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Grindability Evaluation of Ultrasonic Assisted Grinding of Silicon Nitride Ceramic Using Minimum Quantity Lubrication Based SiO_2 Nanofluid

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Abstract

Minimum quantity Lubrication (MQL) is a sustainable lubrication system that is famous in many machining systems. It involve the spray of an infinitesimal amount of mist-like lubricants during machining processes. The MQL system is affirmed to exhibit an excellent machining performance, and it is highly economical. The nanofluids are understood to exhibit excellent lubricity and heat evacuation capability, compared to pure oil-based MQL system. Studies have shown that the surface quality and amount of energy expended in the grinding operations can be reduced considerably due to the positive effect of these nanofluids. This work presents an experimental study on the tribological performance of SiO_2 nanofluid during grinding of Si_3N_4 ceramic. The effect different grinding modes and lubrication systems during the grinding operation was also analyzed. Different concentrations of the SiO_2 nanofluid was manufactured using canola, corn and sunflower oils. The quantitative evaluation of the grinding process was done based on the amount of grinding forces, specific grinding energy, frictional coefficient, and surface integrity. It was found that the canola oil exhibits optimal lubrication performance compared to corn oil, sunflower oil, and traditional lubrication systems. Additionally, the introduction of ultrasonic vibrations with the SiO_2 nanofluid in MQL system was found to reduce the specific grinding energy, normal grinding forces, tangential grinding forces, and surface roughness by 65%, 57%, 65%, and 18% respectively. Finally, regression analysis was used to obtain an optimum parameter combinations. The observations from this work will aid the smooth transition towards ecofriendly and sustainable machining of engineering ceramics.

Keywords Minimum quantity lubrication (MQL), Ultrasonic assisted grinding (UAG), Eco-friendly lubricants, Nanofluid, Grinding, Ceramic

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1 Introduction

Ceramic materials have become prevalent in many manufacturing processes due to their outstanding and highly desired characteristics. Popular ceramic materials often used in the manufacturing industries range from metallic oxides (i.e., Al_2O_3 & ZrO_2), carbides (SiC), and nitrides (Si_3N_4) [1]. Ceramic materials are characterized by superb corrosion, high wear/heat, and chemical resistance. However, their extensive application into different engineering fields has suffered an enormous amount of setbacks due to the exorbitant machining costs, and immense flaws encountered during the machining [2]. Therefore, it is vital to find a cheaper and effective alternative technique for processing the ceramics [3–5].

Common grinding (CG) is the most prominent method of processing the ceramics due to the high amount of material removal and achievable tolerances. Nevertheless, these materials are often very hard and brittle. Also, the quantity of energy expended during machining the ceramics is extremely high [6]. Additionally, grinding of the ceramics also involve extensive tool wears and workpiece deformations. Hence, it is imperious to conduct further research towards achieving improved efficiency in grinding of the ceramics [7, 8]. Grinding of ceramics involve profound abrasion of the material using a grinding wheel to machine these materials at pre-specified grinding depths, and feed rates with extensive cracking of the workpiece [9]. Conversely, it is reported that most of the wheel grits' are not entirely involved in material removal. The unutilized grits are mostly involved in attritions, chafing and ploughing, thereby generating unwanted heat and high grinding power [10–12]. The high amount of heat generated and increased friction encountered during grinding ceramics often results in lower grinding efficacy [13].

Scientist have reported that during the grinding operations, the application of high frequency vibrations (above 16 kHz) onto the workpiece material can produce considerable reduction to the overall energy consumed with a resultant increase of its surface quality [14]. This process which creates a 2D-oscilating trajectory of the work material during a grinding pass is referred to ultrasonic assisted grinding (UAG). Reports have shown that the UAG system improves the surface integrity by more than ~20%, and lowers the grinding energy by about ~ 21% to ~ 69% [15, 16]. Furthermore, reports have shown that UAG system reduced the tool wears, improve material removal volumes, and caused a higher number of the diamond grains to be involved in the grinding operations [17].

Machining systems require efficient lubrication in other to remove chips/debris and vacate thermal energy generated in the contact region [15]. The traditional flood lubricants are currently famous for grinding of engineering materials. However, more governmental regulations have discouraged their usage to its negative environmental impact [18]. The FL are characterized by good lubricity, better cooling and wheel cleaning ability. However, it have been reported that the waste from these coolants have green-house effects, and are extremely precarious to the machine operators. It has been reported that more than 80% of human ailments found in machinists comes from interaction with lubricants [19]. Moreover, the lubricants also account for about twenty percent of total manufacturing expenditures [20]. Hence, in other to reduce cost and simultaneously improve on the overall efficiency of ceramic grinding, it is imperious to create a substitute lubrication technique that is non-hazardous, highly efficient and cheaper [1, 9, 21].

Consequently, some researchers suggested that an environmentally pleasant alternative lubrication technique such as dry-grinding, MQL, cryogenic gas and solid lubricant be used in the grinding process [22–24]. The dry process was found to be highly deleterious to the wheel life, and workpiece surface integrity, even though it significantly reduced lubrication costs [4, 25]. Recent research reports have indicated that these setbacks can be overcome via application of nanofluid based MQL during the machining process [3, 26]. A schematic illustration of the transformation process encountered by switching from the conventional lubrication to eco-friendly MQL systems is presented in Figure 1.

The application of nanofluid based MQL involves suspending the nanoparticles in different fluids in the MQL system [27]. The nanofluid is atomized and delivered into the grinding section at a flow rate of 10–100 mL/h, and an ejection pressure of 4–6 bar [28]. Since the lubricants are sprayed in minute droplets, it was observed that the MQL process is capable of reducing the lubricant consumption during machining by a thousand times [4, 29]. Equally, the results from previous researchers have shown that the MQL system produces a corresponding increase in the overall grinding efficiency with enhanced wheel life [20]. Besides, it has been reported that compared to the CG process, there is improved tribological performance in the MQL system that causes a great decrease of the grinding energy and wears [3].

Although, the MQL system is understood to be associated with many benefits, some researchers have reported the deterioration of the surface integrity in the MQL machined components [30]. Hence, it was suggested that the combination of the MQL technique with 1D-UAG process can reduce the surface defects, and also serve as an alternative technique for machining the super hard materials [31]. Researchers have shown that the grinding efficiency could be increased by applying a lateral

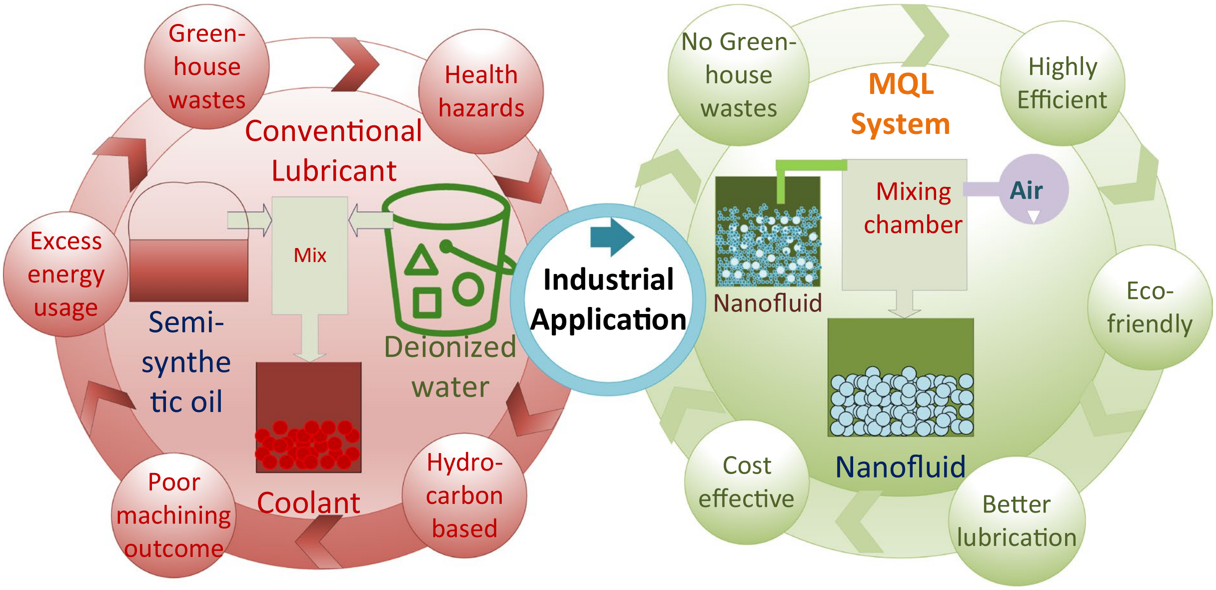


Figure 1 Process transformation from conventional lubricants to eco-friendly lubrication

ultrasonic vibration (1D-UAG) on the work piece during grinding operations [15, 32, 33]. Furthermore, it has been reported that the hybridized machining technique can successfully lead to decrease of the grinding energy for softer materials (e.g., bearing steel) [34], and also hard materials (e.g., ZrO_2, Inconel 718, Al_2O_3) [35–38].

Several nanoparticles are currently utilized in manufacturing nanofluids for the MQL process. Popular nanoparticles are SiO_2, CuO, ZnO, MoS_2, GO, Al_2O_3, diamond, and CNT [39]. In comparison with the numerous nanoparticles, the SiO_2 is low-priced, exhibits excellent thermo-physical and tribological characteristics [1, 40]. Likewise, previous research outputs have shown that the chemical composition of the base oils/fluid utilized to produce the nanofluid do exert a considerable influence on the overall lubricity of the nanofluid. The fluid viscosity, chemical composition, flash & smoke points have been reported to exert significant influence on the lubrication performance of the nanofluids [41].

The preceding review of literature have shown that by combining the nano-enhanced lubricants with the UAG system, an improved machining performance can be achieved for grinding of ceramic materials. Similarly few research works have been focused on overcoming the grindability limitations of Si_3N_4 ceramic materials. So far, there have not been any endeavor to combine the UAG and MQL system for grinding of this advanced ceramic material. Therefore, the presented hypothetical technique of combining SiO_2 based nanofluids, and the UAG system for machining the Si_3N_4 ceramic was investigated. This work involves a full experimental study of the CG and UAG performances of SiO_2 based nanofluids produced using different vegetable oils for grinding of the Si3N4 ceramic material. The grinding performances of the different machining conditions were evaluated based on the surface integrity, grinding forces, specific grinding energy and grinding force ratio. The results were analyzed using qualitatively and quantitative analysis of variance. Finally, mathematical prediction models were developed for the main response parameters of the grinding operations using regression analysis.

2 Methodology

The set-up is designed in other to exert the high frequency vibrations to the Silicon nitride workpiece. A piezo-based electro-acoustic transducer was utilized in generating the low amplitude ultrasound displacements. The high frequency oscillations were then intensified and directed into the workpiece holder with the aid of an ultrasonic klaxon and an amplifier.

The study was done using the experimental set-up presented in Figure 2. The UAG vibrations were generated using a signal generator and transmitted through a 20 kHz electro-acoustic transducer which is attached to a designed horn. The resonant frequency of the electro-acoustic transducer was obtained at 20.40 kHz. Consequently, a corresponding ultrasonic klaxon was constructed based on this frequency in accordance with the explanations of author's [42].

The process involved in the UAG system produces an oscillating trajectory in the work material about the x-y axis. As a result of the discontinuity of the surface

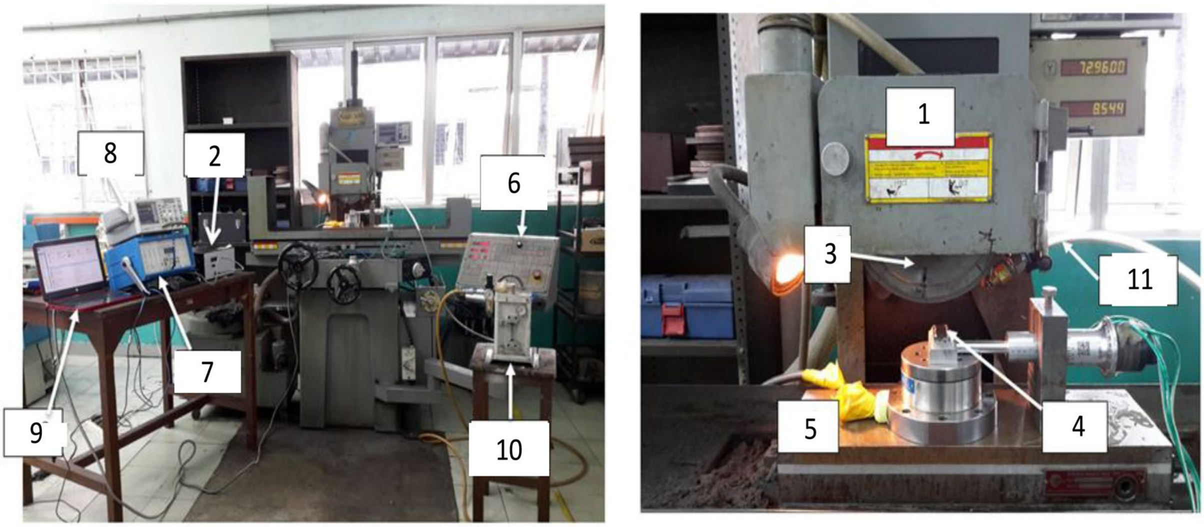


Figure 2 Set-up of grinding system: (1) Grinding wheel, (2) Ultrasonic pulse generator, (3) Work material, (4) Dynamometer, (5) Work table, (6) Machine controller, (7) Amplifier, (8) Oscilloscope, (9) Data analyzer/computer, (10) MQL equipment, (11) MQL extrusion nozzle

interaction occurring at the grinding region, the removal of unit material exhibits both brittle and elastic material removal mechanism. Previous researchers have illustrated that during grinding of ceramics materials using diamond wheels, the mechanism of removing material in ceramics involve crack propagation (See Figure 3(a)). Also, studies have shown that the grain trajectory in UAG differs from the CG method as shown in Figure 3(b).

2.1 Nanofluid: Preparation and Application

Silicon dioxide nanoparticles were reported to exhibit superior strength, high thermal stability, are cheap and easily obtainable. The mechanical properties of Silicon dioxide nanoparticle is given in Table 1). The silicon dioxide based nanofluid is reported to exhibit superior thermophysical and tribological characteristics compared to commonly used nanoparticles. Moreover, the structural design of the SiO_2 nanoparticle enables it to have enhanced chemical and tribological behaviors [1, 45].

The minimum quantity lubrication (MQL) process comprise accurately spurting a small amount of the nanofluid into a grinding area via a nozzle as illustrated in Figure 4. The MQL system combines the compressed air with atomized oil as the lubricant for the grinding operation. Nonetheless, the lubrication behavior of the nanofluid in an MQL system mainly depend on the tribo-chemical characteristic of the fluid/lubricant. The tribo-chemical behavior depend upon the individual functional groups in the base oil and thermal-chemical properties of the base oils. Peng et al. [46] showed that silicon dioxide nanofluids exhibits enhanced tribological behaviors, higher thermal conductivity, and were found to prevent burning sensations compared to other nanofluids. The SiO_2 nanoparticle is seen to successfully improve the sliding between different contacting surfaces with the help of a tribofilm layer.

The SiO_2 based nanofluid was manufacture by suspending the SiO_2 nanoparticles in the oils. Studies have shown that in addition to the tribofilms formed during the machining, the effective transport of the nanofluids into the grinding region also depend on the nozzle orientation, nozzle distance to grinding region, and the propulsion pressure of the atomized fluids.

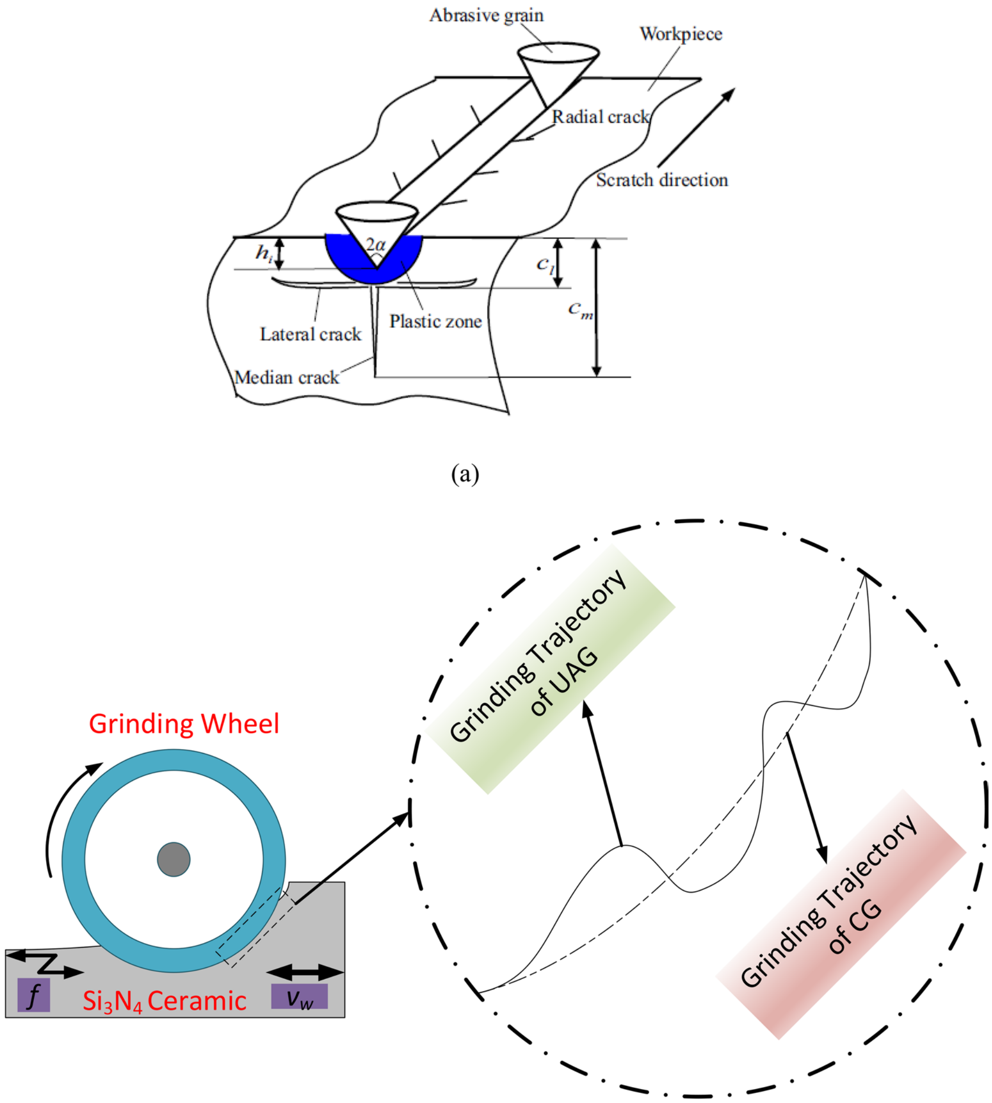
The nanofluid was manufactured by following the steps explained by authors [47]. The production of the nanofluid was done similar to steps taken by authors' (cite). As explained by the previous researchers, the overall weight content of the nanofluid was obtained according to Eq. (1):

$$\text{Nanofluid concentration (\%)} = \frac{\omega n - \omega s}{\omega b + \omega n + \omega s} \times 100\,(\%), \tag{1}$$

where:

ωn is weight of nanofluid (g), ωb is weight of base oil (g), ωs is weight of surfactant (g).

The vegetable oils utilized for this work were chosen because of their superior viscosity at higher temperatures compared to other oils. The oils also exhibit good lubricity and are biodegradable. Table 2 provides the structural arrangement of the fatty-acids present in the oils that were used as fluids for the nanofluid (i.e., canola oil, sunflower oil, and corn oil) [48].



(a)

(b)

Figure 3 Material removal mechanism during grinding: (**a**) Crack propagation method [43], (**b**) Path traced out by grits in CG and UAG methods [44]

Table 1 Physicochemical characteristics of Silicon dioxide (SiO_2)

S/N	Physical quantity	Magnitude
1	Dimension (nm)	5–15
2	Texture	Amorphous
3	Specific heat capacity (J/(g·K))	1.0
4	Heat coefficient (K^{-1})	5.6×10^{-7}
5	Maximum stable temperature (°C)	~ 1600
6	Material density (g/cm^3)	2.2
7	Dielectric constant	3.9
8	Dielectric strength	10^7
9	Heat conductivity (330 K) (W/(cm·K))	0.014

The developed nanofluid was manufactured by suspending the nanoparticle in the vegetable oils using an ultrasonic mixing Homogenizing machine. The ultrasonic homogenizer (model: Sonics/vibracell) with titanium based sonotrode mixed the nanofluid for about of 20 min (machine settings: 750 W, 20 kHz). Subsequently, the entirely mixed nanofluid was utilized in the grinding experiments.

2.2 Experiment

The experiments were done using the NI 450AV2 grinding machine. Furthermore, the wheel type, workpiece

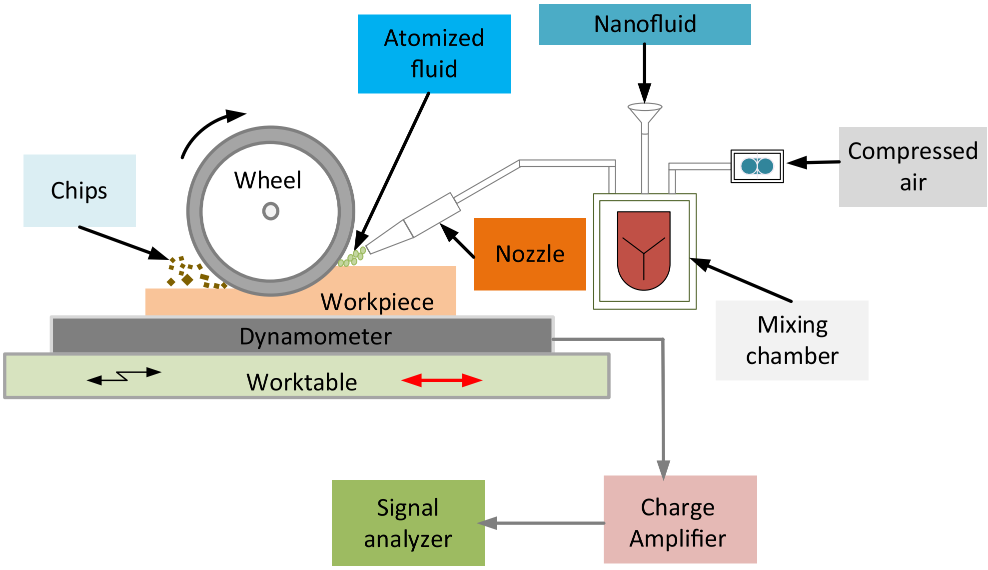


Figure 4 Illustration of MQL in grinding process

Table 2 Fatty acid contents of the vegetable oils

S/N	Composition	Sunflower (gram per 100 g of oil)	Corn (gram per 100 g of oil)	Canola (gram per 100 g of oil)
1.	Palmitic acid	5.9	10.58	4
2.	Stearic acid	4.5	1.85	1.8
3.	Oleic acid	19.5	27.33	56.1
4.	Linoleic acid	65.7	53.52	20.3
5.	Arachidic acid	–	0.43	0.7
6.	Behenic acid	–	–	0.4
7.	Lignoceric acid	–	–	0.2
8.	Palmitoleic acid	–	0.14	0.2
9.	Gadoleic acid	–	–	1.7
10.	Erucic acid	–	–	0.6
11.	Alpha linolenic acid (ALA)	–	1.16	9.3
12.	Myristic acid	–	0.24	–
13	Margaric acid	–	0.07	–

material, grinding conditions were presented therein. The selected variables and their individual levels are given in Table 3. Prior to each experimental run, the grinding wheel was properly dressed under traditional grinding conditions using the machine settings given in Table 4. Thereafter, a full factorial design of experiment was conducted with each setting and results obtained shown in Table 5.

The grinding forces in each grinding experiment was obtained using a KISTLER dynamometer (9272). The magnitude of the force were obtained in a three-channel

Table 3 Machine settings

S/N	Lubricant		Concentration of nanoparticle n_p (%)	Frequency *f* (kHz)
	Conventional lubrication	MQL oil-based Mo		
i.	Water based coolant	Canola	0	0
ii.		Corn	0.5	20
iii.		Sunflower	2	–

Table 4 Machining setting

S/N	Grinding conditions	
	Physical quantity	**Magnitude**
1	Grinding wheel speed v_s (m/s)	31.42
2	Table speed v_w (m/min)	10
3	Depth of cut a_e	10 cycles of 5 μm (50 μm)
4	Grinding wheel	Diamond-SD120M100M
5	Wheel external diameter (mm)	200
6	MQL flow rate (mL/h)	150
7	Pressure (bar)	10
8	Stand-off distance (mm)	55
9	Nozzle inclination angle (°)	30
10	Work material	Si_3N_4
11	Depth of dressing (μm)	20
12	Feed rate of dress (mm/min)	500

amplifier/Kistler charge amplifier (5019). Furthermore, the values of the workpiece roughness was obtained with a Mitutoyo Surftest SJ-210 profilometer (0.8 mm cut-off value in feed direction). A sample of the surface roughness measurements is shown in Figure 5. Moreover, the elemental composition and EDX spectroscopy of the Si_3N_4 work material are respectively provided in Table 6 and Figure 6. Likewise, the thermo-physical characteristics of the three vegetable oils are given in Table 7 [49, 50].

3 Result, Analysis and Discussion

3.1 Influence of SiO_2 Based Nanofluids

The effect of the nanofluids as lubricant of the grinding process is analyzed in this section. The results of grinding forces f_t, f_n, R_a, force ratio (μ) and specific grinding energy (U) obtained from each experimental runs. The force f_n was generally found to be higher than f_t in all the experimental runs. The force f_t which is associated with the grinding power and energy expended during grinding is highly affected by the lubrication process [43, 51, 52]. Figure 7(a) shows that with an increase nanofluid concentration from 0% to 2%, there was about 60% reduction of the force f_t and more than 40% decrease in the force f_n. Thus indicating better lubrication actions at higher nanofluid concentrations. This shows that the SiO_2 nanoparticles effectively perform the desired lubrication. At 0% concentration of the nanofluid, the grinding forces were observed to be very high, indicating absence of efficient lubrication. Also, the nanofluid MQL process with a higher amount of nanofluid concentration performed much better than the conventional coolants. This finding is in agreement with the results of authors' [33, 43, 53]. The results illustrated in Figure 7, indicate that, the canola oil has the superior performance compared to

Table 5 Design of experiment

Run no.	Oil type	Conc. (wt. %)	Ultrasonic (kHz)	f_t (N)	f_n (N)	R_a (μm)	f_t/f_n	U (J/mm^3)
1	Canola	0	0	71.60	144.23	0.5301	0.4964	134.9530
2	Canola	0	20	40.40	100.11	0.4668	0.4036	76.1469
3	Canola	0.5	0	70.22	125.22	0.4792	0.5608	132.3520
4	Canola	0.5	20	36.21	92.36	0.4404	0.3921	68.2494
5	Canola	2	0	66.11	85.51	0.4740	0.7731	124.6060
6	Canola	2	20	29.41	65.08	0.4592	0.4519	55.4326
7	Corn	0	0	73.80	139.89	0.5328	0.5276	139.1000
8	Corn	0	20	41.01	105.01	0.4729	0.3904	77.2777
9	Corn	0.5	0	70.80	126.31	0.4863	0.5605	133.4450
10	Corn	0.5	20	38.20	94.06	0.4402	0.4061	72.0002
11	Corn	2	0	65.02	88.27	0.4752	0.7366	122.5510
12	Corn	2	20	34.40	70.31	0.4627	0.4893	64.8379
13	Sunflower	0	0	73.80	145.25	0.5366	0.5081	139.1000
14	Sunflower	0	20	42.70	102.19	0.4784	0.4179	80.4819
15	Sunflower	0.5	0	71.81	126.13	0.4842	0.5693	135.3490
16	Sunflower	0.5	20	40.63	94.04	0.4512	0.4321	76.5804
17	Sunflower	2	0	68.61	91.20	0.4772	0.7523	129.318
18	Sunflower	2	20	34.80	74.04	0.4690	0.4700	65.5918
19	Flood	–	0	84.00	150.00	0.5614	0.5600	158.3251
20	Flood	–	20	45.80	105.14	0.4566	0.4356	86.3249

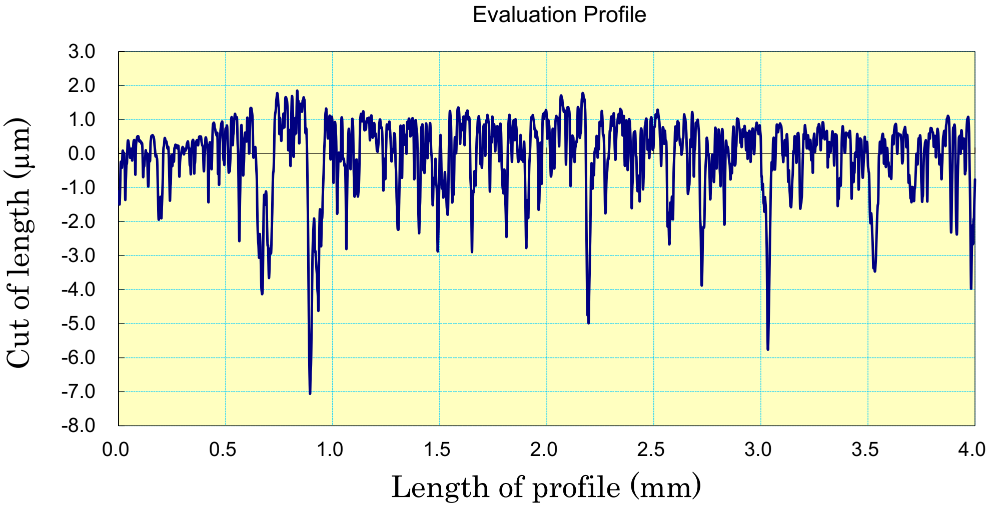


Figure 5 Sample of measurement surface roughness

Table 6 Composition of work material

Element	wt.%	at.%
C_K	07.21	10.04
N_K	41.63	49.69
O_K	21.70	22.67
Al_K	02.58	01.60
Si_K	26.89	16.01
Matrix	Correction	ZAF

corn and sunflower oils. The canola oil formed the lowest grinding force, whilst the sunflower oil produced the largest grinding force. The corn oil based nanofluid can be seen to have produce similar machining outcomes with the canola oil. The result indicates an effective machining outcomes from the MQL based silicon dioxide nanofluid. Moreover, a small layer of spread nanofluid was observed to form tribofilms, through the continuous crushing and bursting of the oil filled nanoparticles. This tribofilm layer was the cause of improved lubricity witnessed during grinding with the nanofluid MQL. Similar finding was substantiated by authors [43, 45, 54].

Additionally, it was found that the two percent nanofluid produced lower grinding forces than the 0% & 0.5% nanofluid concentration, and also the flood coolant. Moreover, the experiments performed with flood coolants were noted to have lesser amount of adhered debris, indicating efficient debris evacuation/flushing. Conversely, the work materials that were ground with the pure vegetable oils were observed to contain enormous surface and sub-surface deformations. This show that the pure oil on its own have reduced lubricity and thermochemical behavior, but upon suspension of the silicon dioxide nanoparticles, the surface quality of the machined components was found to substantially improve. It was also observed that the canola oils exhibit a higher lower viscosity at high temperatures compared to the sunflower and corn oils.

The results of measured surface roughness (R_a) in the grinding direction is given in Figure 7(c). It can be seen that the pure base oils produced the highest roughness values in the MQL condition. The lateral oscillations caused some deterioration of the surface quality due to absence of the positive tribological influence of the nanofluid. However, with increase in the concentration of the nanofluids, the surface roughness was observed to be decreased and overall surface integrity improved.

Considering the complete effect of the grinding variables of the on the frictional coefficient, the force ratio can be used to evaluate the coefficient of friction. Eq. (2) gives the mathematical representation of the grinding force ratio in any grinding operation.

$$G = \frac{f_t}{f_n}. \tag{2}$$

Kalita et al. [55] explained that a smaller value of G indicates effective lubrication actions around the contact region. The measured frictional coefficient under different grinding conditions are provided in Figure 7(d). The results obtained showed that the MQL system have lower values of force ratio as compared to the flood coolants. However, it can be seen that the frictional coefficients tend to increase with higher amount of nanofluid concentration.

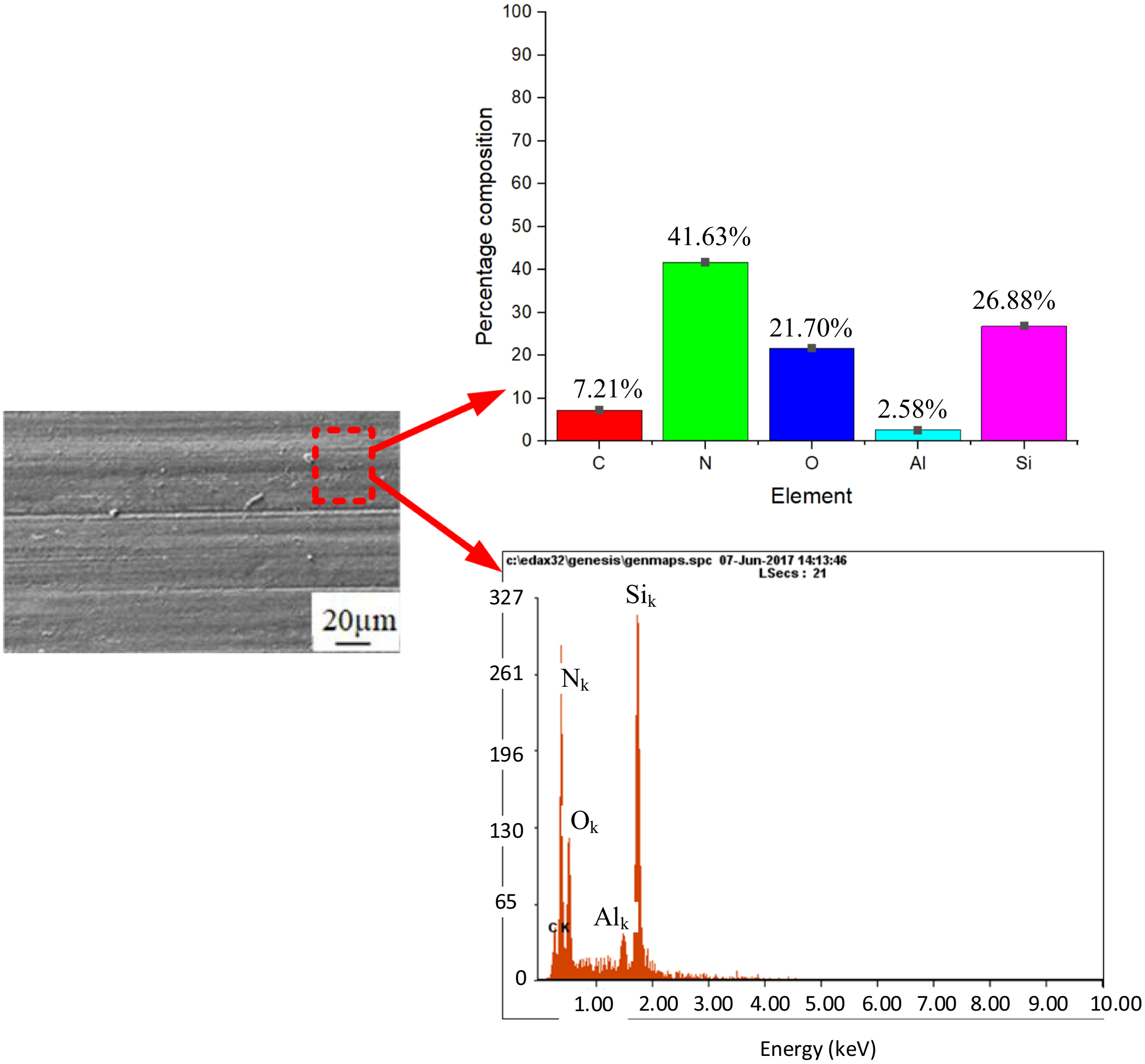


Figure 6 Elemental analysis of work material using an EDX

Table 7 Thermo-physical properties of vegetable oils

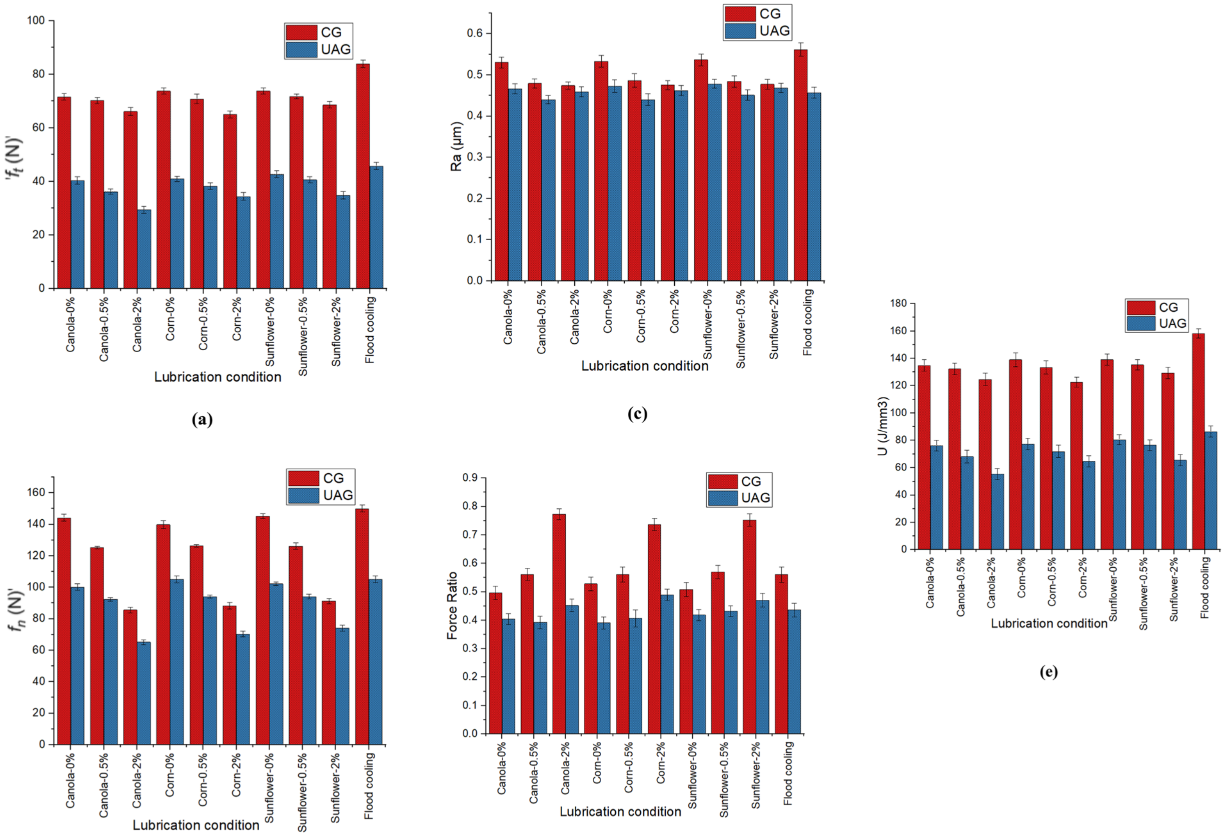
S/N	Oil type	Density at 30 °C (g/cm^3)	Smoke point (°C)	Flash point (°C)	Viscosity at 35 °C (mPa·s)
1	Corn oil	0.9185	232	254	37.92
2	Sunflower	0.9167	232	274	41.55
3	Canola	0.9183	225	280	42.49

Additionally, the specific grinding energy is the energy needed to take out a given amount of material in a grinding process. The specific grinding energy (U) measured in (J/mm^3) is obtained using Eq. (3) [33]:

$$U = \frac{v_s \times f_t}{a_e \times v_w \times b}, \tag{3}$$

where v_s is tool speed (m/s), f_t is tangent force (N), b is width (mm), v_w is feed rate (m/s), a_e is grinding depth (μm).

Generally, the specific grinding energy is used to indicate the overall system efficiency in a grinding operation. It have been explained that a smaller amount of the specific grinding energy in a grinding process, indicates a highly efficient grinding process [55]. From the mathematical relationship in Eq. (3), it can be seen that a lower value of the f_t and broader ground width will produce smaller value of U. The overall effect of the ultrasonic assisted grinding can be



(a) (c) (e) (b) (d)

Figure 7 Results from grinding experiments: (**a**) Tangent force (f_t), (**b**) Normal force (f_n), (**c**) Roughness (*Ra*), (**d**) Grinding force ratio (f_t/f_n), (**e**) Grinding energy *U*

used to effectively reduce the overall energy consumed in a grinding process. The reason for this is because the ultrasonic vibration was capable of reducing the tangential grinding force considerably, and simultaneously increasing the grinding forces as illustrated in Figure 7.

The canola oil was found to expend lower specific grinding energy compared to corn and sunflower oils. This performance can be attributed to the overall effective tribology of the canola oil, due to the existence of various fatty acid functional groups in its composition. The concentration of nanoparticle can be seen to also affect the grinding energy and frictional coefficient. In the case of specific grinding energy, it can be seen that a higher nanofluid concentration reduced the energy expended significantly. However, an opposite trend was observed regarding the frictional coefficient. In general, it was found that the ultrasonic vibration has the most effect on the grinding energy and force ratio, in comparison to the oil types and nanofluid.

3.2 Influence of Ultrasonic Assisted Vibrations

The effect of applying high frequency ultrasonic vibrations of 20 kHz on the workpiece material was also investigated. The results obtained from the 1D-UAG experiments were compared. From Figure 7(a), (b)**,** the results of the grinding forces f_t and f_n were respectively presented. It can be seen that the UAG experiments have lower grinding forces compared to the CG experiments. It was also found that during the 1D-UAG process, the normal force obtained for the different MQL lubricants was reduced by between ~ 38% to ~ 58% as compared to flood cooling lubrication. The 2% nanofluid concentration was found to effect the highest reduction on the normal grinding forces. From the results obtained, it can be seen that when the MQL nanofluid and UAG process were hybridized into the grinding system, the overall results of the normal and tangential grinding forces were significantly decreased. This desired grinding performance can be attributed to the intermittent separations occurring at the grinding zone due to the high frequency oscillations, and effective lubricity of the MQL nanofluids.

Similarly, the results the tangential force obtained in the UAG process were found to be lower by ~ 49% to ~ 70% as compared to the CG. Generally, the ultrasonication helps to significantly lower the grinding forces in grinding operations. The resultant reduction of the grinding forces due to ultrasonication can be attributed to better penetration of the diamond grits into the work material as a result of the complex material removal mechanism existing during the 1D ultrasonic grinding process. Also, the self-sharpening phenomenon explained by Molaie et al. [33] is a major source of this reduction in the grinding forces. It was explained that the self-sharpening process also extends the tool life. The rate of reduction of the grinding forces was found to be when the concentration of MQL nanofluids were high.

Among the vegetable oils used in the study, the canola and corn oil were observed to proffer similar improvement in workpiece surface quality. The samples machined using the CG systems were found to have poor surface quality, with intense cracks, pores, and ridges. By and large, the lubricant with higher concentration of nanofluid combined with ultrasonic assistance was found to have the best performance during the grinding operations.

Compared with the conventional flood cooling lubrication system, the canola oil was found to have the highest rate of reduction of the grinding forces amongst the vegetable oils used in this work. The performance of the oils were found to improve significantly with addition of the SiO_2 nanoparticles. The tangential grinding force in samples ground with UAG and MQL process was found to be lowered by about 49%–69% compared to the flood cooled operations. Similarly, with the hybridization of the MQL nanofluids and UAG process, there was about 10%–37% reductions in surface roughness. The viscosity and composition of oils play a significant role in their tribological performance during the grinding operations.

3.3 Influence of Vegetable Oils on Grinding Performance

The tribological behaviour of each vegetable oils differs considering the differences in their chemical compositions. With increasing calls for discarding the use of synthetic and mineral based oils as lubricants in machining processes, the performance of vegetable oils need to be enhanced significantly to serve as alternative replacements of the traditional lubricants. Previous works have shown that due to high amount of energy expended in grinding operations, the dry grinding is not a viable alternative to the non-environmental friendly oils. Hence, based on results of the reports from previous works, the preeminent and high performing vegetable oils such as corn oil, canola and sunflower oils were chosen in this investigation. The pure oils (0% concentration) were found to exhibit relatively poor lubrication and tribological performances. This is evident from the several types of surface defects observed on the workpiece, in addition to high rate of wheel wear when pure oils were used in the MQL system. Also, intense chip weld and macro-fractures were observed in the samples ground with pure vegetable oil in the MQL system.

According to the results obtained for the grinding performances of each vegetable oil, it could be seen that the canola oil had superior tribological properties than the corn and sunflower oils. The overall hierarchical tribology of the oils is sunflower oil< corn oil < canola oil. Due to the similarities in molecular structures of the corn and canola oils, it can be confirmed that the molecular composition significantly affects the tribological behaviour of the oils. Furthermore, the higher tribological characteristics of the canola oil can be attributed to its superior opposition to oxidations especially at elevated temperatures. The double bond of carbon in the structure of these vegetable oils (illustrated in Figure 8) can be seen to be a formidable point of attack for the oxygen atoms, thereby initializing the oxidation process. Furthermore, the corn oil contains about 59.7% polyunsaturated fatty acid (PUFA) and 24% monounsaturated fatty acid

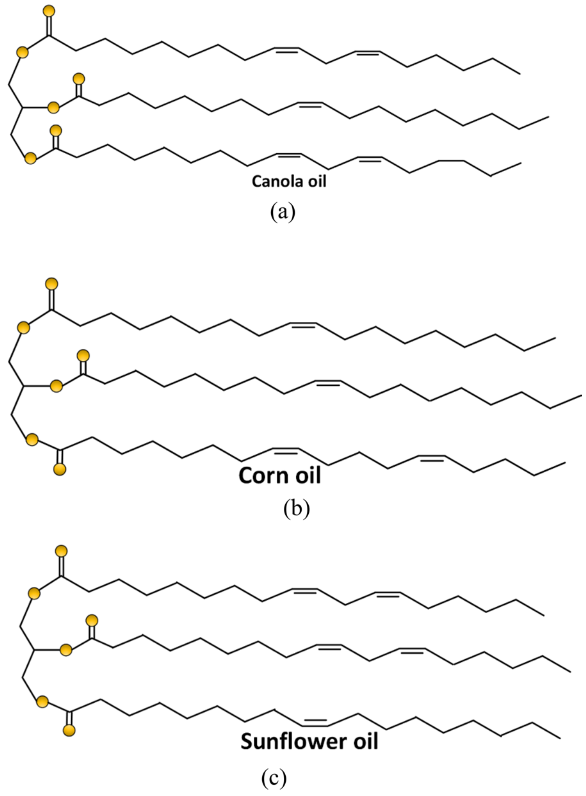


Figure 8 Molecular structure of vegetable oils: (**a**) Canola oil, (**b**) Corn oil, (**c**) Sunflower oil

(MUFA) total fatty acid content. Similarly, the sunflower oil contains about 66% polyunsaturated fatty acid (PUFA) and 23% monounsaturated fatty acid (MUFA) total fatty acid content. However, the canola oil can be seen to contain only 28.1% of the PUFA and 63.3% of the MUFA. Hence, the superior tribological performance of the canola oil can be attributed to its higher resistance to oxidation compared to other vegetable oils [56]. This finding is similar to the results obtained by Singh et al. [57]. The mono-unsaturated and poly-unsaturated vegetable oils are observed to contain single and multiple C-C double bonds respectively. A thin tribofilm was observed to be formed on the surface of the workpiece material. Besides, the length of the carbon chain in the molecular structure of the oil also affect the energy adsorbed by this tribofilm. It can be seen that the higher length of carbon chain in the oil, the more will be energy adsorption by the oil. Hence, any vegetable oil that contains a higher amount of the polyunsaturated fatty acid molecules will have a higher affinity to oxidation reactions.

Likewise, studies have also shown that the thermophysical properties of a vegetable oil have significant effect on the tribological behaviour of that oil. A higher specific capacity and viscosity implies better tribological characteristics of the selected vegetable oil. Hence, this study illustrated how the molecular composition and structural characteristics of each vegetable oil can have significant effect on the tribological behaviour of the nanofluids produced from it. Figure 9 shows an illustration of the hierarchy of the tribological characteristics of the base oil according to the composition and molecular texture of the oils.

Additionally, Figure 10 shows the surface images of the best and worst surface quality for each lubrication condition. The images were obtained using a scanning electron microscopes with 500× magnification. In the MQL process, the best surface quality was obtained when the grinding operation was performed with higher nanofluid concentration and UAG system altogether. Moreover, the 0% nanofluid concentration under CG systems was found to have the poorest surface quality.

Most of the ground samples were characterized by different categories of furrows, grooves, debris adherance and microfractures. Since the main cause of poor surface quality is the poor lubrication, excessive heat and wear out of the diamond grits, it is believed that effective lubrication can reduce these setbacks. As seen in Figure 10, the samples with high surface roughness exhibit tremendous rubbing lines, uneven furrows, microstructural damages and deep grooves. These defects are majorly due to the poor lubrication phenomenon, which lead to excessive microplowing and chipping actions. Also, the UAG and nanofluid

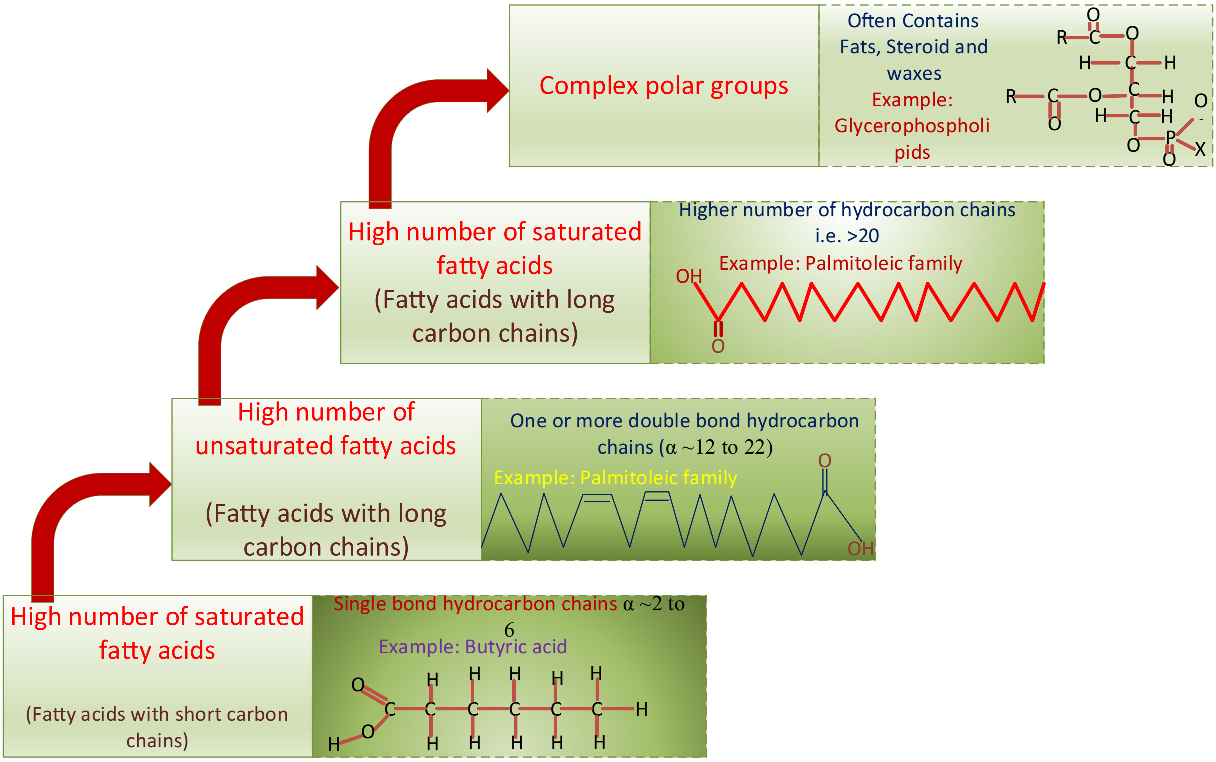


Figure 9 Effect of molecular structure and composition on Lubrication performance

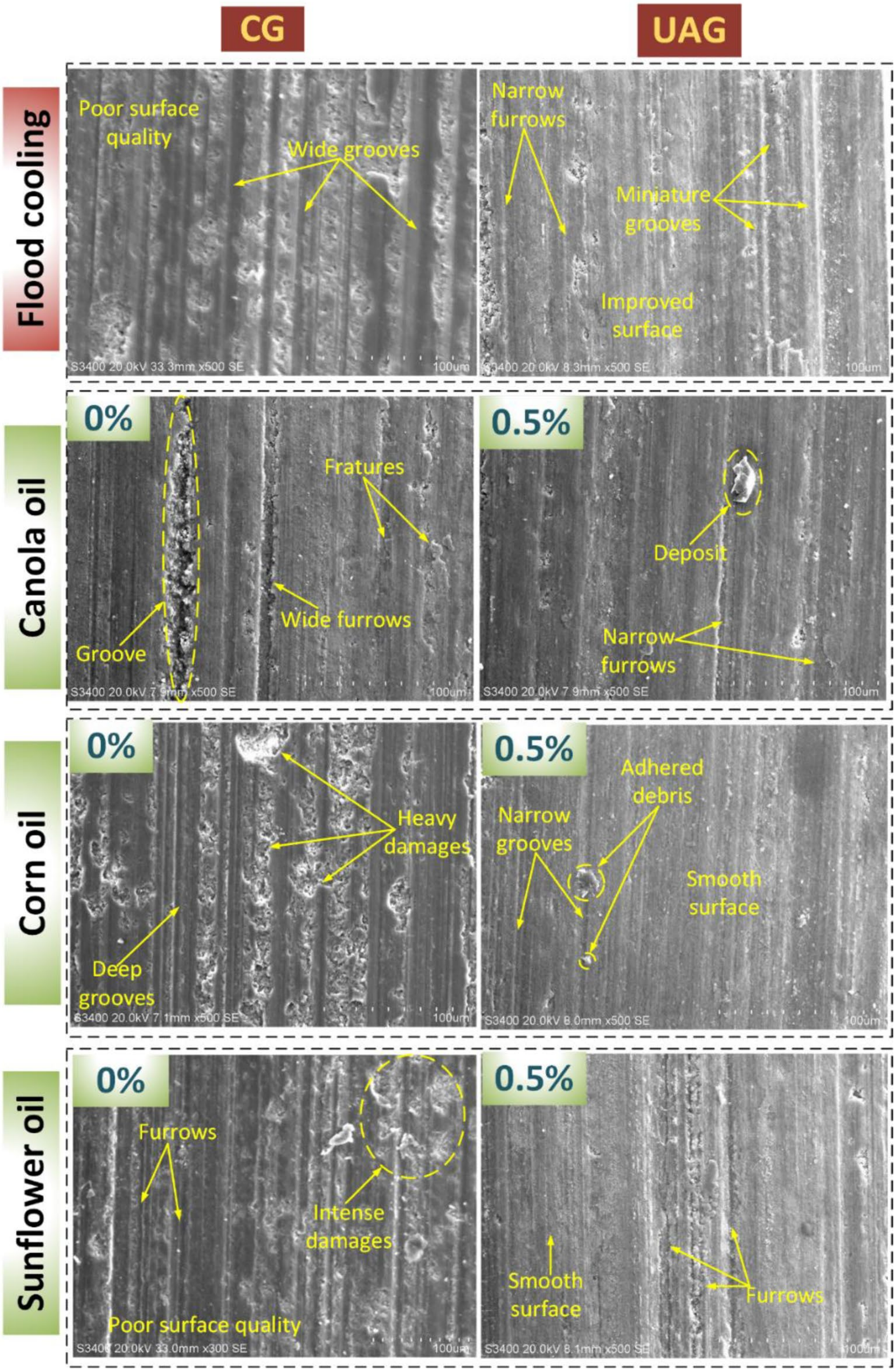


Figure 10 SEM images of ground samples for the worst and best surface quaility under different lubricating conditions

MQL samples showed lesser debris adherance compared to CG components. Also, smaller furrows were noticed in the nanofluid MQL samples compared to those ground with conventional flood cooling. Additionally, the samples ground with the 1D-UAG system appear smoother with minimal surface defects. It is evident that during grinding with the 1D-UAG system, the grinding wheel maintains a higher sharpness of the diamond grits even after a number of grinding passes. Furthermore, the SEM images illustrate how the tribological behavior of the vegetable oils were immensely altered by the SiO_2 nanoparticles. At 0% nanofluid concentration, the pure canola oil under CG process produced a surface roughness of 0.4972 μm, whereas pure corn oil under CG process produced a surface roughness of 0.5271 μm. However, under UAG process and the additon of SiO_2 nanoparticle into both oils at 0.5% concentration, the surface roughness achieved under this experimental condition by the canola and corn oil was 0.4402 μm and 0.4404 μm respectively.

3.4 ANOVA Analysis

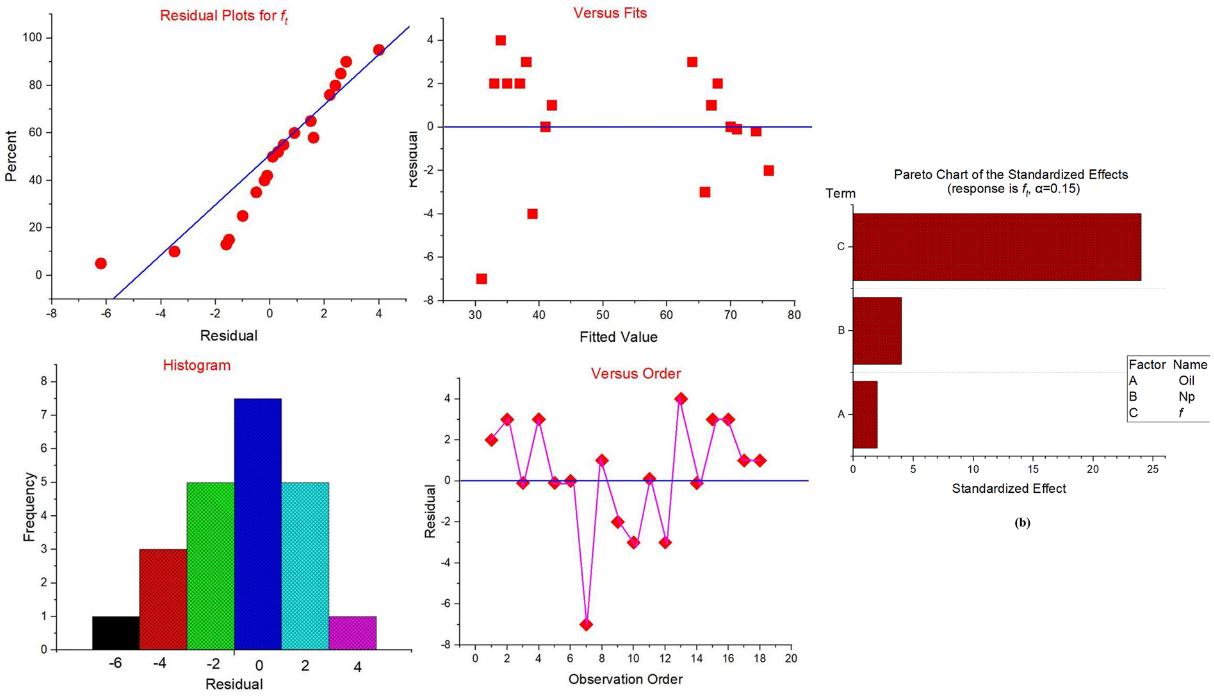
The experimental results were then analysed using the full factorial analysis of variance. The analysis was conducted using the results of the MQL process only, in other to statistically ascertain the effect of each of the 1D-UAG, and MQL process parameters. The analysis was conducted on Minitab software with a single replicate full factorial design (18 runs). The Residual and Pareto plots were used to indicate the level of significance of each variable on the corresponding output response. From Table 8, it can be seen that the effect of the type of vegetable oil used has less impact on the tangential force compared to the other variables, i.e., nanofluid concentration and ultrasonic vibrations. Figure 11(a) shows the residual plots of the results obtained for the tangential grinding force f_t. The normal plot of the developed model showed that the points are close to the straight line, with only one unusual observation away from the line, an abnormal observation found in experimental run 18. The histogram of residuals also shows a rationally normal distribution of the residuals. The Pareto chart of the analysed result is shown in Figure 11(b), and it indicates that all the factors are at least 90% significant in the developed model. It can also be seen that the ultrasonic vibration exhibits the highest influence on the tangential grinding force, followed by the nanofluid concentration and then the type of oil utilized. Furthermore, the mains effect of the variables are illustrated in Figure 11(c). The mains effect shows that applying the MQL nanofluid with ultrasonic vibration decreases the tangential grinding force, f_t. Moreover, the canola oil exhibits the lowest values of f_t compared to the corn and sunflower oils. The optimal settings obtained from the developed model shows that the minimum value of tangential grinding force can be obtained when canola oil was used, and a higher nanofluid concentration of 2 wt.% with the 1D-UAG. The overall model summary indicates that the hierarchy of influence of the grinding process variables on the tangential grinding force is $f > n_p > Mo$. The analysis indicate that the variation in response can be explained by the model with accuracy of about 97.30% (see Table 9). Finally, the regression model for the tangential grinding force is presented in Eq. (4):

$$\begin{aligned} f_t = {} & 53.397 - \{2.067 * \mathrm{Mo1}\} + \{0.473 * \mathrm{Mo2}\} \\ & + \{1.594 * \mathrm{Mo3}\} + \left\{3.819 * \mathrm{n_p1}\right\} \\ & + \left\{0.281\ \mathrm{n_p2}\right\} - \left\{4.101 * \mathrm{n_p3}\right\} \\ & + \left\{16.799 * f1\right\} - \left\{16.799 * f2\right\} \end{aligned} \tag{4}$$

Similar to the result obtained for f_t, Table 10 shows that the oil type has less significance to the corresponding measured normal grinding force, f_n. As seen, the P-value of the oil type is 0.081, which is greater than 0.05, clearly indicating the effect of this variable is not conspicuous as compared to the resultant effects observed in the other factors, i.e., nanofluid concentration, ultrasonication and their interactions. The residual plots of the analysis for the normal grinding force is shown in Figure 12(a). The result presented by the normal probability plot and residuals' histogram indicates

Table 8 Analysis of variance of f_t

S/N	Source	DF	Adj SS	Adj MS	F-Value	P-Value
1	Model	5	0.006998	0.001400	172.81	<0.0001
2	Linear	5	0.006998	0.001400	172.81	<0.0001
4	Oil type	2	0.000056	0.000028	3.45	0.066
5	Concentration	2	0.000302	0.000151	18.64	<0.0001
6	Ultrasonic	1	0.006640	0.006640	819.88	<0.0001
7	Error	12	0.000097	0.000008		
8	Total	17	0.007095			



(b)

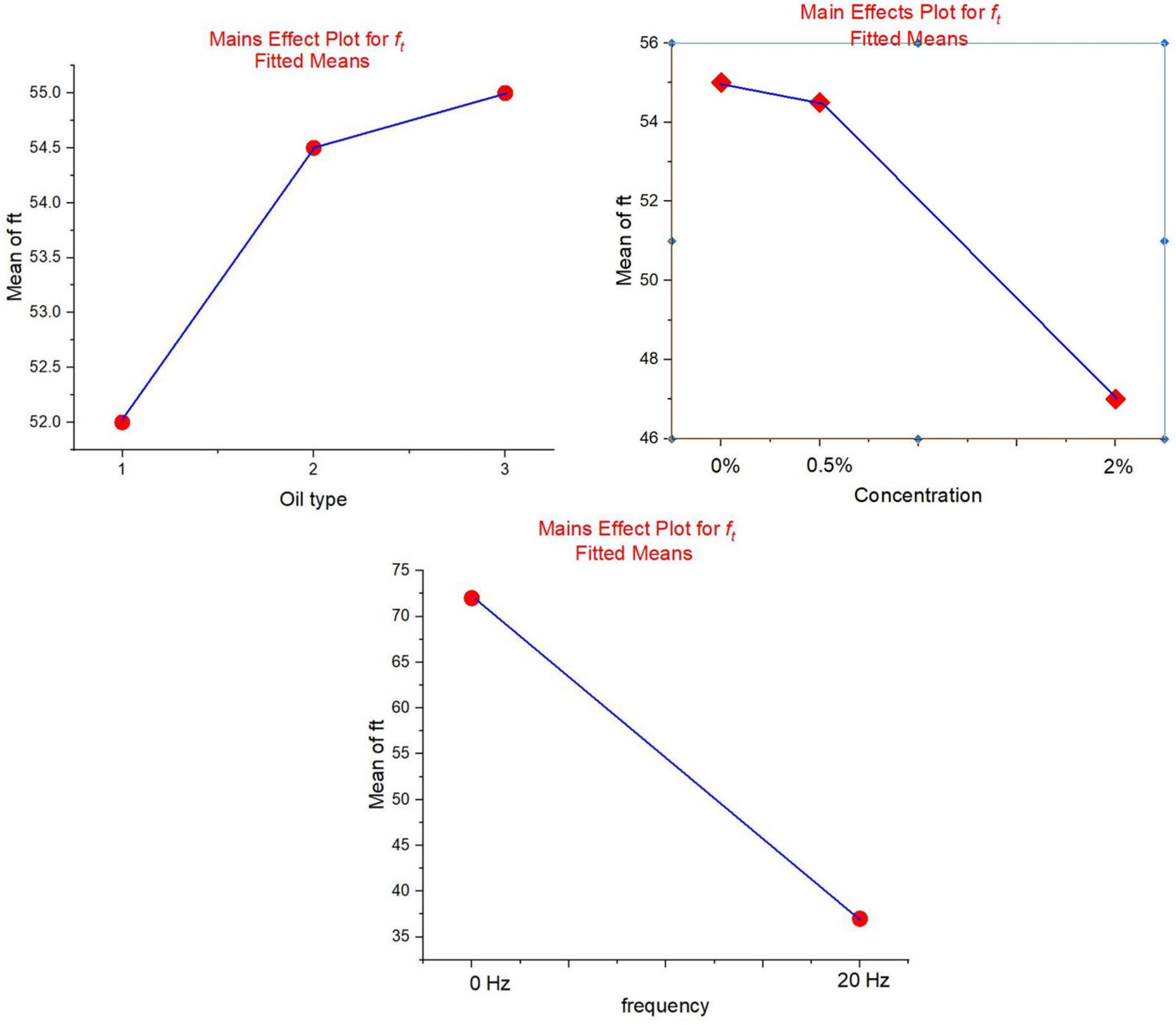
(a)

Figure 11 (**a**) Residual plots for f_t, (**b**) Pareto chart of f_t, (**c**) Mains effect plots for f_t

that the result were normally distributed along the line. Similarly, the Pareto chart of the developed model show that the input variables have at least 99% significance, with the nanofluid concentration having the highest influence on the values of f_n (see Figure 12(b)). The overall prediction accuracy of the model was also found to be 99.16% (see Table 11). The mains effect shown in Figure 12(c) illustrates the effect of each process parameter on the normal grinding force. It can be seen in Figure 12(c) that the nanofluid concentration have the highest effect exhibiting the steepest decline from 0% value to 2% nanofluid concentrations. The result also show that higher amount of nanofluid concentration and simultaneously using the 1D-UAG vibrations produced lower values of the f_n. In addition, the canola oil was found to have the lower values of f_n as compared to corn and sunflower oils. Finally, the optimal parameter setting for the lowest values of f_n is canola oil, 2 wt.% nanofluid concentration and 1D-UAG. Finally, the regression model for the normal grinding force is presented in Eq. (5):

$$\begin{aligned} f_n = {} & 104.43 - \{4.84 * \mathrm{Mo1}\} - \{6.07 * \mathrm{Mo2}\} \\ & + \{10.91 * \mathrm{Mo3}\} + \left\{23.35 * \mathrm{n_p1}\right\} \\ & + \left\{2.84 * \mathrm{n_p2}\right\} - \left\{26.19 * \ \mathrm{n_p3}\right\} \\ & + \left\{9.37 * f1\right\} - \left\{9.37 * f2\right\}. \end{aligned} \tag{5}$$

Table 12 shows that all the process variables and the interaction between some parameters significantly affects the values of surface roughness. The model shows that the oil type, nanofluid concentration and the ultrasonic vibration have significant effect on the surface roughness. Additionally, Table 13 show that the regression model can be used to determine the amount of variance between each variable can be explained by the developed model with accuracy of about 99.21%. More so, it can be seen that the two way interaction of the nanofluid concentration and the 1D-UAG process is also significant. Figure 13(a) gives an illustration of the residual plot of the surface roughness results. The points on the normal plot of the model were closely aligned along the straight line of the plot. This is indicative of the model's accuracy, and validity. Also, the histogram of the residuals is bell shaped, which is indicative of normal distribution of the residuals. Additionally, Figure 13(b) illustrates the Pareto chart of the analysed result of surface roughness. The analysis in the Pareto chart shows that the 1D-UAG ultrasonic vibrations have the highest effect on the surface roughness, followed by the nanofluid concentration and then interaction between these two factors. The oil type was found to have the least effect on the surface roughness. A striking observation can be seen from



(c)

Figure 11 continued

Table 9 Model summary for transformed response

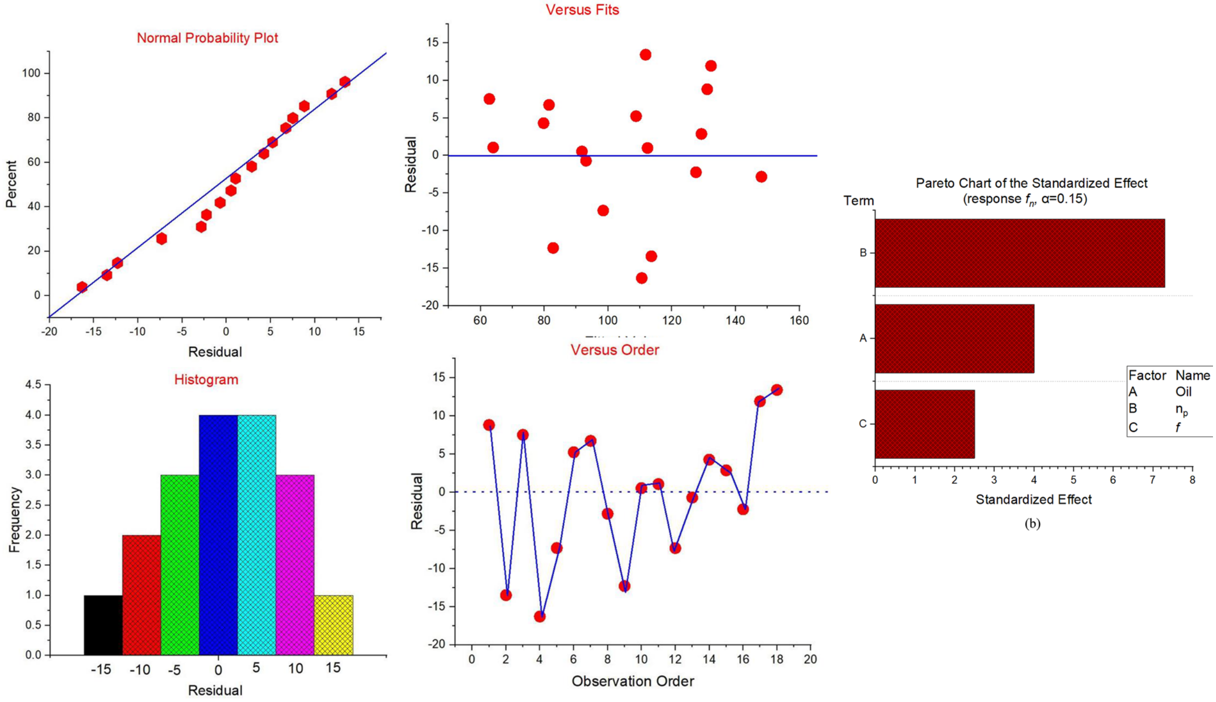
S/N	S	R-sq (%)	R-sq(adj) (%)	R-sq(pred) (%)
1	2.93309	98.09	97.30	95.71

Figure 13(c) whereby it is seen that excess nanofluid concentration causes an increase the workpiece surface roughness. The 0.5 wt.% of nanofluid was found to produce the best surface roughness when used with 1D-UAG system. Similarly, the corn oil exhibits the lowest surface roughness, followed by the canola oil and lastly the sunflower oil. Lastly, the regression model for the surface roughness of the ground components is given in Eq. (6):

$$\begin{aligned} R_a = {} & 0.478689 - \{0.003772 * \mathrm{Mo1}\} - \{0.000306 * \mathrm{Mo2}\} + \{0.004078 * \mathrm{Mo3}\} + \left\{0.024244 * \mathrm{n_p1}\right\} - \\ & \left\{0.015106 * \mathrm{n_p2}\right\} - \left\{0.009139 * \mathrm{n_p3}\right\} + \left\{0.018600 * f1\right\} - \left\{0.018600 * f2\right\} + \left\{0.011633 * \mathrm{n_p1} * f1\right\} - \\ & \left\{0.011633 * \mathrm{n_p1} * f2\right\} + \left\{0.001050 * \mathrm{n_p2} * f1\right\} - \left\{0.001050 * \mathrm{n_p2} * f2\right\} - \left\{0.012683 * \mathrm{n_p3} * f1\right\} + \\ & \left\{0.012683 * \mathrm{n_p3} * f2\right\}. \end{aligned} \tag{6}$$

Table 10 Analysis of variance of f_n

S/N	Source	DF	Adj SS	Adj MS	F-Value	P-Value
1	Model	7	10645.9	1520.85	287.14	<0.0001
2	Linear	5	10269.5	2053.89	387.78	<0.0001
3	Oil type	2	34.6	17.31	3.27	0.081
4	Concentration	2	6039.3	3019.63	570.11	<0.0001
5	Ultrasonic	1	4195.6	4195.59	792.14	<0.0001
6	2-Way Interactions	2	376.5	188.23	35.54	<0.0001
7	Concentration*Ultrasonic	2	376.5	188.23	35.54	<0.0001
8	Error	10	53.0	5.30		
9	Total	17	10698.9			



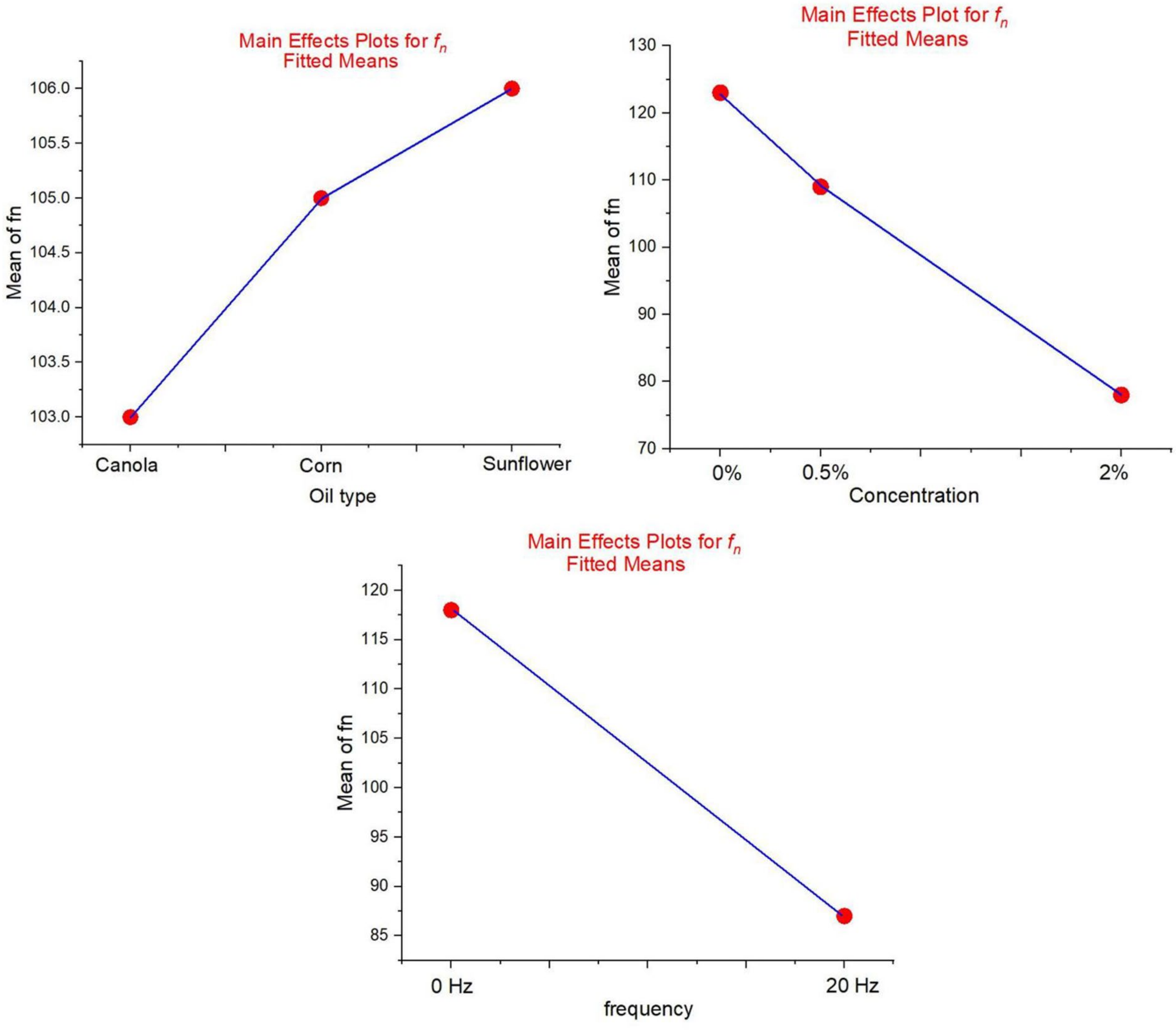
(b)

(a)

Figure 12 (**a**) Residual plots for f_n, (**b**) Pareto chart of f_n, (**c**) Mains effect plots for f_n

4 Conclusions

The present study is focused on investigating the grinding performance of SiO_2 nanofluid formed using ecofriendly vegetable oils during machining of Si_3N_4 ceramic. The MQL process is a promising alternative to traditional flood cooling lubrication methods in grinding of superhard materials. The flood coolants are presently being used are mostly synthetic hydrocarbon-based, and have been found to be hazardous to the environments, and costly. The literatures reviewed showed that the MQL process help to reduce the amount of energy expended in grinding operations. Further, it was also reported that



(c)

Figure 12 continued

Table 11 Model summary

S/N	S	R-sq (%)	R-sq(adj) (%)	R-sq(pred) (%)
1	2.30142	99.50	99.16	98.40

there is a corresponding increase of the workpiece surface integrity and increased lifespan for the grinding wheels. In terms of overall grinding costs, the MQL process was reported to significantly reduce the lubricant consumption by 1000 times. Qualitative and quantitative analysis was employed to observe the overall performance of the nanofluid MQL system and compared to other lubricant types. The grinding performance was examined using the grinding forces, specific grinding energy, frictional coefficient and workpiece surface roughness. Based on the experimental results obtained, the main findings of this work can be summarized as follows:

1. The 1D-UAG process has a much higher process efficiency than the CG process. This is because it produces the lowest value for grinding forces and surface roughness during grinding of the ceramic materials. Also, the MQL system when combined with UAG system, it outperformed the common grinding system and the traditional lubricants.
2. The optimum grinding performance was obtained when the experiments were performed combining

Table 12 Analysis of variance of R_a

S/N	Source	DF	Adj SS	Adj MS	F-Value	P-Value
1	Model	7	0.013594	0.001942	306.57	< 0.0001
2	Linear	5	0.011810	0.002362	372.87	< 0.0001
4	Oil type	2	0.000186	0.000093	14.66	0.001
5	Concentration	2	0.005397	0.002698	425.99	< 0.0001
6	Ultrasonic	1	0.006227	0.006227	983.07	< 0.0001
7	2-Way Interactions	2	0.001784	0.000892	140.80	< 0.0001
8	Concentration*Ultrasonic	2	0.001784	0.000892	140.80	< 0.0001
9	Error	10	0.000063	0.000006		
10	Total	17	0.013657			

Table 13 Model summary

S/N	S	R-sq (%)	R-sq(adj) (%)	R-sq(pred) (%)
1	0.0025169	99.54	99.21	98.50

the MQL system (canola oil with 2% nanofluid concentration) and the 1D-UAG process.

3. The use of both UAG and SiO_2/canola based nanofluid reduced the specific grinding energy, normal grinding forces, tangential grinding forces, and surface roughness by 65%, 57%, 65%, and 18% respectively, as compared to the CG with the traditional lubricants.
4. Finally, a full factorial analysis of the ultrasonic and MQL system was used to obtain an optimized settings of the process variables. The grinding performance of the corn oil was found to be similar to that of the canola oil based lubricants. Whereas the sunflower oil was observed to exhibit the poorest lubrication ability among the vegetable oil based lubricants.

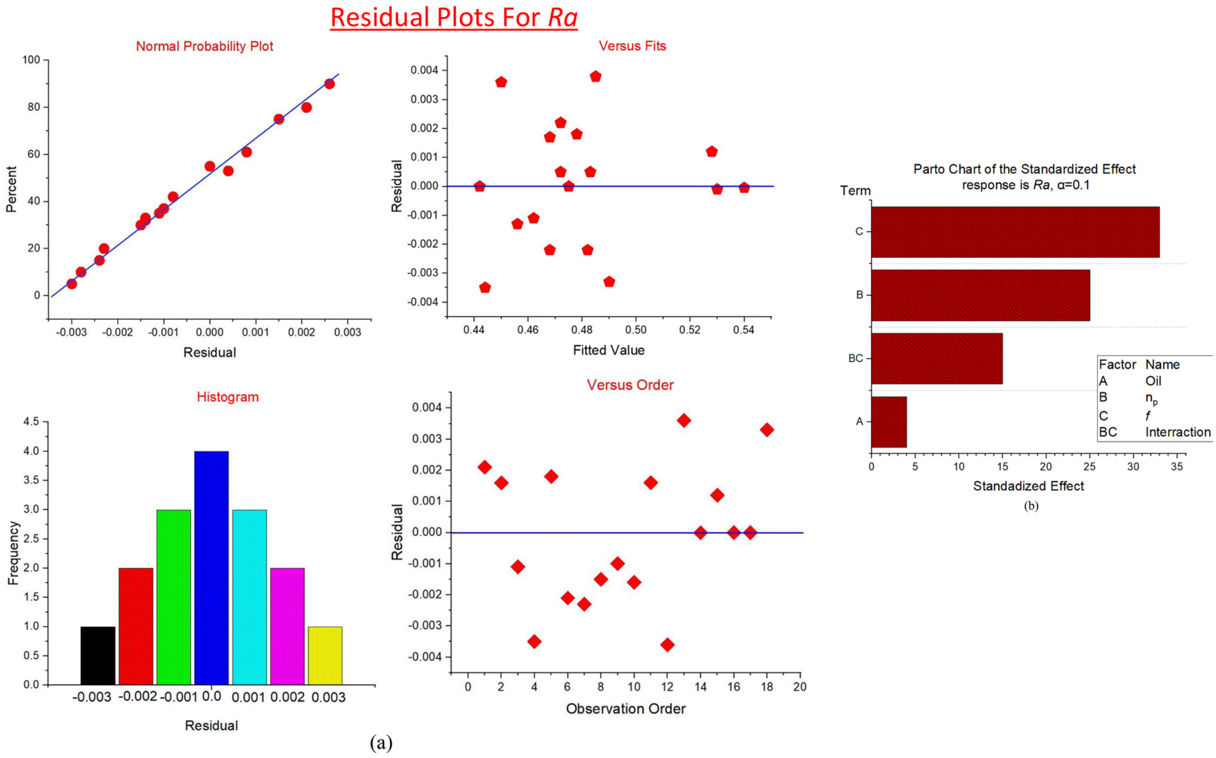
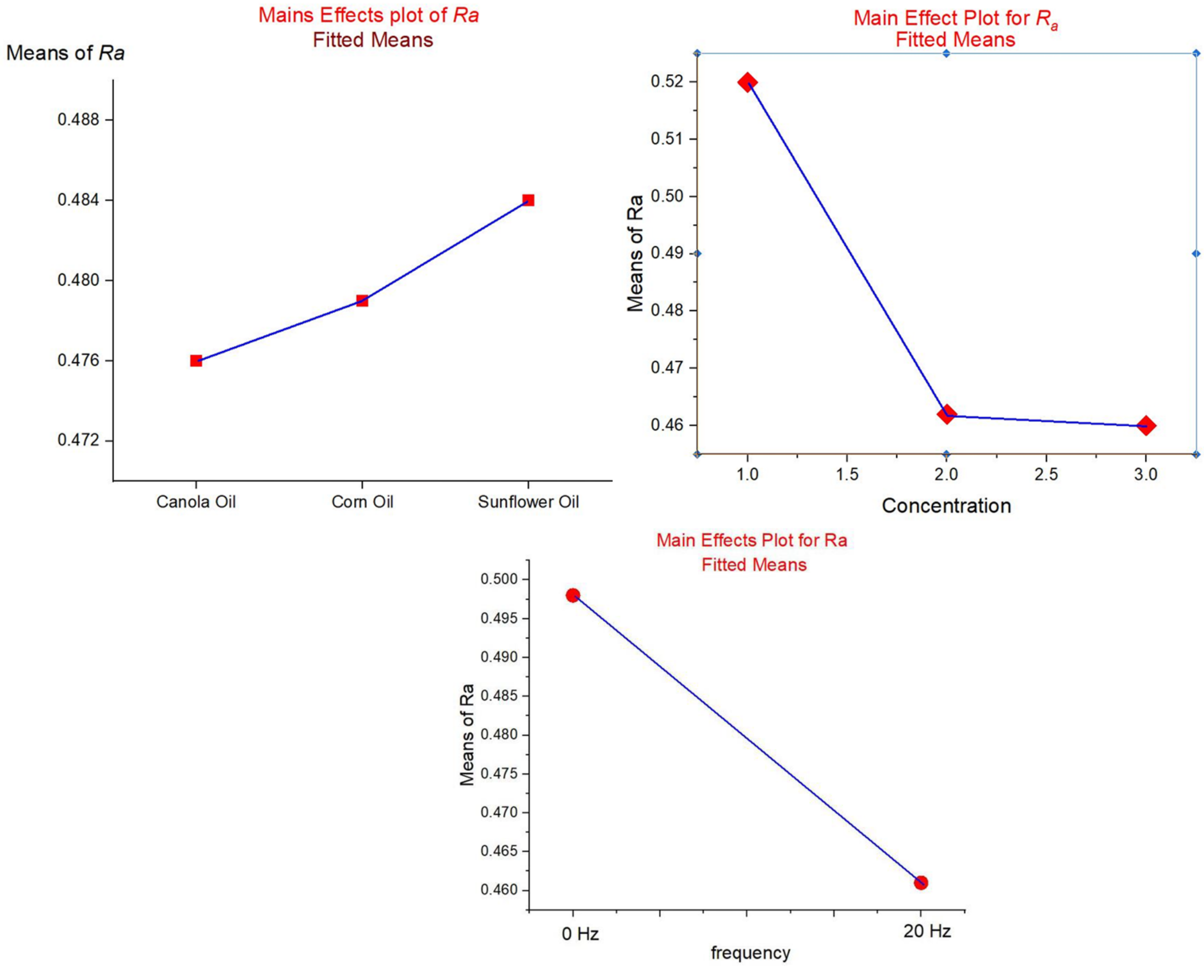


Figure 13 (**a**) Residual plots for R_a, (**b**) Pareto chart of R_a, (**c**) Mains effect plots for R_a



(c)

Figure 13 continued

Abbreviations

FL	Traditional flood lubricant
MQL	Minimum quantity lubrication
U	Specific grinding energy
NMQL	Nano-fluid minimum quantity lubrication
CC	Cryogenic cooling
f_n	Normal grinding force
f_t	Tangential grinding force
R_a	Surface roughness
SiO_2	Silicon dioxide
ND	Nano-diamond
Mo	MQL base oil
F	Ultrasonic oscillation frequency
CoF	Coefficient of friction
SEM	Scanning electron microscope
CNT	Carbon nanotubes
MWCNT	Multi-walled carbon nanotubes
CG	Conventional grinding
UAG	Ultrasonic assisted grinding
EDX	Energy dispersive X-ray
f_t/f_n	Force ratio
n_p	Nanoparticle concentration
Q	MQL flow rate

Authors' Contributions

DYS wrote the manuscript and coordinated the experiments. MS, AADS, MY, BL, ML, YZ, ZS and ZZ provided some suggestions and analysis of the results in the work. ZS put forward some suggestions on the contents of the paper. MS, AADS and LC read and approved the finalized manuscript. All authors read and approved the final manuscript.

Declarations

Competing Interests

The authors hereby confirm that there are no conflict of interest in the publication of this article.

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