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Original Article

Influence of graphene reinforced sunflower oil on thermo-physical, tribological and machining characteristics of inconel 718



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ABSTRACT

Owing to the extreme heat generated during Inconel 718 machining, the application of a minimum quantity lubrication (MQL) strategy is restricted to mild cutting conditions. By incorporating vegetable-based cutting oils reinforced by nanoparticles as possible additives, the effectiveness of MQL can be improved in high-speed machining. In this study, hybrid nano-green oils were developed by combining graphene nanoparticles in various volume concentrations with sunflower oil. Subsequently, dispersion stability, thermal conductivity, viscosity, and wetting angle of nano-green oils were measured. An MQL device is used to disperse the smallest amount of nano-green oils throughout the machining area. Later, the experimentally optimized graphene-based green oil is used for milling experiments. Furthermore, hard machining experiments were conducted with cutting speed of 80 m/min, feed rate of 0.2 mm/rev, and depth of cut of 0.5 mm under four different lubricating mediums: dry, flooded, sunflower oil, and 0.7% graphene reinforced sunflower oil. Comparative results show that 0.7% graphene reinforced sunflower oil performs better and reduces surface roughness by 49%, cutting force by 25%, cutting temperature by 31%, and tool wear by 20% as compared to dry machining environment. Finally, elemental analysis of cutting insert reports that adhesion is the major wear mechanism in all mediums.

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1. Introduction

There is extreme friction within tool-chip interfaces while machining nickel-based alloys [1,2]. As a result, extreme heat is produced and a greater proportion of it is subsumed by the tool-tip, resulting in plastic deformation of the tool materials and a reduction in tool life [3,4]. Due to the low modulus of elasticity of nickel alloys, intense vibration and chattering were experienced during high-speed machining, which results in a substandard surface quality [5–8]. Numerous lubrication strategies for machining aerospace materials have been proposed by researchers [9,10]. However, flooded lubrication is ineffective when machining nickel alloys due to its superior hardness and low thermal conductivity. As a result, the minimum quantity lubrication (MQL) technique emerges as a viable alternative to traditional lubrication systems. MQL also referred to as “Near Dry Machining,” is the foremost advantageous method of delivering lubricants where a high-pressure air-oil mixture is employed on the machining zone [11–13]. Numerous scientific articles have been published in the literature examining the beneficial impacts of MQL technology on cutting efficiency [14–18]. Additionally, as industries expand, poisonous and hazardous chemicals become more prevalent, impacting not only the environment but also

people's health [19,20]. Hence, principles such as green, safe, and sustainable production became critical components of contemporary practices. The government has also enacted several acts and policies to ensure a safe manufacturing climate. Nevertheless, manufacturing companies must provide a new structure for achieving sustainability objectives. The appropriate approach to enhance sustainability output is to minimize power utilization, recycle industrial wastes, maximize the utilization of commercial assets, advances lubrication technologies, and conserve environmental resources [21,22]. To address these concerns, researchers are motivated to employ MQL technologies in order to minimize the usage of hazardous fluids during metal cutting [23–25].

Notable research was done recently on the use of low-volume eco-friendly lubricants during machining operations. Additionally, if the economy and ecological protection are the main priorities, the combination of MQL and vegetable oil provides exquisite possibilities to machine heat-resistant superalloys. The existence of carboxylic acid groups is responsible for the exceptional lubricity of green oils. Belluco and De Chiffre [26] conducted a drilling experiment utilizing several bio-oils as a lubricant, where AISI 316L is used as workpiece material. According to the findings of this case study, vegetable oil can enhance tool life by about 177% in comparison to dry cutting. Ojolo et al. [27] investigated the lubrication

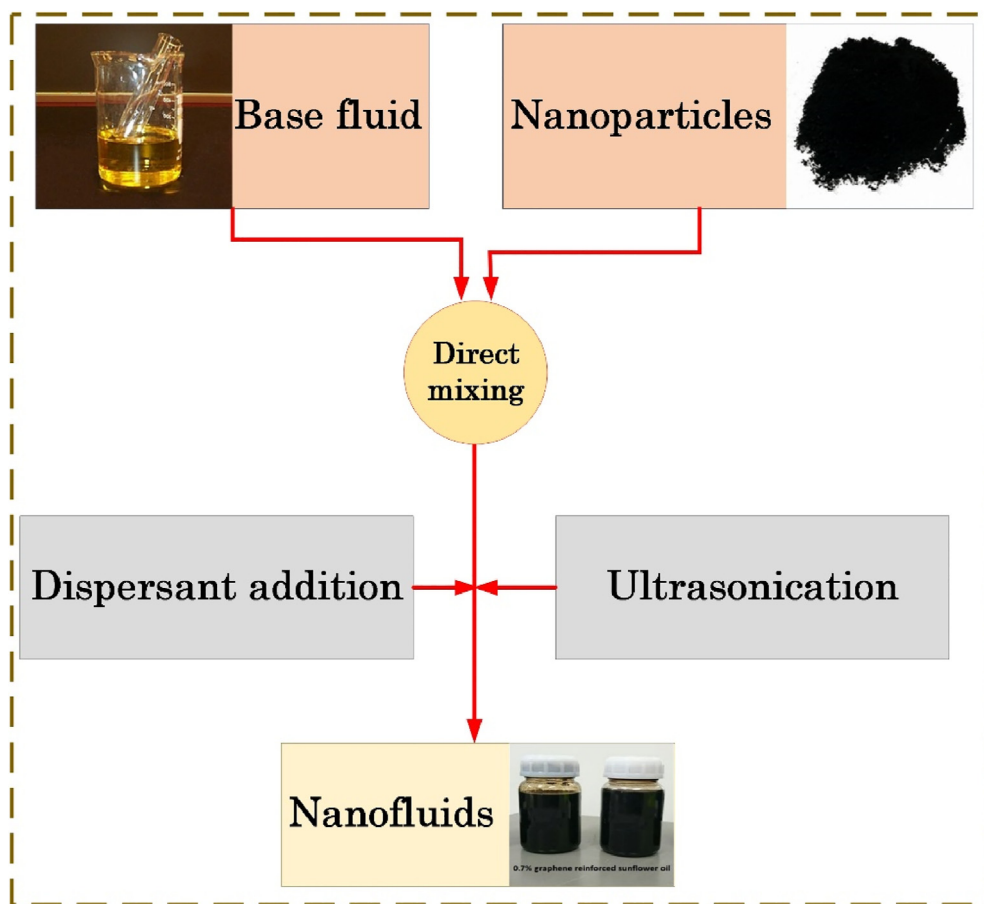


Fig. 1 – The stages involved in nano-green oil processing.

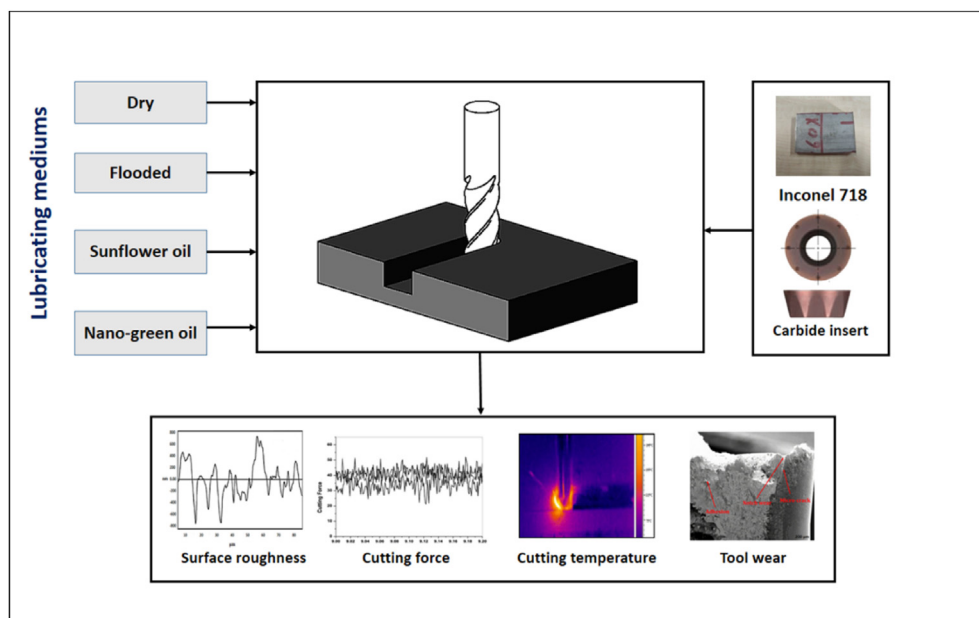


Fig. 2 – The schematic view of the machining stages.

capacity of different vegetable lubricants when cutting of ductile materials. Following the experiment, the researchers noted that the cutting force differed according to the material being machined. Nevertheless, groundnut and palm oil outperform karnel, coconut, and shear butter oil, indicating the need for additional research on these lubricating oils. Khan et al. [28] explored a synergic impact of MQL and green lubricant on the machining of AISI 9310. The experiment was conducted with an uncoated carbide insert. Tool wear, chip morphology, surface roughness, and cutting temperature were considered to be machining responses. Furthermore, identical machining conditions were used for dry and flooded machining. Finally, the researchers demonstrated that MQL aided machining outperforms other machining environments. Nonetheless, the MQL strategy had minimal impact on the tool wear mechanism. To determine the lubrication ability of some green oils, Xavier and Adithan [29] conduct an

experimental study using AISI 304 steel and carbide tool. The researchers discovered that coconut oil greatly decreased tool wear rate and the roughness value of the machined surfaces. In contrast, vegetable oil soluble in the water had a negligible effect on machining performances. Accordingly, experts recommend coconut oil as a lubricant for industrial operations. Kuram et al. [30] carried out an MQL-drilling on AISI 304 steel using HSS-E drill bit. The researchers determined the roughness of the machined surface and the cutting forces applied to the workpiece. The outcome of this experiment demonstrated that using bio-oil as the MQL fluid effectively reduces tool-work friction compared to dry machining. Mia et al. [31] used a minimum quantity of olive oil-based green biodegradable coolant for machining hardened steel. They evaluated machining efficiency in terms of the cutting zone's surface quality and tool-work temperature. After comparing olive oil with other lubricants, researchers determined that

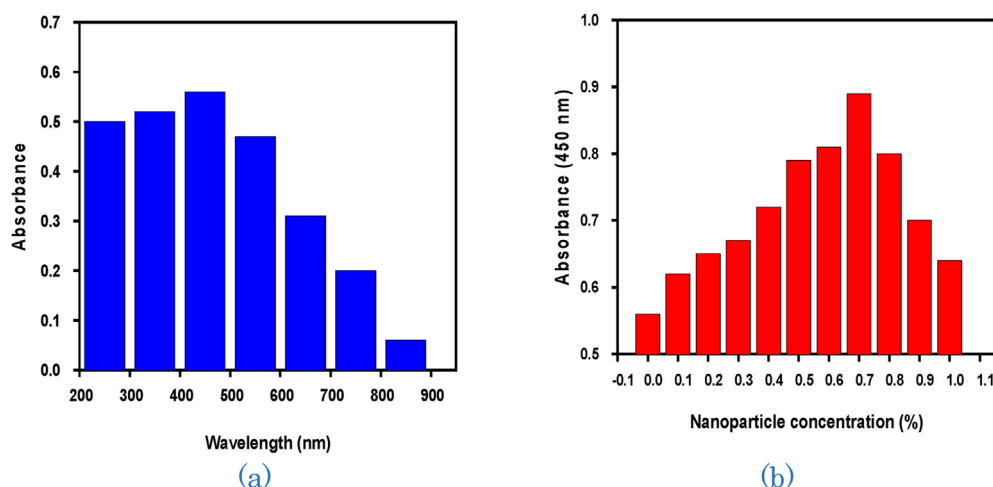


Fig. 3 – Variation of absorbance with (a) wavelength and (b) solid lubricant concentration.

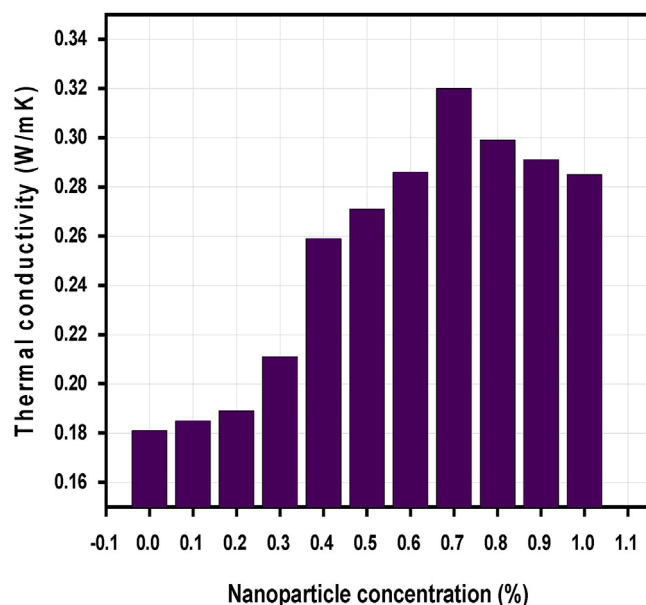


Fig. 4 – Impact of nanoparticles concentration on thermal conductivity value.

olive oil-based lubricants can be a better choice for sustainable machining operations.

Additionally, nanoparticles are vastly applied as a reinforcing material due to their exceptional physico-chemical properties such as high melting point, remarkable thermal strength, and exceptional lubricity. Vasu et al. [32] conducted a comparison to assess the effects of lubricating mediums on machining responses, including vegetable oil, alumina, and dry conditions. The findings of the study demonstrated that alumina reinforced vegetable oil successfully decreased surface roughness, force, and temperature relative to its competitors. Mandal et al. [33] mixed Al_2O_3 in deionized water and investigated the impact of the ratio nanoparticles on lubricity abilities. Throughout the research, alumina concentrations ranging between 1 and 5% were dispersed into the cutting area via an MQL device. The investigators noticed that a high concentration of nanoparticles results in decreased lubricating effect during the machining of AISI 52100. Zhang et al. [34] conducted MQL aided drilling to evaluate the lubricity of MoS_2 based nanofluid. MoS_2 nanoparticles were reinforced in a variety of plant oils including soybean, rapeseed, and palm. The test findings indicated that MoS_2 reinforced soybean oil had a higher lubricating capacity than other nano-green lubricants. Padmini et al. [35] expanded this analysis by combining MoS_2 nanoparticles with sunflower, coconut, and sesame oil. According to the experimental analysis, 0.5 percent MoS_2 deposited coconut fluid provides superior lubrication and decreases force, surface roughness, wear, and temperature by 37%, 39%, 44%, and 21%, correspondingly, relative to reference cutting medium (dry machining). Nam et al. [36] combined vegetable and paraffin oil with 30 nm diamond nanoparticles. The developed lubricants were atomized with a MQL device during the machining of Aluminium alloy. The experimental outcomes indicate that these nanofluids were equally effective at minimizing drilling

Table 1 – Mechanical properties of Inconel 718 [45].

Property	Value
Density (g/cm^3)	8.192
Vickers hardness number (VHN)	440–450
Melting point ($^{\circ}C$)	1350
Modulus of elasticity (GPa)	210
Poisson's Ratio	0.25–0.35
Thermal conductivity (W/mK)	10–11

torque, yet diamond reinforced paraffin oil has a higher degree of lubricity than diamond reinforced vegetable oil. Nam et al. [37] have shown in another article that large diamond nanoparticle does not offer improved lubrication while machining. In order to test the lubricity of bio-oils, Sarhan et al. [38] conducted a comparison between silica-nanofluid and mineral oil. The results of this experiment confirmed that silica-nanofluids seem to be more effective at lowering the specific cutting energy required for machining aluminium alloy. Sayuti et al. [39] investigated the effects of SiO_2 nanoparticle on hard machining operation. The outcomes showed that a 0.5% silica reinforcement could reduce the tool-work friction and lower the values of surface roughness and tool wear. Rao et al. [40] performed a turning operation to ascertain the effects of carbon nanotube machining responses. The investigators differed the CNT concentration in the fluid and discovered that the lowest values of tool wear and cutting temperature can be achieved with a CNT inclusion of 2%.

In view of the preceding studies, it has been determined that the employment of nano-green oils in MQL aided cutting operations has remained minimal. Moreover, no work was performed on the synergistic benefit of graphene-doped sunflower oil on the machining of aerospace alloys. Hence, the ability assessment of graphene-reinforced sunflower in MQL assisted milling of Inconel 718 is a matter of curiosity from the perspective of sustainable machining. Accordingly, an

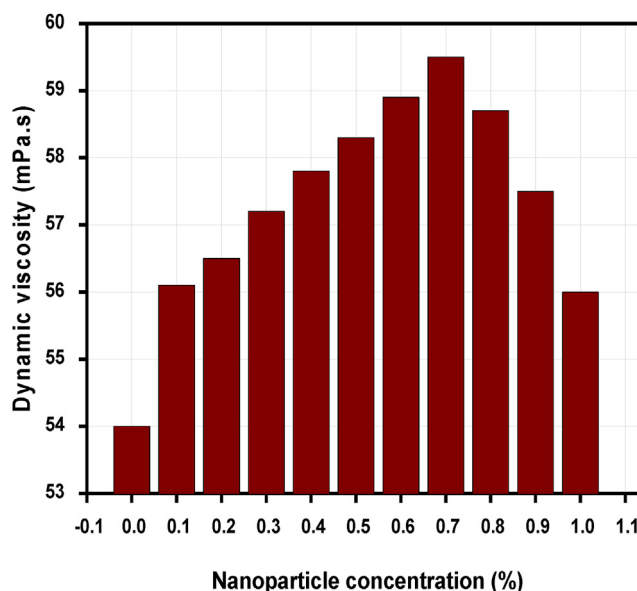


Fig. 5 – The variation of the dynamic viscosity with nanoparticles concentration at 34 °C.

Table 2 – Specifications of Cutting insert.

Specification	Details
Code	QPMT10T335PPEN
TRS (GPa)	3.3
Hardness (HRA)	91.4
Grain size	1 μm
Base metal	Fine-grained carbide
Coating	None

endeavor has been developed to equate the performance of dry, flooded, sunflower oil, and 0.7% graphene reinforced sunflower oil conditions by evaluating critical machining indicators i.e., surface roughness, cutting force, cutting temperature, and tool wear. To end, the tribological behavior and film-forming capacity of nano-green mixture is evaluated. Thus, the importance of this effort can be rationalized as a podium to address the distinct knowledge gap wherein the applicability of nano-green lubricants needs to be explored to strengthen the concept of sustainability in the machining domain.

2. Materials and methods

2.1. Preparation and characterization of nano-green cutting fluids

To produce nano-green oils, ten different concentrations (0.1–1.0%, with 0.1% increment) of graphene nanoparticles were employed. To produce nano-green oils, graphene nanoparticles and sunflower oil were hybridized. For the development of nano-green oils, a two-step technique [41] was implemented. To begin, a mixture of graphene and sunflower oil was ultrasonicated for 30 min in a sonicator (Johnson Plastosonic, ITB-32D4A76D). Following that, it was stirred for 45 min at 600 rpm with a magnetic stirrer (Abdos, MS-H280-Pro). All stages were repeated until uniform dispersion of graphene in sunflower oil was found. The developed graphene-based nano-green lubricants have a black appearance. The stages included in the processing of nano-green oil are depicted in Fig. 1.

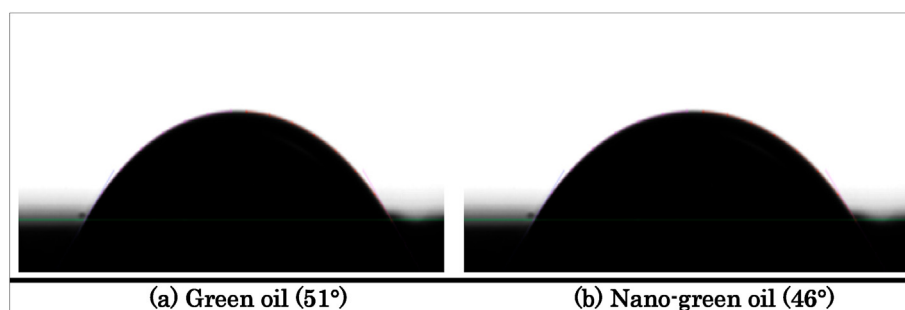
The absorbance value of monochromatic light with a fixed wavelength in the UV range is proportional to the reference beam. The absorbance of spectral UV rays implies the

amounts of light received by a sample of a given length. The absorbance of a specimen is relative to the volume of a substance in it. The absorbance of various amounts of graphene nanoparticles in sunflower oil was determined to ensure their suspension consistency. Precise nanoparticle dispersion in cutting fluid is a critical requirement for the production of nanofluids. UV spectroscopy was used to determine the dispersion of nanoparticles of different concentrations in every nano-green oil solution. To begin, 1:250 dilution specimens of each nanofluid were prepared and placed in a cuvette to determine the dispersion wavelength utilizing a Spectroscopy technique. Additionally, absorbance at the specific wavelength of UV rays was considered to determine the dispersion stability.

The potential of a nanofluids to remove heat is typically determined by their thermal conductivity value. As a result, the thermal conductivity of nano-green oil was also determined using a thermal property analyzer (KD2 Pro). This system is developed based on transient line heat source theory and is used to determine thermal conductivity. The analyzer is equipped with a needle that is connected to heater and temperature sensor. The needle is completely inserted into prepared nanofluid sample. The heater, along with the sensor, monitors the temperature of the nano-green oils from which the analyzer determined thermal conductivity value. The lubrication properties of nano-green oils are also dependent on their viscosity. As a result, the viscosity of nanofluids was determined as a function of temperature employing a rheometer (Anton Paar, MCR-101). The viscosity of every nano-green oil was measured with a 7 ml sample. The tests were performed in accordance with the suggestion of Gajrani et al. [42].

Table 3 – Machining conditions.

Input	Value
Machining environments	Dry, Flood, MQL
Cutting fluids	Sunflower, Graphene reinforced Sunflower
Cutting speed	80 m/min
Feed rate	0.2 mm/rev
Depth of cut	0.5 mm
MQL flow rate	30 ml/h
MQL jet pressure	0.5 MPa
MQL nozzle angle	45°

**Fig. 6 – Effect of graphene concentration on surface wettability.**

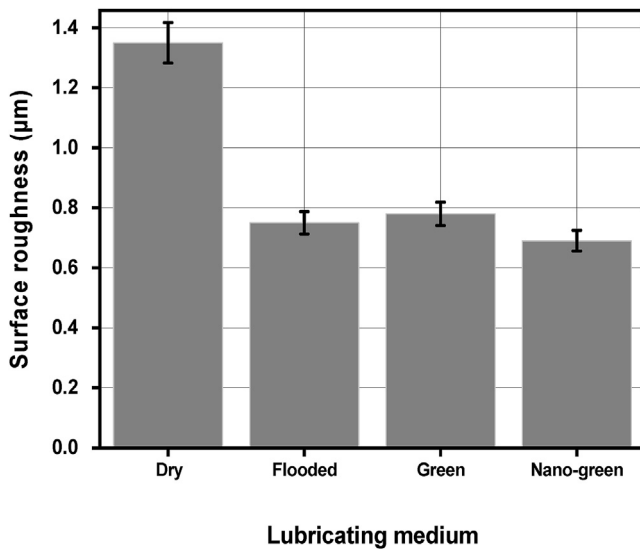


Fig. 7 – The measured value of surface roughness under different lubricating mediums (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

Once a droplet of fluid rests on a solid object, an outline is formed; the angle formed by the droplet and the outline of the contact area is referred to as the wetting angle. It determines the potential of cutting fluids to wet the tool substrate. A liquid drop with low surface tension on a solid surface takes a circular appearance resulting in a low wetting angle and hence improved wettability. Wettability was determined for two separate oils such as sunflower oil and 0.7% graphene reinforced sunflower oil using a goniometer. 2 μ l oil droplets were retained on the tool substrate for 15 s. Following that, the contact angle was determined using a goniometer (Holmarc, HO-IAD-CAM-01B).

2.2. Machining experiments

Inconel 718 rectangular pieces of 150 × 80 × 10 mm were selected for this study. The composition of Inconel 718 is Ni 50–55%, Cr 17–21%, Ti 0.65–1.15%, Al 0.2–0.8%, Mo 2.8–3.3%, C 0.08%, Si 0.35% and S 0.015% [43]. Machining experiments were conducted using uncoated carbide inserts mounted in a commercial tool holder. Tables 1 and 2 detail the mechanical properties of the workpiece and the design specifications of the cutting insert. A CNC milling machine was used to perform machining tests. The experiments were performed for an MQL environment with sunflower oil and 0.7% graphene reinforced sunflower oil. Additionally, for comparative study, tests were conducted in a dry and flooded medium also. Cutting oils were supplied to the tool-chip interface through a commercial MQL setup (Coolubricator, UNIST) that is capable of controlling both air pressure and oil flow rate. The machine feed was coupled to flexible nozzle system, which has a slit of 1 × 5 mm². Fixed air pressure (0.5 MPa) and fluid flow rate (30 mL/h) were used in experiments. Depending on existing literature [44], the 30 mm nozzle distance and 45° nozzle angles were maintained. The machining conditions are detailed in Table 3.

2.3. Measurement of machining responses

The roughness of the machined zone is observed with a 3D optical profile (Taylor Hobson CCI MP). Where 20x Magnification and 4.7 mm cut-off distance are maintained during the measurement. The said profilometer measures the surface roughness of five places in the cutting region. For perfect measurement, the path is kept perpendicular to the machining direction. Like so the forces exerted by insert are measured with a piezoelectric dynamometer (Kistler 9272). For precise measurement, the dynamometer is placed below the workpiece material. The charge produced by the

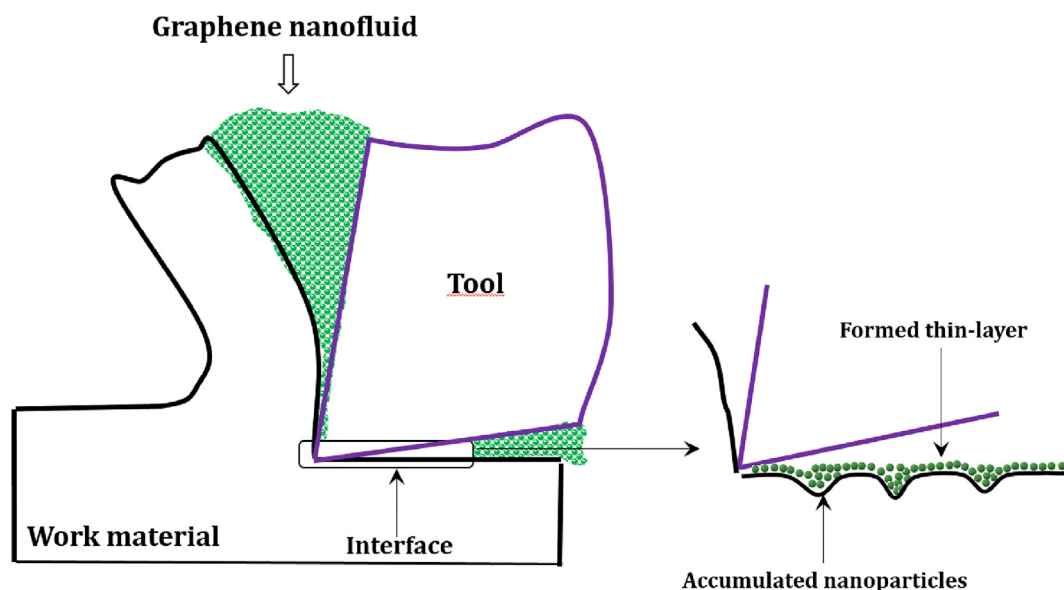


Fig. 8 – Tribological effect of nanoparticles during machining operation (Adopted and modified) [44].

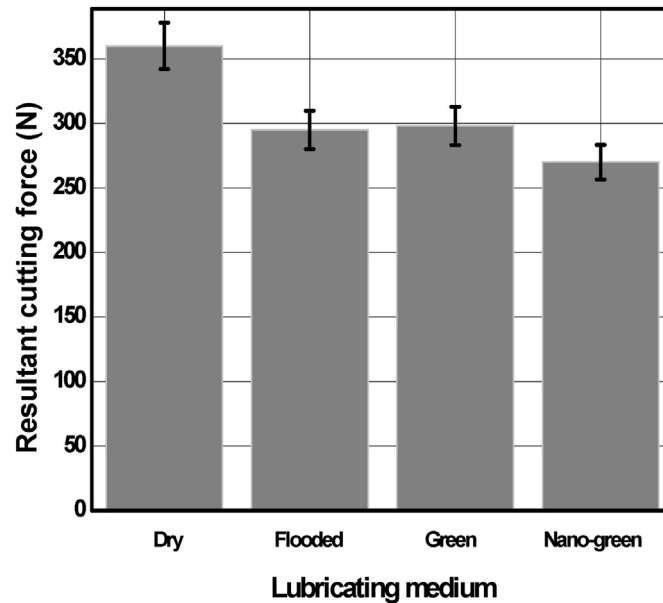


Fig. 9 – The measured value of resultant cutting force under different lubricating mediums (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

dynamometer is amplified by a multi-channel amplifier. At the charge amplifier, a low-pass filter was used. The force sensor is then filtered to reduce the noise produced by process variables. A thermo-graphic camera (Thermo Pro TP8) is used to measure the tool-work interface temperature, which provides an image of real-time temperature. The most important setting in thermal cameras is to determine the emissivity value. In this case, the emissivity value is set to 0.5, which can be calibrated as required. A thermal camera is started during a

machining operation which is capable of measuring temperature from 0 to 900°. The stated thermal camera can take clear images up to 80 Hz frequency and 382×288 pixels. As the wear recorded by an optical microscope was highly non-uniform, the maximum flank wear was considered instead of average flank wear. Furthermore, the micro-graphs of machined surfaces and tool wear profile are captured by a Scanning electron microscope (ZEISS, Sigma 300). Fig. 2 demonstrates schematically the machining stages of the current study.

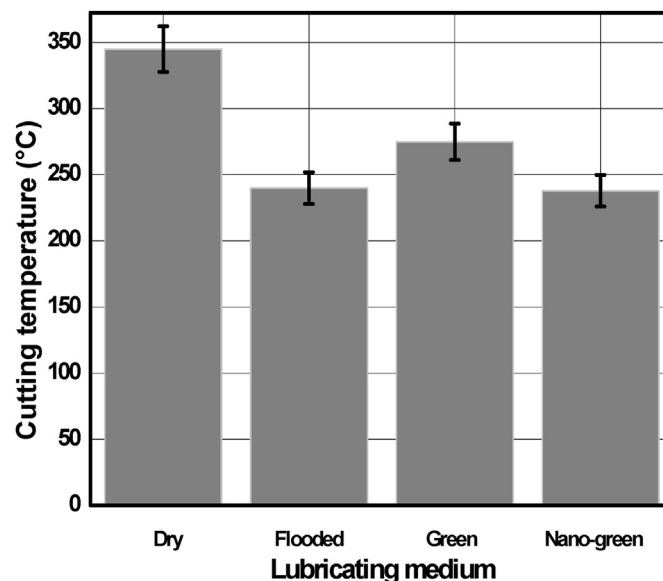


Fig. 10 – The measured value of cutting temperature under different lubricating mediums (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

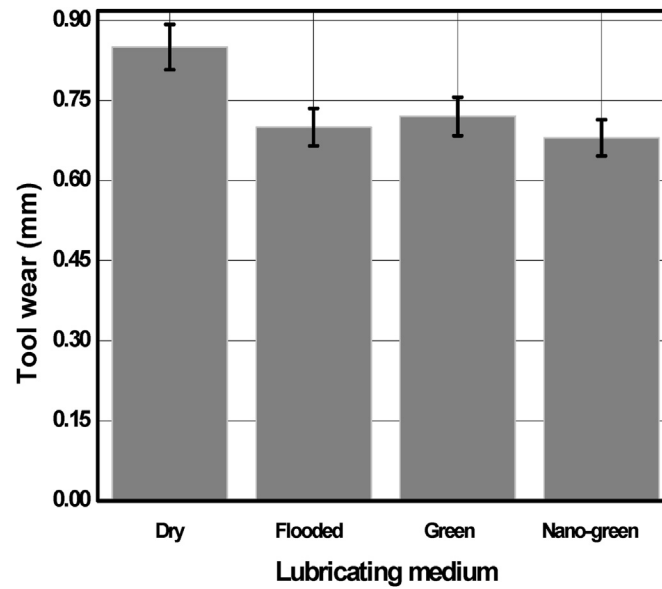


Fig. 11 – The measured value of tool wear under different lubricating mediums (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

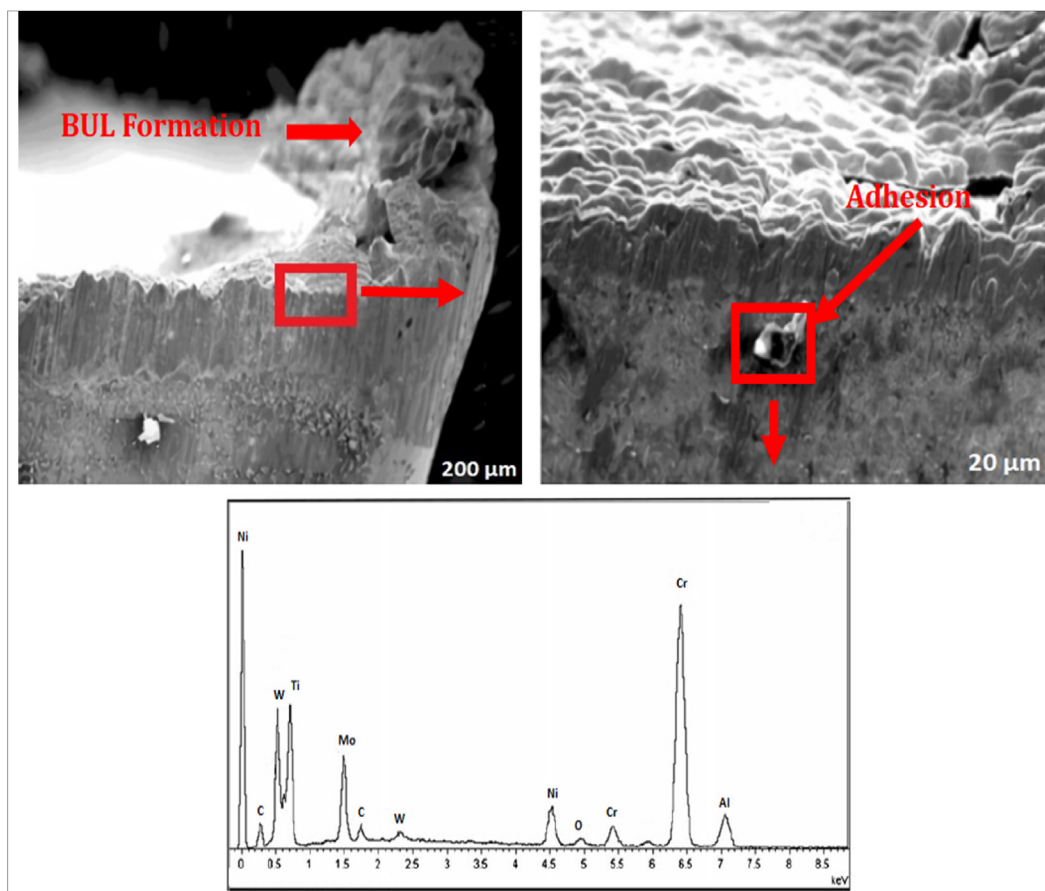


Fig. 12 – SEM-EDX micrographs of uncoated carbide insert under dry machining condition (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

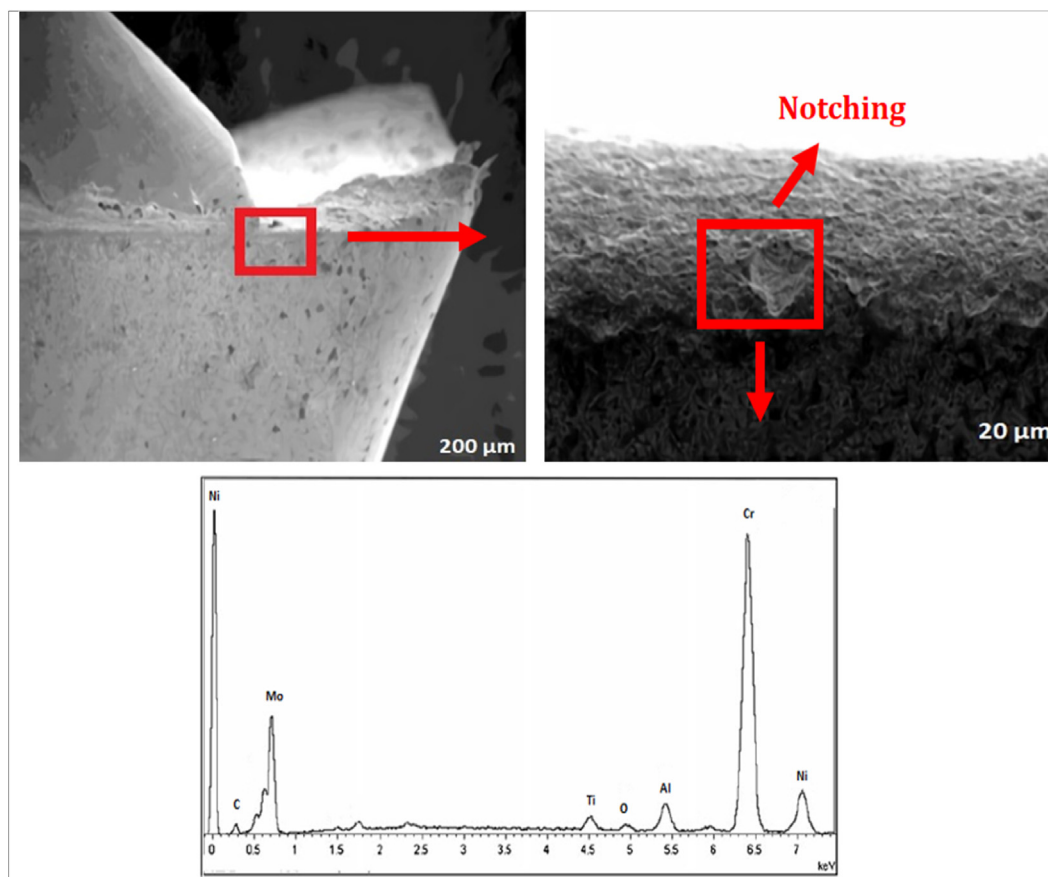


Fig. 13 – SEM-EDX micrographs of uncoated carbide insert under flooded machining condition (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

3. Results and discussions

3.1. Analysis of dispersion stability

Adequate nanoparticle dispersion in the base fluid is a complex procedure. Particles with a nano-sized appear to suspend and accumulate. As a result, surfactants are often required to disperse the coagulated nanoparticles. Basically, hydrophobic surface and electrostatic repulsive forces distributed the nanoparticles properly into the base fluid. Here, CTAB at a concentration of 0.02% was utilized as a surfactant to ensure uniform distribution and improved consistency of nanofluids. Fig. 3(a) illustrates the absorbance variation of nano-green oils as a function of wavelength. At 450 nm, a clear peak is appeared, indicating the dispersion test wavelength. Fig. 3(b) depicts the impact of the concentration of nanoparticles on absorbance value, which shows the dispersion of graphene in sunflower oil. Sunflower oil has an absorbance of 0.54. Although, as the nanoparticles (vol%) increases the absorbance value improves proportionately, up to a 0.7% graphene concentration (saturation point). After which the absorbance value decreases significantly, which has two possible reasons. The first is attributable to the inclusion of a small amount of surfactant, which is insufficient for proper dispersion of

graphene. Additional surfactant could not even be added since it alters the characteristics of the prepared nano-fluids. Another explanation is that nanoparticles sediment as their concentration is increased in the base fluid. Agglomeration of nanoparticles was detected after 0.7% nano-concentration. Hence, 0.7% can be considered as the optimum volume concentration of graphene in the sunflower oil.

3.2. Analysis of thermo-physical properties

The thermal conductivity of prepared nano-green oils with graphene concentrations ranging from 0.1% to 1% was determined. Fig. 4 illustrates the influence of nanoparticle concentration on the thermal conductivity value of nano-green oils. Thermal conductivity was found to increase with graphene concentrations up to 0.7%. After that, the thermal conductivity is reduced significantly. Indeed, the increased thermal conductivity of nano-green oil is a result of the elevated thermal conductivity of graphene. Similarly, Murshed et al. [46] noticed a remarkable improvement in thermal conductivity value as the concentration of nanoparticles are increased. Additionally, Fig. 5 illustrates the dynamic viscosity of nano-green oils with varying nanoparticle concentrations. Sen et al. found that as the temperature increases, the dynamic viscosity of nano-green oil decreases.

This is attributable to thermal energy that separates cutting fluid particles by weakening molecular bonds [47]. Nevertheless, as the concentration of graphene increases, the dynamic viscosity of nano-green oils increases until it reaches a saturation point. This improvement in viscosity is a reflection of the incorporation of graphene, which provides additional flow resistance. As a result, the torque needed for rotating the spindle is raised. Beyond 0.7%, an increase in graphene concentration results in a reduction in viscosity value. As previously mentioned, an excess of nanoparticles in sunflower oil results in ineffective dispersion and cluster sedimentation. As a result, increased nanoparticle concentrations are undesirable.

The wettability of lubricants on the tool substrate is vital since it has a significant impact on the lubricating potential also. The wettability of the lubricants is predominantly dependent on lubricant-cutting insert chemistry that influences interactive surface tension. The wetting angle of green and nano-green oils on the cutting tool surface is shown in Fig. 6 (a-b). It was noticed that green oil has a greater wetting angle than nano-green oil. Wetting angle with sunflower and 0.7% graphene reinforced sunflower oil were 51° and 46° , respectively. It was attributable to the lower surface tension of graphene deposited green oil as compared to sunflower oil. As a result, nano-green droplets disperse more quickly, providing superior lubrication when compared to sunflower oil.

3.3. Analysis of machining responses

3.3.1. Surface roughness

The roughness of the milled surface influences the working performance, the interaction between the tool-workpiece, and the machined product's service life. Thus it is one of the essential criteria in the machining domain. The previous researchers found that the parameters, like cutting tool geometry, coating type, and lubricating medium influence surface roughness values [48,49]. However, in the present work, the effects of various lubricating mediums on surface roughness were examined by keeping other parameters constant. Here, surface roughness values of the milled zone were inspected by a 3D profilometer under different lubricating conditions. The measured value of surface roughness under different lubricating mediums is shown in Fig. 7.

In this context, it can be revealed that nano-green droplets were successfully penetrated in the tool-workpiece boundary and reduced the surface roughness. Besides, the diminution in resultant cutting force and cutting temperature values under minimum quantity sunflower oil conditions also confirmed the above situation. Previous studies such as [35,50–52] show that nanofluids have the exceptional capability to reduce the roughness of the machined zone. The researchers also depicted that nanoparticle enriched vegetable oil medium shows better surface morphology than other lubricating

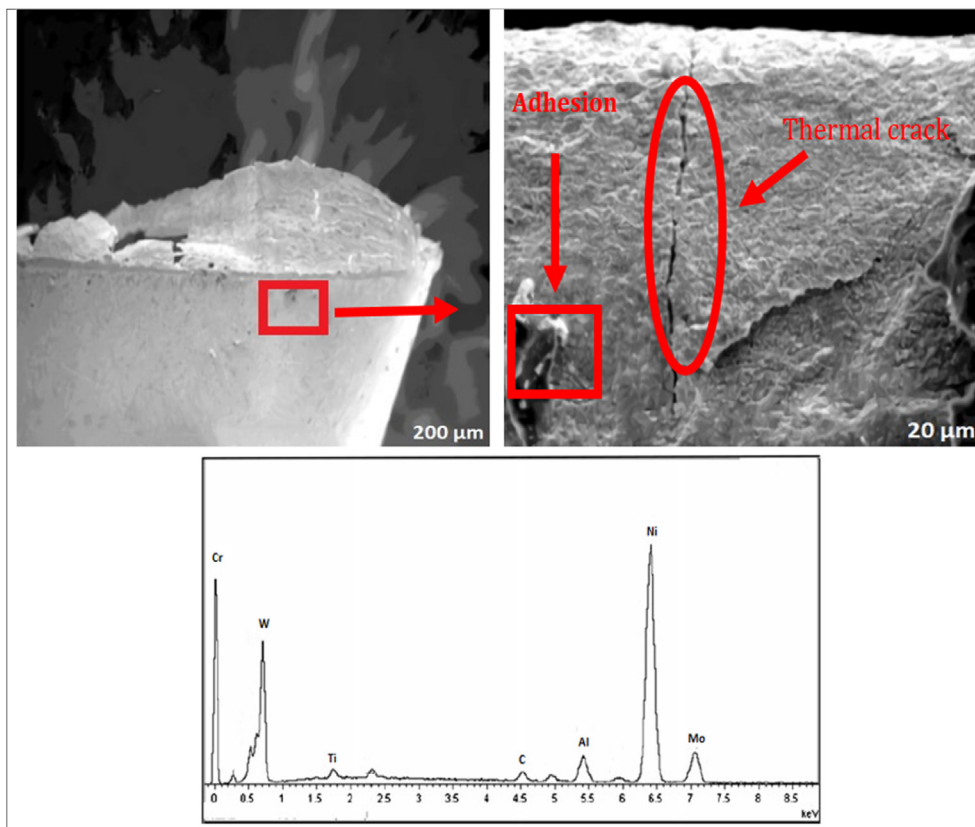


Fig. 14 – SEM-EDX micrographs of uncoated carbide insert under green machining condition (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

media. Here, the lowest surface roughness value was achieved by machining done with graphene enriched sunflower oil condition. The surface roughness values measured under the 0.7% graphene deposited sunflower oil demonstrated 49%, 8%, and 12% drop as compared to dry, flooded, and sunflower oil conditions. As stated earlier, graphene-enriched sunflower oil possesses a higher value of viscosity than sunflower oil, enabling the existence of a nano-green mixture in the machining zone for an extended period. Moreover, other possible reasons underlying the improvement of surface quality can be mentioned as small amounts of nanoparticles filling micro channels on the workpiece surface, developing a thin nano-lubricating film, removing debris from the machined surface, reducing direct contact between the tool-working interface, and minimizing friction [50]. A visual representation of the tribological effect of the nanofluid on the machined surface can also be seen from Fig. 8. The characterization of nano-green lubricates showed that the optimum concentration of graphene in Sunflower oil was 0.7%. The insufficient amount of nanoparticle concentration failed to induce rolling effects on the tool-workpiece interface, while higher nanoparticle concentration promotes the agglomeration phenomenon. Thus, nanoparticles were behaving like ordinary fluid and restrict thin film formation.

3.3.2. Resultant cutting force

As we know, cutting force is an essential quality of machining that determines the force of the workpiece and the power

consumption. Besides, cutting force directly impacts the quality of machining, and the tool-work interface temperature also. Hence, a higher cutting force value negatively influences the surface integrity and tool wear pattern. In this study, the cutting force exerted by the tool on the workpiece was measured by a dynamometer to determine the impacts of lubricating mediums on the said parameter. Accordingly, the force components viz., radial thrust force, tangential force, and feed force were measured, and the resultant value was determined [47]. The deviation of resultant cutting force values in accordance with the lubricating medium is presented in Fig. 9. The resultant cutting force measured in dry machining conditions depicts high value, while the application of lubricating oil successfully reduced that value. As MQL has the exceptional ability to penetrate the fluid droplets in the cutting zone, thus a significant reduction in tool-work friction was observed. As previously described, nanofluid had a significant impact on machining responses. Here, also, a similar scenario is perceived. 0.7% graphene deposition considerably decreases the cutting force values as compared to the other mediums. Moreover, 0.7% graphene-enhanced sunflower oil reduced the cutting force by 25%, 8%, and 9%, respectively, compared to the other mediums. Here also, the identification of the optimum nanoparticle concentration in the base fluid should be necessary unless better lubrication can't be achieved. The excessive nanoparticle depositions sometimes hamper the generation of tribo-film on the work surface, while minimal nanoparticle concentration reduces

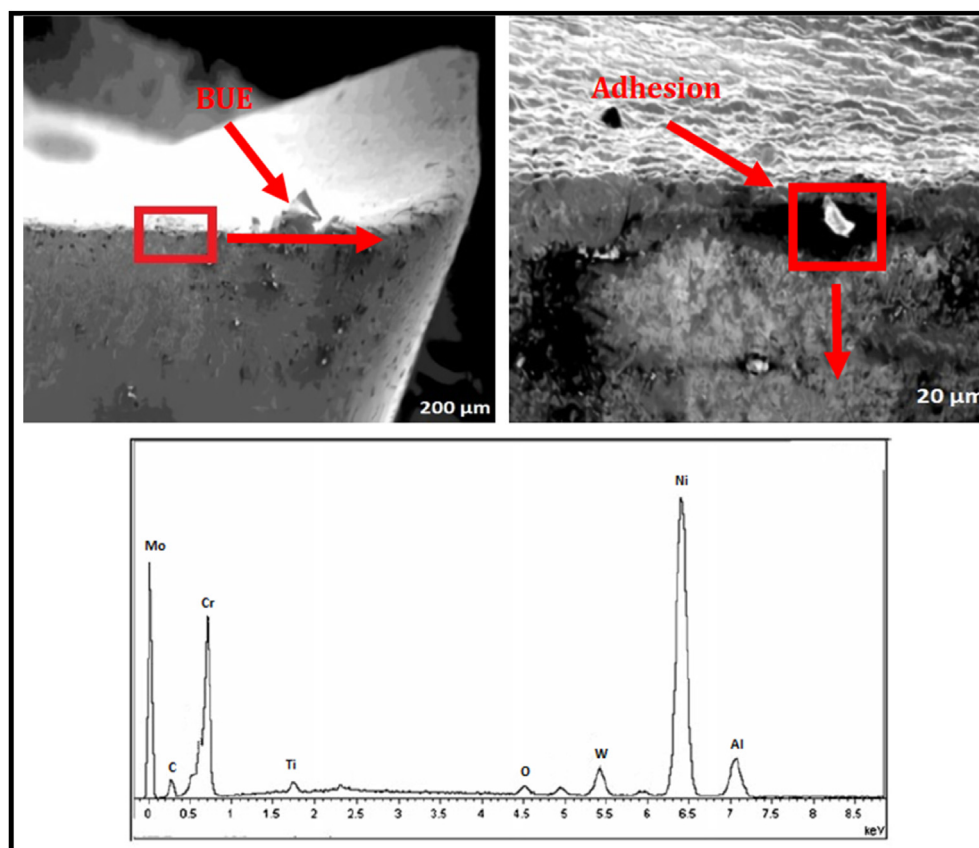


Fig. 15 – SEM-EDX micrographs of uncoated carbide insert under nano-green machining condition (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

the viscosity of the nanofluid, which perhaps affects the existence of nanofluid in the machined zone. Note that nanoparticles successfully rolled over the tool-chip contact interface. As a result, the sliding friction is converted into rolling friction, leading to a lower value of resultant cutting force.

3.3.3. Cutting temperature

During machining operation, the friction between the tool-chip and tool-workpiece produces high temperature in the

slide-plane. As these temperature increases, they cause severe surface deterioration and reduce tool life. Thus, cutting temperature measurement has tremendous importance while evaluating the mechanism of machining operation. In this study, the maximum cutting temperature values were measured using a thermal infrared camera under different lubricating mediums (Fig. 10). It was apparent that due to the absence of any lubricating medium, dry machining condition generates the highest value of cutting temperature (345 °C) as compared to the other three mediums. In this context, it can

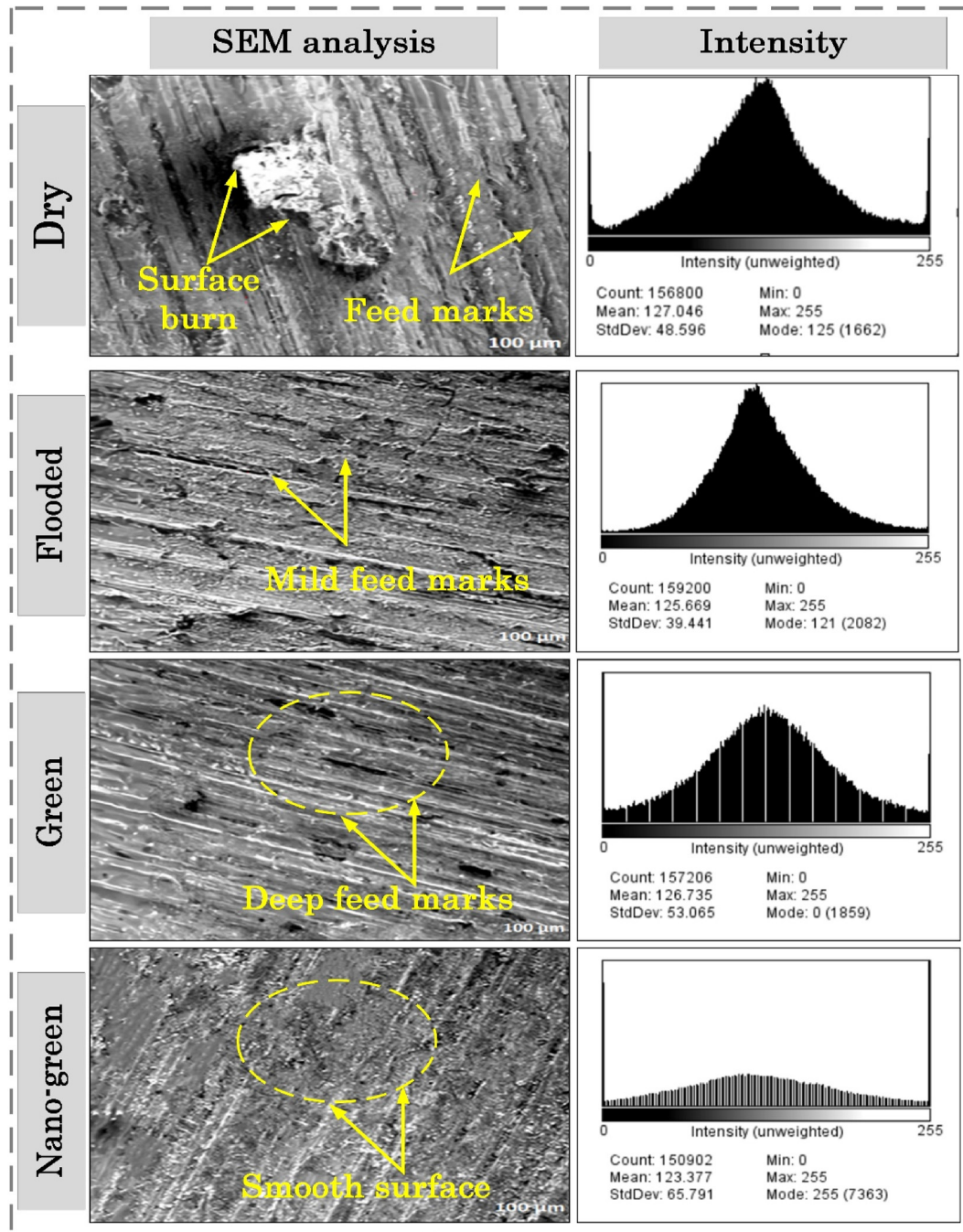


Fig. 16 – SEM images and intensity analysis of specimen machined under different lubricating mediums (Cutting speed = 80 m/min, Feed rate = 0.2 mm/rev, and Depth of cut = 0.5 mm).

be said that the droplets of sunflower oil successfully fully penetrate the tool-work interface, forms a tribo-film on the machined zone, and also assists the chip removal process. However, the lowest cutting temperature was achieved at 0.7% graphene deposited sunflower oil medium. As seen earlier, nanoparticle concentration successfully advances the thermal conductivity value of the base fluid. Hence, when two different MQL base fluids were compared, the lubricant having a higher value of thermal conductivity generates lower cutting temperature. It was witnessed from the nanofluid characterization that the thermal conductivity increased significantly with nanoparticle concentration. Interestingly, after the saturation point (0.7%), the increment in the thermal conductivity value was no longer significant. Thus, the determination of the optimal nanoparticle concentration in the base fluid is crucial for the effective reduction of the cutting zone temperature. However, the temperature values measured under the 0.7% graphene deposited sunflower oil condition demonstrated 31%, 1%, and 13% drop in cutting temperature value compared to dry, flooded, and sunflower oil conditions.

3.3.4. Tool wear and its mechanism

Tool wear is the most dynamic feature of the machining operation, directly influencing the machining quality and cost incurred in machining. In the present study, milling operation was continued for 25 min, and maximum flank wear value was calculated to evaluate the lubricating effect produced by a different lubricating medium such as dry, flooded, sunflower oil, and 0.7% graphene reinforced sunflower oil. During the evaluation process, all the machining inputs were kept constant; merely the lubricating mediums were changes. Each milling experiment was performed for 30 min, and maximum flank wear values were calculated using an optical microscope. It has been observed that the minimum quantity lubricating medium successfully reduces the tool wear value by reducing the friction of the tool and work boundary. The progression of tool wear with the cutting time in the various lubricating medium is presented in Fig. 11, which shows the superior lubrication ability of 0.7% graphene reinforced sunflower oil medium as compared to dry, flooded, Sunflower oil. In short nano-green medium improved the tool wear value by 20%, 3%, and 6%, respectively, compared to the dry, flooded, sunflower oil medium. However, previous literature [47] confirmed that the percentage of nanoparticle deposition in the MQL fluid had a significant impact on the wear profile of the cutting tool. In this context, the observations of Sirin et al. [44] are crucial. They found that the increase in nanoparticle concentration has positively impacted tool wear up to a specific limit. However, as the nanoparticle concentration exceeds the saturation limit, an adverse effect was observed thereafter. A higher percentage of nanoparticle deposition enhances the base fluid's viscosity, which restricts the fluidity of the base fluid. As a result, the nanofluid become sticky and lost its lubricating ability. When the nanofluid lost its lubricity, the friction between the tool and work increased tremendously, and the tool life was hampered. As discussed earlier, higher nanoparticle deposition also enhances the possibilities of nanoparticle agglomeration. Thus, the measurement of optimal nanoparticle concentration is crucial to achieve superior lubricity.

Furthermore, the SEM and EDX analysis of the subjected inserts were executed to observe the influences of the lubricating medium on the tool wear mechanism. The SEM and EDX micrographs are presented in Figs. 12–15. These micrographs demonstrated that Adhesive wear were the governing wear types in different lubricating mediums. As the EDX spectrums were analyzed, the presence of workpiece material on the rake faces of the end-mill was observed. During machining, the upper layer of the uncoated carbide was wrapped off; thus, the successive layer of the tool was exposed, and a similar process was recurring throughout the machining. Additionally, high temperature, and pressure, was generated during the machining operation; thus welding of tool and chips were taken place, resulted in the formation of an adhesive layer. Nevertheless, the formed adhesive layer was partially removed by a new layer; thus, the fresh layer was strengthened by the partially removed layer and enhanced the chance to develop the built-up layer. On the contrary, a high cutting force applied to the tool drives the debris to the extreme edge, enhancing the possibilities of built-up layer formation. However, the high affinity of chemical bonding between the tool and work was an important factor in BUL formation. Additionally, a crack was found on the flank face of the milling insert under a green lubricating medium. As per Sugihara and Enomoto [53], the cracks formed as a result of the unstable adhesive layer falling off and reforming repeatedly during the milling process. Whereas Grzesik [54] stated that thermal cracking is induced mostly by stochastic heating or chilling involved with disrupted cutting, and the elevated temperature gradients at the cutting edge produce thermal crack. As a result, we can conclude that the crack observed was caused by repeated and persistent load fluctuations during the milling operation. Nevertheless, Lima et al. [55] introduce a solution for minimizing the thermal-cracking of carbide tool. In this case, hot air was blown into the idle phase of the milling cutter. The researchers observed that the heating of the idle phase helped to reduce the number of thermal cracks and tool wear.

3.4. Analysis of the nano-green tribology

Naturally, graphene is extremely hydrophobic and oleophilic. Sunflower oil is very polar and exhibits a heavy attraction to metals. Owing to graphene's super-oleophilicity and sunflower oils' polarity, a synergistic tribo-film comprising of sunflower oil and graphene is formed on the workpiece surface. Which led to an increase in tribological behavior and a reduction in friction. Likewise, several graphene nanoparticles from the tribo-film were adsorbed in the machined surface's micro-porosities. The presence of graphene in the tribo-film and its adsorption on the machined surface was verified not only by the improved machining efficiency but also by the excellent wear resistance. Owing to the weak van der Waals forces that hold the multilayers of graphene together, they have a low shearing power [50]. The existence of graphene in the tribo-film and the interlayer slip behavior of the graphene resulted in a decrement in the contact surface between tool and workpiece, which resulted in enhanced surface morphology and machining efficiency. SEM inspection and intensity analysis of the machined surfaces also revealed

a high degree of surface quality. Likewise, graphene nano-additives in vegetable oil resulted in decreased surface roughness, cutting force, cutting temperature, and tool wear values. Furthermore, Nickel-based alloys exhibit low thermal conductivity, and sunflower oil used as a lubricant demonstrates poor stability as well. Heat transfer from the cutting zone was necessary for maintaining the dimensions and integrity of the surface. Although the chosen vegetable oils had a low thermal conductivity, the graphene reinforcement in the vegetable oil compensated for this shortcoming since graphene has high conductivity and surface area. Fig. 16 depicts the SEM image and intensity analysis of a sample machined with various lubricating mediums. Where, the sample milled in the dry condition displayed significant surface irregularities including surface burns and maximum intensity, as shown in Fig. 16. Flooded and vegetable oil-based MQL mediums had resulted in mild feed marks and the values of intensity confirms this result. Finally, 0.7% graphene concentration in sunflower oil shows the absence of surface burns, feed marks, and surface cracks. Hence, it was established that nanoplatelets possess supreme tribological characteristics which can be utilized as tribological additives in vegetable oils.

4. Conclusions

Graphene-based nanofluid with variable concentration was formed and characterized. The absorbance, thermal conductivity, viscosity, and wettability of the formed nano-green oils were used to optimize their concentrations. Hard milling experiments were executed under dry, flooded, sunflower oil, and 0.7% graphene reinforced sunflower oil medium. The findings are as follows:

- Spectrophotometric analysis showed that pure sunflower oil has an absorbance of 0.54, and absorbance potential steadily increases as graphene is deposited. The maximum absorbance value was observed at 0.7% graphene concentration, indicating that graphene reinforcement has reached its saturation stage. After reaching saturation, a decrease in absorbance was detected.
- The thermal-physical property analysis showed that nanoparticle deposition tremendously increases the thermal conductivity of Sunflower oil. However, after 0.7% graphene deposition, the thermal conductivity was reduced gradually.
- The dynamic viscosity of nano-green oils was improved by increasing the graphene concentration. However, beyond 0.7% concentration, a lessening in viscosity value is observed. The dynamic viscosity of 0.7% nano-green oil at 34 °C was increased by 10.18% as compared to pure sunflower oil.
- Surface wettability analysis showed that 0.7% graphene reinforced sunflower oil exerts less contact angle value as compared to pure Sunflower oil. It is due to the graphene-based nanofluid's lower surface tension as compared to sunflower oil.
- Among four lubricating mediums, the minimum machining responses are obtained in a nano-green

medium containing 0.7% of graphene. It reduces the amount of surface roughness, cutting force, cutting temperature, and tool wear by about 49%, 25%, 31%, and 20% respectively as compared to the dry medium.

- SEM micrographs demonstrated that Adhesive wear was the governing wear mode in different lubricating mediums, and nano-green medium is unable to alter the mode of failure.
- The existence of graphene in the tribo-film and the inter-layer slip behavior of the graphene resulted in a decrement in the contact surface between tool and workpiece, which resulted in enhanced surface morphology and machining efficiency.

Author contribution

Mohd Danish: Investigation, Formal analysis, Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **Munish Kumar Gupta:** Conceptualization, Writing – review & editing. **Saeed Rubaiee:** Investigation, Formal analysis, Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **Anas Ahmed:** Investigation, Formal analysis, Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **Murat Sarikaya:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

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