried to eliminate this disadvantage of castor oil by mixing it with soybean oil, corn oil, peanut oil, sunflower oil, palm oil, and rapeseed oil. They obtained the optimum performance in the castor oil–soybean oil mixture. Specific grinding force decreased by 27.03% compared to castor oil.

1.2. Novelty and Literature Gap

However, despite the extensive research on MQL and nano-lubricants in machining, a critical gap remains in understanding their comparative effects in different bio-based lubrication environments, particularly in aluminum machining. Most of the existing studies have primarily focused on conventional coolants, dry machining, or single-type nano-lubricants, overlooking the direct comparison between olive oil and sunflower oil-based nano-lubricants. Moreover, while the tribological benefits of nanoparticles are well-documented, their specific influence on chip morphology, tool wear mechanisms, and SEM-based microstructural changes under different lubrication conditions has not been systematically explored. This study aims to fill this gap by providing a comprehensive evaluation of the machining performance of Al6082 alloy under five distinct environments—dry, olive oil, nano-enhanced olive oil, sunflower oil, and nano-enhanced sunflower oil. By assessing key parameters such as surface roughness, tool wear, cutting forces, cutting temperature, and chip morphology, this research will offer new insights into the synergistic effects of nano-lubricants and bio-based oils, paving the way for sustainable and high-performance machining solutions.

2. Materials and Methods

In this section, information is provided about the experimental study, machine tools, cutting tools, cutting fluids, and cutting parameters. As a result of similar studies and literature research, the effects of nanoparticles in the MQL technique on the turning process were evaluated. The cutting speed values recommended by the cutting tool company were selected, and experiments were conducted to examine the surface roughness and cutting forces by adding different volumetric concentrations of abrasive powder to the MQL system. The materials, devices, and setups used in the experiments are as follows.

In order to conduct the experiments, the De Lorenzo S547-8899 conventional lathe available at Selcuk University Faculty of Technology was used. AA6082 alloy (Seykoç, Kocaeli, Turkey) was selected for machining in the experiments. This material is generally used in the automotive and defense industries. The diameter of the test material is 50 mm, and its length is 200 mm. The feed rate, cutting depth, and cutting speed levels used during the experiment were determined as a result of preliminary experiments. In the experiments, a cutting length of 40 mm was applied for each cutting environment, two repetitive experiments were performed, and the average results were analyzed. The results have a ± 5 deviation for all results, as demonstrated in the result figures. A Carbide cutting insert with CCMT 09T308 geometry was used in the experiments (Korloy, Seoul, Republic of Korea). The tip shape of the cutting insert is 80° , and the free angle is 7° (Figure 2). Five alternative cutting environments and cutting parameters applied in turning experiments are presented in Table 1.

Table 1. Cutting conditions.

Description	Value
Cutting speed, m/min	65, 130
Feed rate, mm/rev	0.1, 0.2
Cutting depth, mm	0.3, 0.6
Cutting environment	Dry MQL (Sunflower oil) method-MQL(S) MQL (Olive oil)-MQL(O) MQL (Sunflower Oil) + 1% SiO ₂ -nano-MQL(nS) MQL (Olive Oil) + 1% SiO ₂ -nano-MQL(nO)
Lubricant flow rate	5 bar

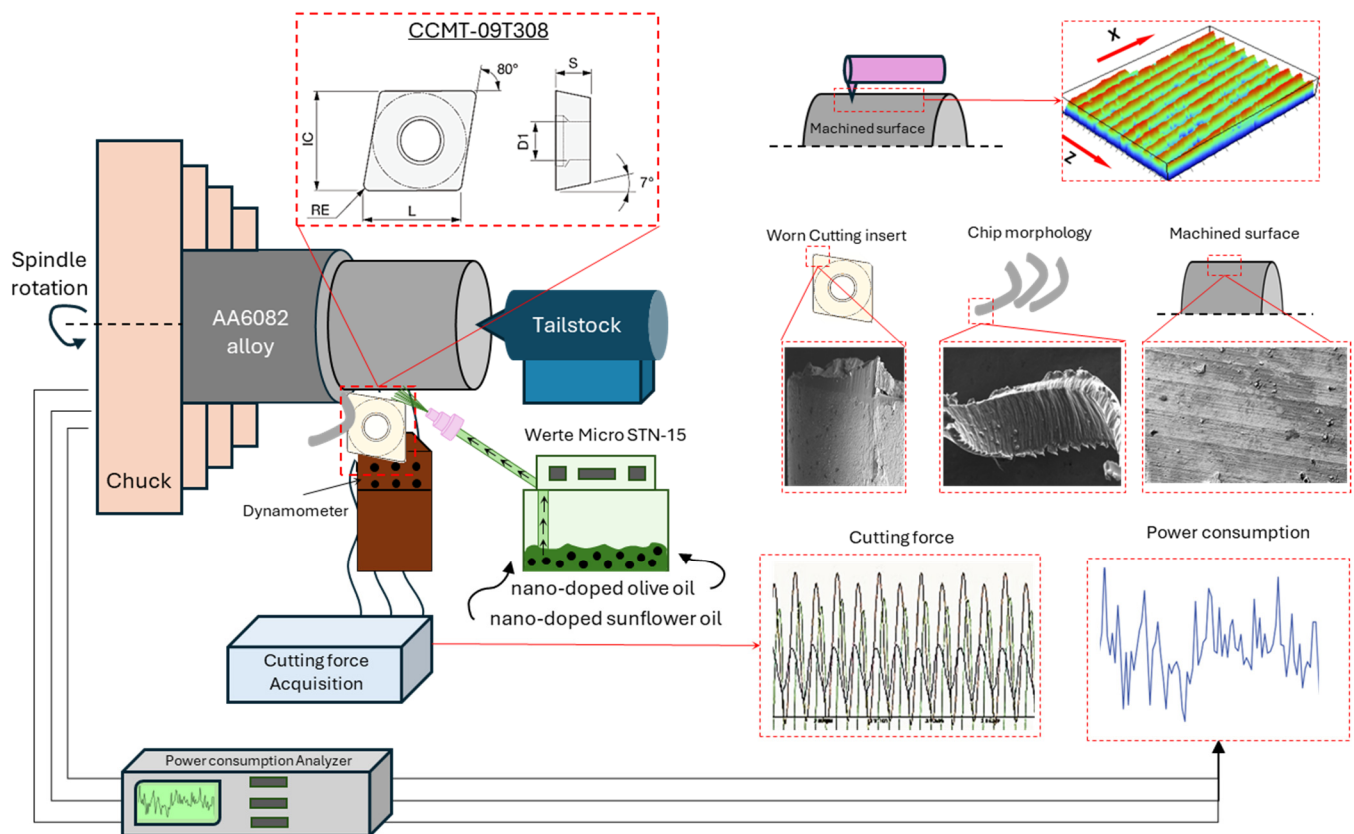
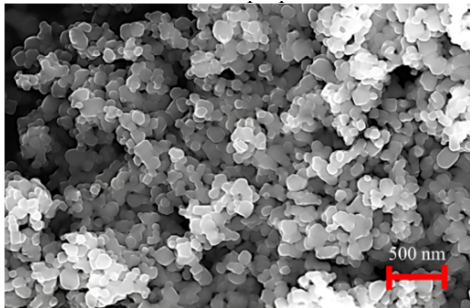
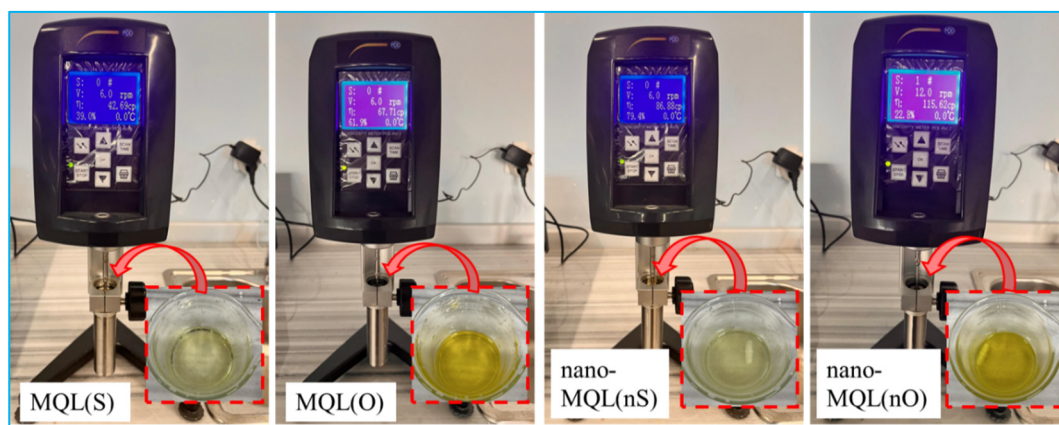


Figure 2. Experimental demonstration.

Considering the machine tool on which the experiment will be performed and the experimental conditions, the WerteMist 15-STN System (Kar-Tes, İstanbul, Turkey), suitable for external MQL applications, was preferred. The basic schematic of the MQL system is presented in Figure 2. This system can be integrated into almost any machine and enables an external MQL application. Two types of vegetable oils are used in the system to perform the MQL application. The lubricants were supplied with a nozzle of 3 mm in diameter and a pressure of 5 bar by locating it 45 mm away from the cutting zone at a 45° angle. In the experiments, SiO₂ nanoparticles were used to create a nanofluid by adding them to the cutting fluid. Using the “Precisa” brand precision scale, 2 different nanofluid cutting fluids were created by adding 1% to the weight of sunflower oil and olive oil. In the preparation of nanofluids, nanoparticles are added to the cutting fluid on a volume or mass basis to determine the mixing ratio. After adding predetermined amounts of nanoparticles to the selected suitable working fluid, the mixture is initially subjected to magnetic stirring. Following this, mechanical stirring is applied to obtain a homogeneous distribution. In the final stage, the resulting mixture is subjected to ultrasonic stirring to prevent the sedimentation of nanoparticles and to provide a more stable system. At the end of this process, a homogeneous and stable nanofluid is obtained. Table 2 shows the technical properties and SEM image of the SiO₂ nanoparticle used in the experiments. Figure 3 displays the viscosity measurements by PCE-RVI 2 Viscosity Meter (PCE-Instrument, Germany) for various vegetable oils and nano-doped versions of them (nano-MQL(nS), nano-MQL(nO)). The particle and tool wear images were analyzed in a Carl Zeiss Ultra Plus Gemini-branded (Zeiss, Jena, Germany) scanning electron microscope (SEM).

Table 2. Technical properties and SEM image [37] of the SiO₂ nanoparticle.

Property	Value
Chemical Formula	SiO ₂
Crystal Structure	Amorphous
Particle Size (nm)	22
Appearance	White opaque
SEM image	

**Figure 3.** Viscosity measurements of different types of vegetable oils and nano nano-doped versions.

The Mahr Perthometer M1 (Mahr, Göttingen, Germany), equipped with a PHT6-350/2 μm probe, was used to measure surface roughness values. The cut-off length was set to 0.8 mm, and the sample length was set to 5.6 mm in order to measure the average surface roughness (R_a) values that were created during machining on the workpiece based on ISO 4287. Moreover, roughness measurements were conducted with at least four repetitions to ensure the reliability of the surface roughness results. The ambient temperature was approximately 20 ± 1 °C. In the turning experiments, a dynamometer was used to measure the cutting force (TelC DKM 2000-Germany). The temperature measurement sensor (TelC-Germany) was used to measure cutting temperature during the experiments. To make the applicability of the experimental results more effective, the measuring devices and sensors were calibrated. Data obtained from force and temperature measurement sensors were collected via computer software (XKM2000-Germany). In addition, the energy consumed during turning with selected cutting parameters and different cutting conditions was measured. For this purpose, the Kael Multiser 02 PC TFT Network Analyzer (Istanbul, Turkey) was used to measure energy consumption. In this system, three current transformers with a capacity of 60/5 A were connected to the three-phase lathe with a capacity greater than 30 A to reduce the amount of power consumed. The details of the procedure applied to measure energy consumption can be found in our previous study [38].

3. Results and Discussion

3.1. Viscosity Assessment

By employing the nano-MQL technique, the viscosity of the lubricants undergoes a change during the investigation. Figure 4 illustrates the viscosity of the lubricants used for lubrication at a temperature of 20°. By examining Figure 4, it is evident that the viscosity of pure sunflower oil (MQL(S)) is the lowest, measuring 42.69 cS, while pure olive oil (MQL(O)) follows at 67.71 cS, with an increase of 59%. By adding nano-SiO₂ to pure oils, the viscosity has increased to 86.88 cS and 115.62 cS for the nano-MQL(nS) and nano-MQL(nO), respectively. The viscosity measurements of nano-MQL(nO) fluids were found to be 33% higher compared to those of nano-MQL(nS).

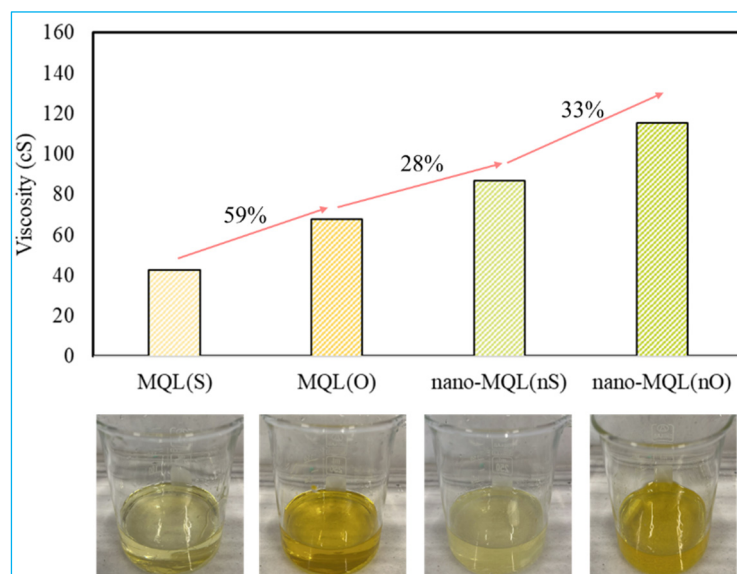


Figure 4. Viscosity changes in sunflower and olive oil and their nano-doped versions.

In general, viscosity increases with the addition of nanoparticles to pure lubricants. The general agreement is that nanofluids significantly affect their physical and chemical characteristics [39]. Nanoparticles are added to the molecular structure of the base oil, changing the fluid structure of the liquid. They enter the spaces between the oil molecules and increase the internal friction of the liquid [40].

3.2. Surface Roughness Assessment

Surface roughness is a critical quality characteristic in turning operations, as it directly influences the performance and functioning of machined components [41]. In turning operations, surface roughness is influenced by several variables, including cutting parameters (such as feed rate and cutting speed), tool geometry, tool wear, and material qualities [42]. In turning operations, surface roughness is often quantified by the Ra parameter, indicating the average departure of the surface profile from the nominal surface. Attaining a smooth surface is essential for applications involving components exposed to fatigue, friction, and wear, since surface imperfections may serve as stress concentrators that diminish mechanical performance. The correlation between cutting parameters and surface roughness is intricate, since several elements interact during the machining process. The aforementioned data indicate that an increase in feed rate often elevates surface roughness, since a higher feed rate results in greater uncut chip thickness, hence producing a coarser surface finish. At elevated cutting speeds, excessive heat production may lead to material adhesion on the cutting tool, resulting in a worn edge that compromises surface smoothness [43,44].

When the graph in Figure 5, which shows the change in average surface roughness with different lubrication methods, is examined, the average values are generally obtained as 1.39–1.02–0.71–0.62–0.60 according to the working environment order in the figure. When the percentage changes between these values are examined, it is observed that the highest change is in the study conducted using a dry environment and nano-MQL(nO). This change rate is 56.80%, and the value in the study conducted using nano-MQL(nO) is better. When the parameters are evaluated in general, a change of 12.8% is obtained according to cutting speed, 87.8% according to feed rate, and 31.14% according to cutting depth.

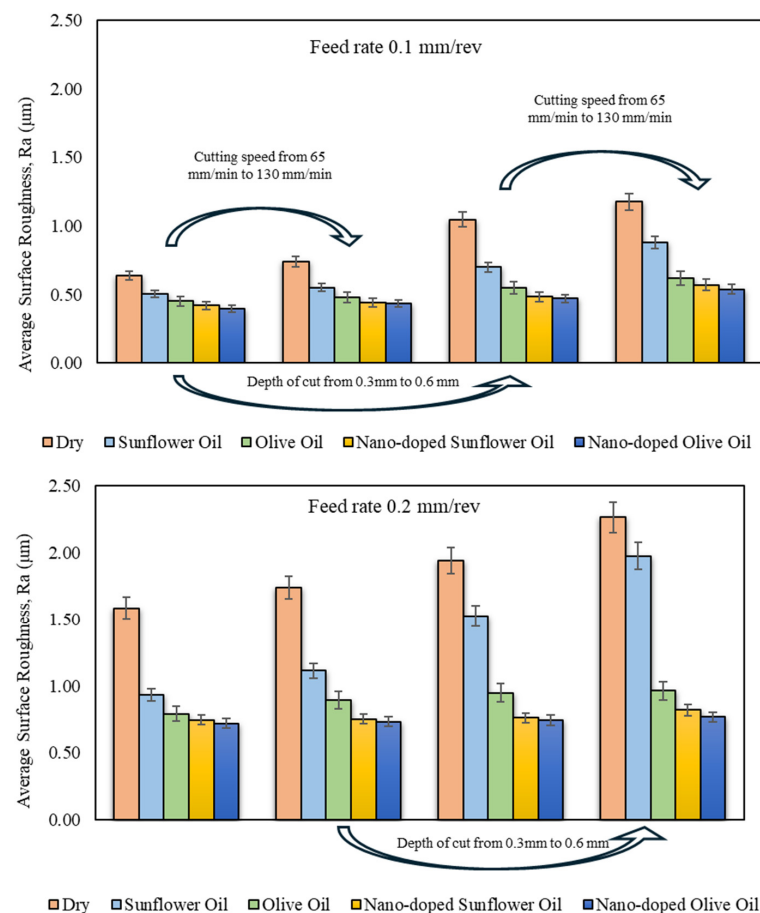


Figure 5. Average surface roughness variations consistent with sustainable environments.

This situation can be clarified by stating that the MQL method has better lubrication and cooling effects, thus reducing friction, heat, and tool wear at the tool–workpiece interface, and preventing chip adhesion, which, in turn, reduces surface roughness [45]. In addition, the fact that the nano-MQL environment has better surface quality than pure MQL can be explained by the fact that the viscosities of nanoparticle-enhanced vegetable oils are higher than pure MQL and form a better thin film layer at the tool–chip interface. Since nano-MQL(nO) has a viscosity 33% higher than nano-MQL(nS), the surface quality is improved.

According to the workpiece surface topography in Figure 6, it can be seen that the surface structure obtained in the studies carried out with MQL and nano-MQL cooling methods is smoother than that of dry machining. Compared to dry machining, MQL and nano-MQL applications help decrease the wear, assist the chips in moving away from the cutting zone, prevent adhesion, and extend tool life [46]. For this reason, in dry machining, there is a possibility of wear and breakage in the cutting tool, thus reducing surface quality, as also stated by Yılmaz et al. [47].

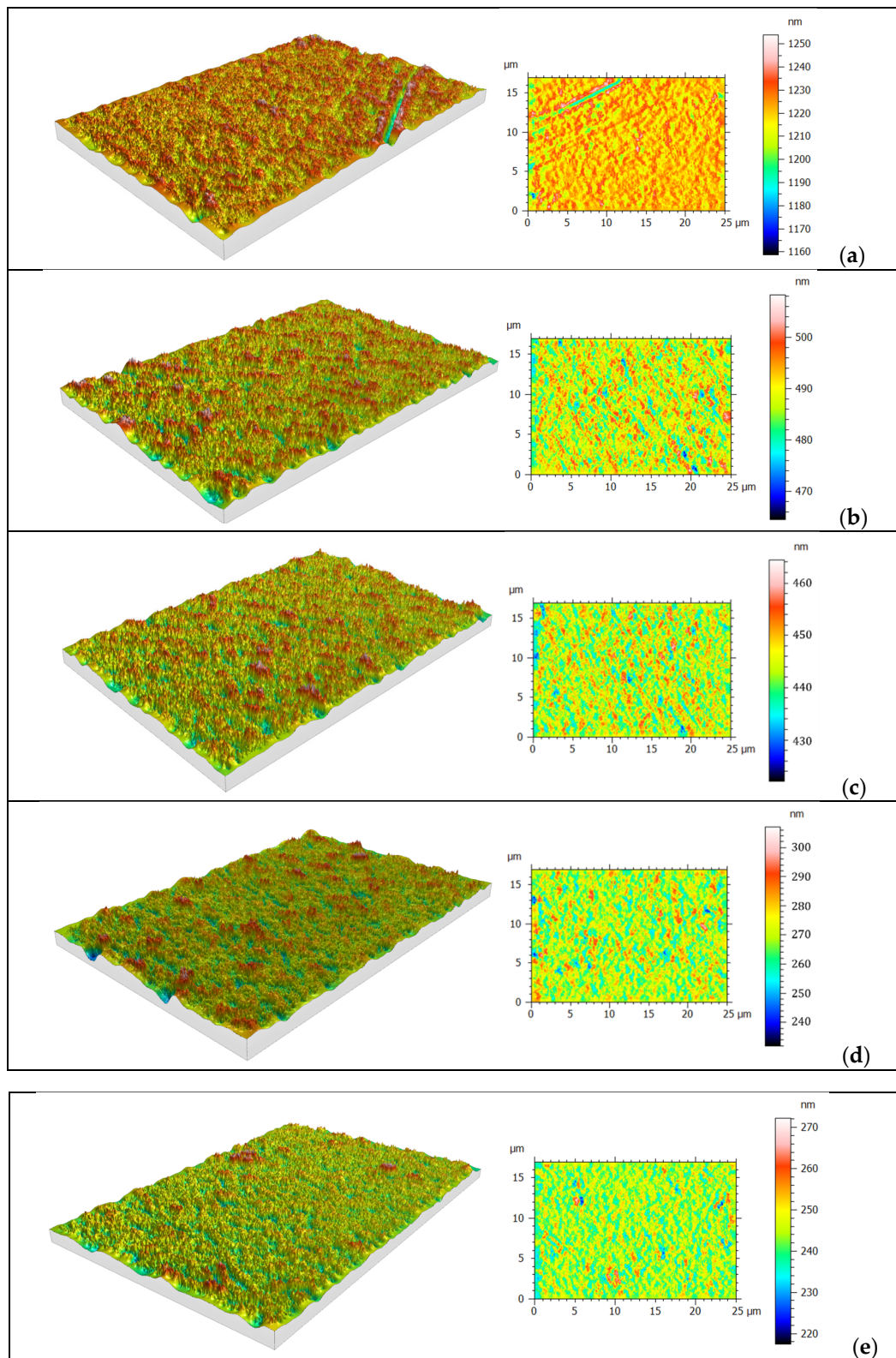


Figure 6. Surface topography of the machined surface consistent with sustainable environments, (a) Dry, (b) MQL(nS), (c) MQL(nO), (d) nano-MQL(nS), (e) nano-MQL(nO).

3.3. Cutting Force Assessment

Lubricant at the tool–workpiece interface helps decrease cutting forces and the friction coefficient, further minimizing heat generated and extending tool life. The reduction in

friction leads to lower cutting forces, resulting in lower power consumption and reducing the likelihood of tool wear [48].

The graph, drawn according to the average values obtained in each environment, is shown in Figure 7. Here, first of all, if the surface changes in the input parameters are determined regardless of the evaluation environment, it is determined that it is 63.17% according to the feed rate, 8.78% according to the cutting speed, and 28.39% according to the cutting depth. According to the cutting conditions, the averages of the dry, sunflower oil, olive oil, nano-doped sunflower oil, and nano-doped olive oil values are 65.68, 52.05, 48.90, 43.63, and 38.75, respectively, without separating the parameters. According to these values, the highest change occurred as a 41% decrease in roughness between dry and nano-MQL(nO).

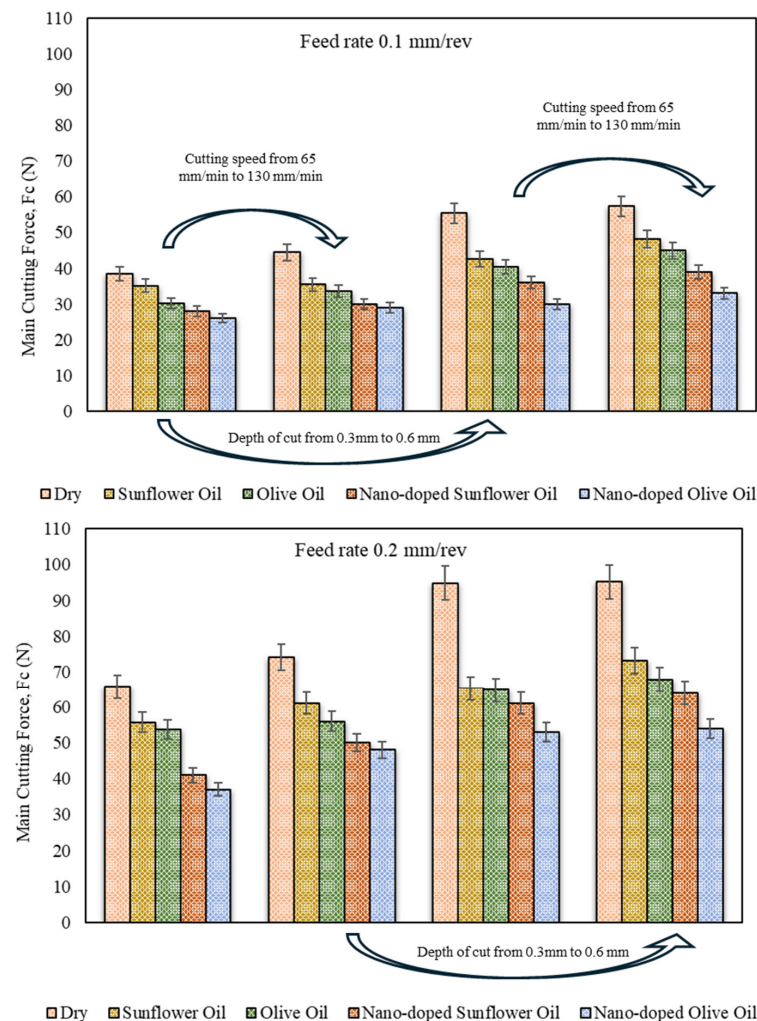


Figure 7. Cutting force variations consistent with sustainable environments.

The graph in Figure 7 shows that when the cooling technique is changed, the cutting force is lower when nano-MQL(nO), nano-MQL(nS), and pure MQL are used compared to dry machining. Comparing dry machining circumstances, the cooling fluid penetrates the interface of the cutting tool and the workpiece more effectively when using the MQL and nano-MQL technologies. The nanoparticles decrease friction and create a better oil film layer, which, in turn, reduces the cutting forces. The nano-MQL(nO) method produces less cutting force than the nano-MQL(nS) method. This is because the nano-MQL(nO) method has better lubricating properties, which allows it to penetrate the cutting area more effectively. Additionally, it has a high thermal conductivity coefficient [49], which allows it to remove the chip from the area quickly, as also specified by Yi et al. [50]. As a result, the cutting force values are lower.

3.4. Cutting Temperature Assessment

Cutting parameters, such as cutting speed, feed rate, and depth of cut, significantly affect the amount of heat generated during machining [51]. Higher cutting speeds result in higher stress rates and increased cutting temperatures due to friction effects [52]. The feed rate also affects heat generation, with higher feed rates resulting in more intense plastic deformation and higher heat at the tool–workpiece interface [53]. The choice of cutting tool material and coating is also a major factor affecting heat generation [54]. Furthermore, tool coatings serve to reduce heat through lower coefficients of friction and improved thermal resistance.

The main sources of heat generation in the machining process are [55]:

- Plastic deformation in the primary zone: Significant heat is generated due to high strain rates as the workpiece material deforms to form chips.
- Friction at the tool–chip interface: The sliding motion of the chip on the tool rake face causes frictional heating, contributing to tool wear and increased cutting temperature.
- Friction at the tool–workpiece interface: Additional heat is generated due to the friction between the tool flank and the freshly cut workpiece surface. Figure 8 shows the areas that cause heat generation during the cutting process.

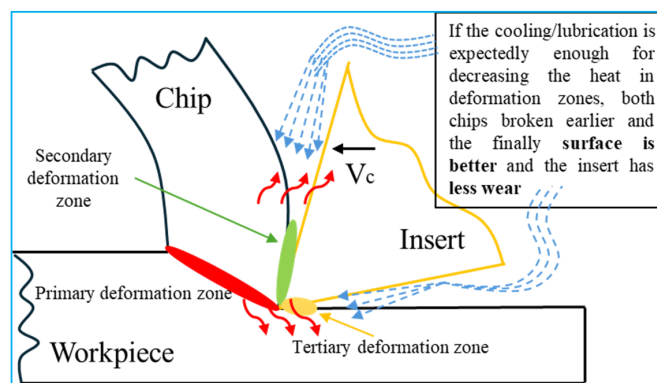


Figure 8. Heat generation and deformation zones during the cutting process.

The changes in temperature values according to the machinability input parameters were determined as a 1.2% increase according to the cutting speed, a 4.01% increase according to the feed rate, and a 2.27% increase according to the increasing depth of cut, regardless of the working environment. In this case, it can be said that the increasing parameter values cause an increase in temperature values. The percentage changes made, regardless of the parameters and according to the working environment, were determined to be a 2.61% decrease between dry and MQL(S), a 1.01% decrease between MQL(S) and MQL(O), a 2.14% decrease between olive oil and nano-doped sunflower oil, and finally a 0.5% decrease between nano-MQL(nS) and nano-MQL(nO). The biggest change was between dry and nano-MQL(nO), and this value was calculated as a 6.12% decrease.

The graphs in Figure 9 demonstrate how the temperature of the cutting zone changes with the cooling method. When analyzing these graphs, it is noted that the cutting temperature is lower when nano-MQL(nO), nano-MQL(nS), and pure MQL are applied compared to dry machining. Because the cutting fluid is supplied to the cutting zone under pressure, it penetrates more effectively into the cutting tool, chip, and workpiece interfaces, providing greater lubrication and resulting in a lower cutting temperature. Furthermore, the heat transfer coefficient, wetting, and lubricating characteristics of the cutting fluids can be improved by adding a certain quantity of SiO_2 particles that are approximately 22 nm in size. As a result, the nano-MQL(nO) and nano-MQL(nS) methods decrease the

amount of friction between the cutting tool and the workpiece, which, in turn, lowers the temperature of the cutting process. The reason the nano-MQL(nO) technique has a lower cutting temperature than the nano-MQL(nS) method is that the heat transfer coefficient is high, which means that heat is swiftly transferred from the cutting zone along with the chip, as noted by Sayuti et al. [56].

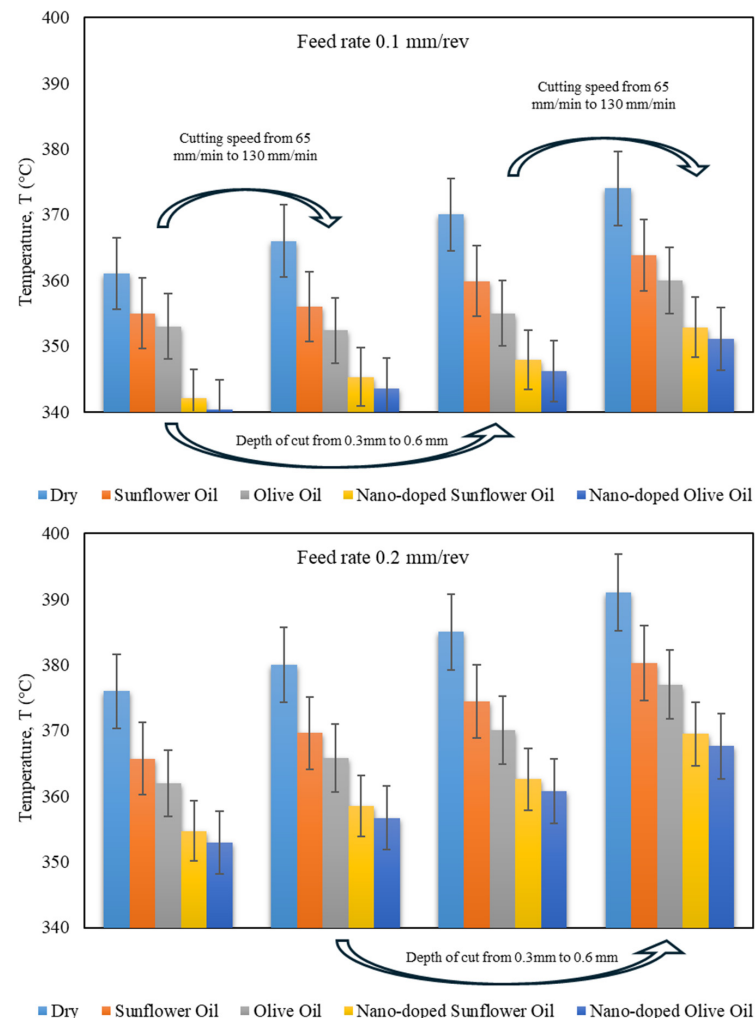


Figure 9. Cutting temperature variations consistent with sustainable environments.

3.5. Tool Wear Assessment

In machining, it is desired that the cutting tool maintain its geometry for a maximum period of time during machining. A tool whose geometry is deteriorated as a result of wear has a harder time cutting. This causes both a worse workpiece surface and sudden increases in temperature in the cutting area due to increased friction in the cutting area [57]. Sudden temperature increases trigger faster wear of the tool, like a vicious cycle [58].

Lubricants play an important role in dissipating the heat generated during machining operations [59]. The primary function of these fluids is to reduce the high temperatures generated in the cutting area by lubricating and cooling the cutting tool and the workpiece [60]. Effective use of coolants directly affects surface quality, dimensional accuracy, tool life, and overall productivity. Especially at high speeds and feeds, a significant amount of heat is generated due to friction between the cutting tool and the workpiece, as well as between the cutting tool and the chips. Coolants help to remove this heat and reduce the risk of thermal damage to the tool and the workpiece. They also help prevent edge wear on the cutting tool, which can negatively affect machining performance and surface quality [61].

When the change in tool wear with the cooling method is examined in Figure 10, it is observed that tool wear decreases when nano-MQL(nS), nano-MQL(nO), and pure MQL are applied compared to dry machining. The reason why tool wear is lower in MQL and nano-MQL methods compared to dry machining is that the cooling fluids obtained with nanoparticles and other substances in the mixture reduce the cutting zone temperature and decrease wear. At the same time, in the nano-MQL(nO) method, the cooling fluid penetrates the cutting zone better than nano-MQL(nS), reduces the cutting temperature, and results in lower tool wear values.

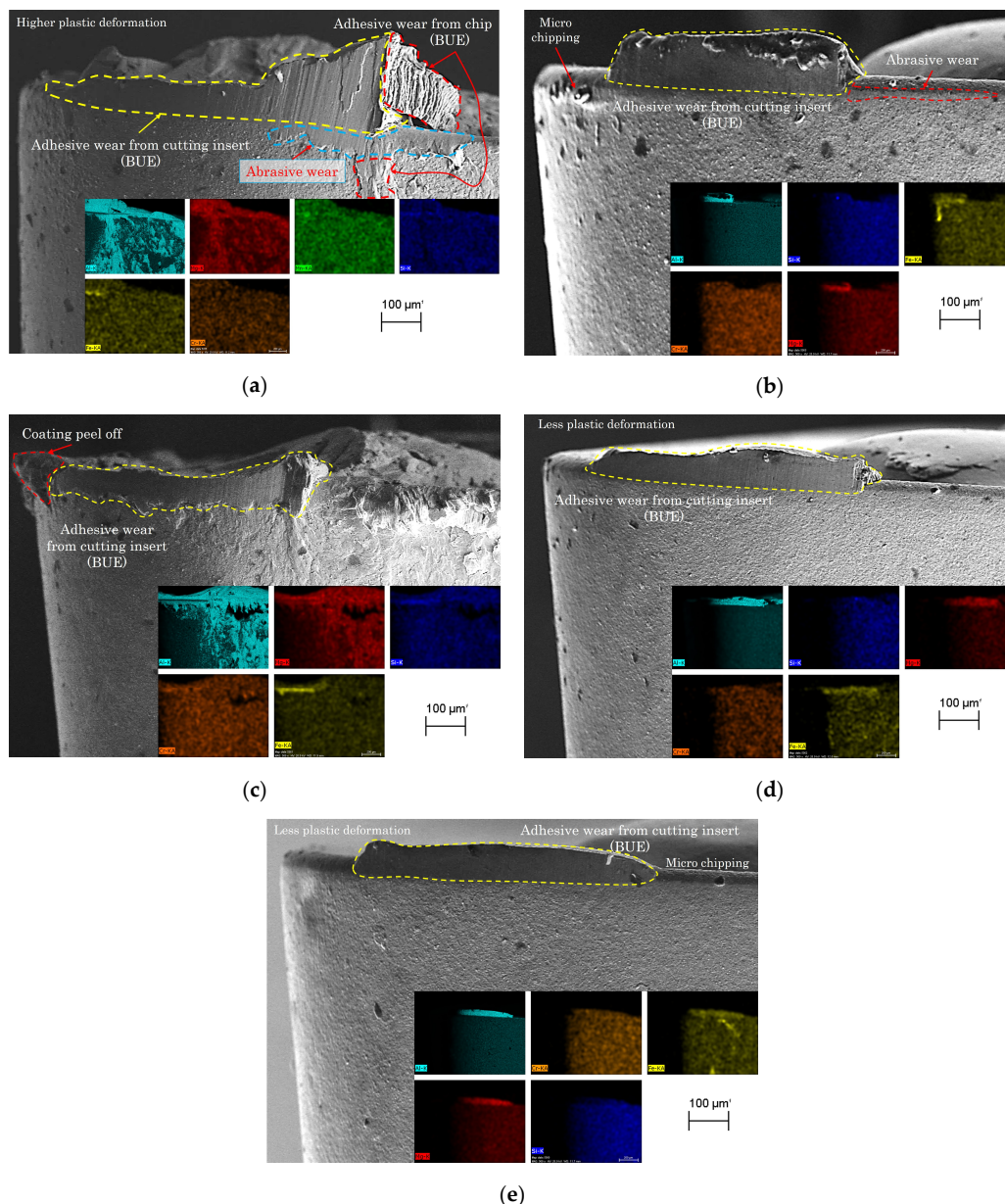


Figure 10. SEM images of cutting inserts consistent with sustainable environments, (a) Dry, (b) MQL(nS), (c) MQL(nO), (d) nano-MQL(nS), (e) nano-MQL(nO).

The reason for the wear in Figure 10 is adhesive wear that occurs as a result of the chips not being removed from the cutting zone, sticking to the cutting tool and smearing, followed by the separation of the smeared chips. The reason the adhesion in MQL(nS) and MQL(nO) is less than in dry cutting is that the chips are immediately removed from the cutting zone with pressurized oil. However, due to the softness of aluminum alloys,

even the MQL method cannot completely prevent adhesive wear. When examining nano-MQL(nS) and nano-MQL(nO), the increased heat transfer coefficient and viscosity due to nanoparticles significantly reduce adhesive wear compared to pure MQL, preventing the chip from sticking excessively, as suggested by Maruda et al. [62].

3.6. Energy Consumption

Energy is used throughout the processing steps that take place during fundamental industrial operations [63]. Machining is one of the key components of the manufacturing industry, and it has played a major role in the growth of the economy. In the machining industry, research has been carried out on a variety of aspects, including cutting tools, cooling and lubrication methods, and cutting settings [64,65]. A significant amount of work has been put into developing a method that is both cost-effective and environmentally friendly throughout these studies. As technology continues to advance, the cutting speeds of cutting instruments are also improving at a rapid pace. In the metal cutting business, the use of cooling fluids during the processing of steels can improve surface quality and extend the life of cutting tools. However, the petroleum-based cutting fluids that are most often used today might lead to serious issues that cannot be fixed, both in terms of human health and the economy [66]. This section examines how energy usage is affected by various cutting fluids and cutting settings.

The changes in energy consumption according to processing parameters were 117.56% for cutting speed, 63.08% for feed rate, and 27.20% for depth of cut (Figure 11). These values were determined as increases, and it was observed that increasing the parameters led to higher energy consumption. According to working environments, they were determined as 20.38–6.42–10.35 and 10.90% in consecutive environments, respectively. These values represent decreasing figures, and energy consumption can be reduced by changing the working environment.

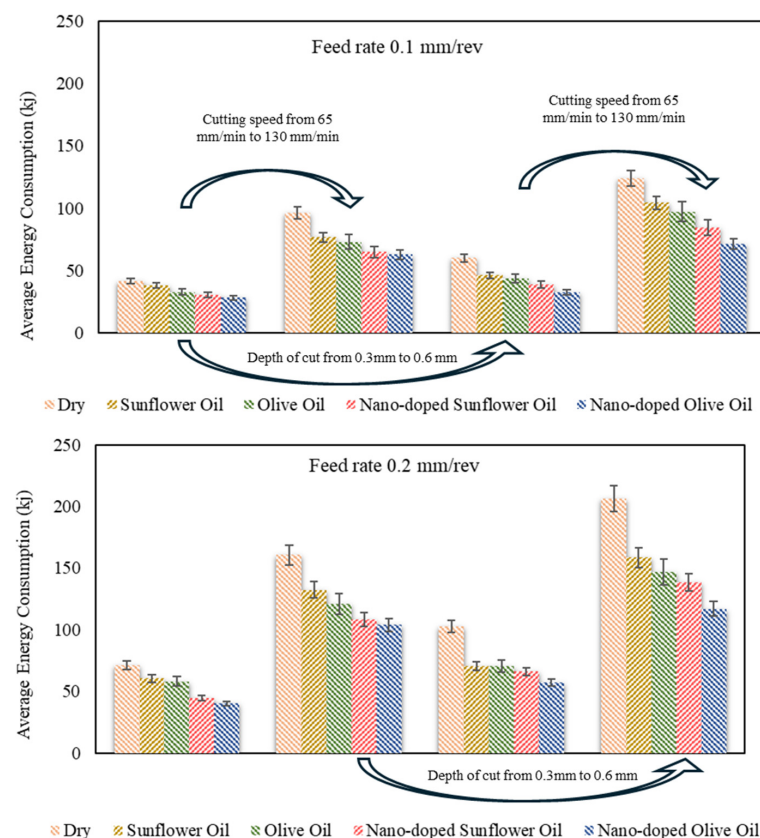


Figure 11. Average energy consumption variations consistent with sustainable environments.

The nano-additive MQL method was also used in the grinding process by Yaogang Wang et al. [67]. They used the nano Al_2O_3 additive and nano-additive-free MQL methods during the grinding of Ni-based superalloy. The specific grinding energy decreased by 34.1% in the nano Al_2O_3 additive MQL method compared to the nano-additive-free method. They determined the optimum nano-additive ratio as 2% by volume. They stated that although the oil film thickness increased in the usage above this ratio, there was no decrease in friction and tool wear.

3.7. Chip Morphology

Chip morphology in turning defines the shape, size, type, and structure of the chips formed during the machining process. Chip morphology varies depending on factors such as workpiece material, cutting tool properties, cutting parameters, and the use of coolant [68]. It is believed that it helps to remove chips from the cutting environment due to high temperatures. Chip morphology is an important parameter that directly affects the efficiency of the machining process, surface quality, and tool wear [10]. Since cutting speed and feed rate influence the cutting temperature, they can cause the formation of different chip modes. Chip morphology is directly connected to numerous machinability criteria, including superior surface quality, optimal tool wear, and vibration [69]. Furthermore, the shape, color, and size of the chips that are created provide valuable information on the performance of the machining process. It is anticipated that the chips will be more readily removed from the cutting zone with brief interruptions during the machining process, which will result in greater surface quality and cleaner machining, as also indicated by Das et al. [70].

After the chip morphologies acquired as a consequence of the tests were investigated in terms of cooling/lubrication conditions, it was found that the chips that were created in the dry environment had a structure that was more curved and serrated. The serrations were found to be far apart from one another and unevenly spaced. When dry machining conditions produce a lot of heat, the material softens, which can cause chips to develop that are curved, continuous, and irregular [71]. In addition, the serrated chip formation, supported by the BUE formation, occurs especially in the machining of ductile materials with low thermal conductivity in a dry environment, as observed [72]. Due to this formation, chip segments (lamella structure) are formed in different sizes, and thus the chip curve radius is usually shortened. Thanks to the MQL application, this formation is minimized or eliminated, providing the formation of more homogeneous lamella structures and a smooth chip form.

The use of cooling/lubricating environments instead of dry environments improved chip morphology and increased the formation of regular chip forms (Figure 12). During experiments, it is desired for chips to bend and break after reaching a certain length. It was observed that the chips obtained in pure MQLs and nano-MQL(nS)-nano-MQL(nO) were more regular and less saw-tooth than those in dry environments, especially not even seen in nano-MQL(nS)-nano-MQL(nO). It was observed that the chips obtained in nanofluid environments were smoother and closer to the desired chip form than those in MQL environments. When the cutting surfaces of the chips were examined, it was seen that the surfaces in MQL and nanofluid environments were smoother and were in accordance with the surface roughness measurements. It was observed that the surface quality of the chips in nanofluid environments was good in terms of chip surfaces, as well as in surface roughness values.

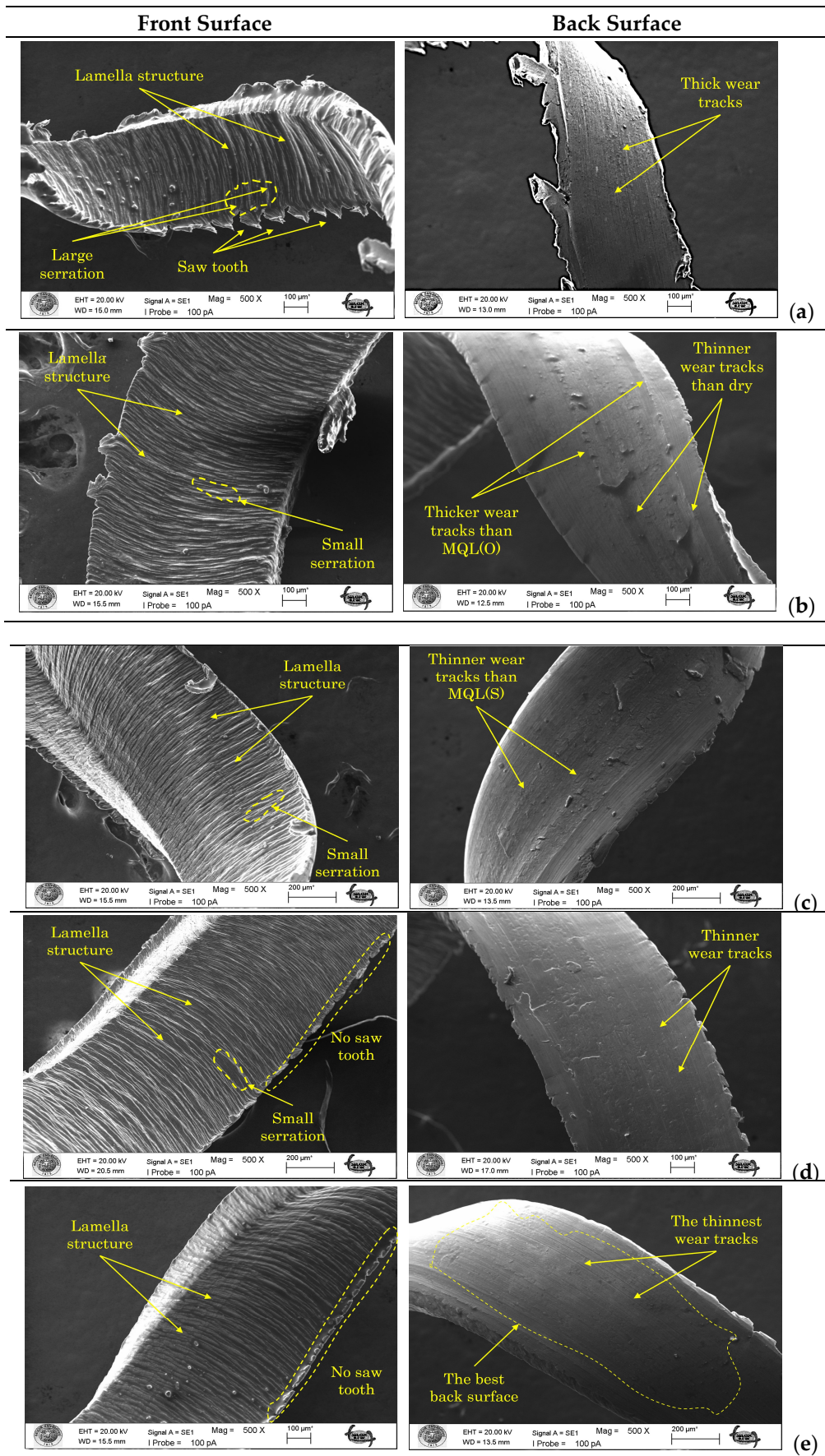


Figure 12. Chip morphology consistent with sustainable environments; (a) Dry, (b) MQL(nS), (c) MQL(nO), (d) nano-MQL(nS), (e) nano-MQL(nO).

Chips with the most serrations were produced during dry machining because of the considerable friction and plastic deformation that occurred at the chip–tool contact. It was noted that chips with larger cross-sections were produced in MQL and nanofluid settings. It is believed that this scenario arises from an increase in heat transfer from the machining zone while using MQL and nanofluid, as well as a decrease in the friction effect at the chip–tool contact. Machining under MQL and nanofluid conditions reduces the contact area between the chip and the tool. It has been observed that MQL and nanofluid applications are significant for regulating friction at the chip–tool contact. The fact that chips with a smaller bending radius are formed in a nanofluid environment is proof that the quality of lubrication is enhanced when nanofluid is used. This is also in line with the findings of earlier experiments, which showed that chips with a smaller bending radius provide improved penetration and lubrication when using MQL and nanofluid [73,74]. Furthermore, when using nanofluid, powdered oil particles assist in the removal of chips by creating a thin layer between the cutting tool and the chip surface. Since there is no cooling in dry machining, the cutting region can become quite hot and experience a great deal of friction. As a result, the chip types that are produced by dry machining have an uneven structure. Consequently, the nanofluid chilling technology may be used to create chip types that are more appropriate for machining. The quality of chip formation has improved due to the better cooling and lubricating conditions; as a result, it has been seen that this provides considerable advantages to other machinability parameters that are impacted by chips.

4. Conclusions and Future Recommendations

This study presents the sustainable machining of the Al6082 aluminum alloy under five alternative sustainable environments: dry, MQL (sunflower oil) method -MQL(S), MQL (olive oil)-MQL(O), MQL (nano-doped sunflower oil) + 1% SiO₂-nano-MQL(nS), MQL (nano-doped olive oil) + 1% SiO₂-nano-MQL(nO). The common results of the study have been summarized below.

- Pure sunflower oil has the lowest viscosity at 42.69 cS, while pure olive oil has a viscosity of 67.71 cS, representing a 59% increase. The incorporation of nano-SiO₂ into pure oils has resulted in a viscosity increase of 86.88 cS for nano-MQL(nS) and 115.62 cS for nano-MQL(nO). The viscosity of nano-MQL(nO) fluids was determined to be 33% greater than that of nano-MQL(nS) fluids.
- The average values are often seen to be 1.39, 1.02, 0.71, 0.62, and 0.60, according to the sequence of the working environment depicted in the figure. The most significant percentage change is observed in the trial conducted in a dry environment with nano-MQL (nO). The rate of change is 56.80%, and the outcomes from the study utilizing nano-MQL (nO) are superior. Overall, the cutting speed constitutes 12.8%, the feed rate 87.8%, and the cutting depth 31.14%.
- The surface variations in the input parameters are quantified as follows: 63.17% attributed to the feed rate, 8.78% to the cutting speed, and 28.39% to the cutting depth, irrespective of the assessment setting. The average values for dry, sunflower oil, olive oil, nano-doped sunflower oil, and nano-doped olive oil, based on the cutting circumstances, are 65.68, 52.05, 48.90, 43.63, and 38.75, respectively, without parameter separation. The most significant alteration seen was a 41% reduction in roughness when contrasting dry machining with nano-MQL(nO) machining.
- The temperature variations attributable to machinability variables were identified as follows: a 1.2% increase from cutting speed, a 4.01% increase from feed rate, and a 2.27% increase from increased depth of cut, irrespective of operating circumstances. In this instance, elevated parameter values result in increased temperature readings.

The percentage variations, independent of the parameters and based on the working environment, were identified as a 2.61% reduction between dry and MQL(S), a 1.01% reduction between MQL(S) and MQL(O), a 2.14% reduction between olive oil and nano-doped sunflower oil, and a final 0.5% reduction between nano-MQL(nS) and nano-MQL(nO). The most significant alteration occurred between dry and nano-MQL(nO), reflecting a decrease of 6.12%.

- Tool wear diminishes while employing nano-MQL (nS or nO) and pure MQL in contrast to dry cutting. Tool wear is reduced in MQL and nano-MQL procedures compared to dry machining, as the cooling fluids containing nanoparticles effectively lower the temperature in the cutting zone and diminish wear. In the nano-MQL(nO) approach, the cooling fluid penetrates the cutting region more efficiently than in the nano-MQL(nS) method. This decreases the cutting temperature and minimizes tool wear.
- The variations in energy consumption based on processing parameters were 117.56% for cutting speed, 63.08% for feed rate, and 27.20% for the depth of cut. The data indicated an increase, and it was seen that when the parameters elevated, energy usage correspondingly increased. The working circumstances were quantified as 20.38%, 6.42%, 10.35%, and 10.90% sequentially.
- The chips produced in pure MQLs and nano-MQL(nS)-nano-MQL(nO) exhibited greater smoothness and reduced roughness relative to those fabricated under dry circumstances, with diminished gaps between the rough edges. The chips produced in nanofluid environments exhibited greater smoothness and conformed more closely to the required shape compared to those manufactured in MQL environments. Upon examination of the cutting surfaces of the chips, it was seen that the surfaces under MQL and nanofluid conditions exhibited more smoothness, correlating with the surface roughness measurements. The chips exhibited excellent surface quality and smoothness when evaluated in nanofluid environments.
- Determining the ideal concentrations of nano-additives used is important both for the effectiveness of the lubricant and for preventing viscosity problems. In addition, how tool wear changes in long-term machining processes can provide a better understanding of the effects of different nano-additive lubricants on tool life.
- The effect of nano-lubricants on heat dissipation can be investigated more deeply using thermal imaging techniques or simulations that detail the temperature distribution in the cutting zone. In addition, a detailed life cycle analysis on the cost-effectiveness and environmental impacts of nano-additive lubricants will contribute to sustainable production processes.
- In order to contribute to sustainability, using data such as cutting force, temperature, and surface roughness can be utilized with machine learning and artificial intelligence models to determine the most appropriate cutting parameters.

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