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# Influence of the graphene nanoplatelets addition to corn oil on surface quality and machining performance

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**Abstract**

Cooling using cutting fluid in the CNC machining process of AISI 1045 steel is crucial for producing products with good surface quality. However, the long-term use of cutting fluid can have negative impacts on both the environment and human health. This study aims to analyse the characterisation and machining performance of corn oil-based cutting fluid with added graphene nanoplatelets (GNPs) using the minimum quantity lubrication (MQL) method. It demonstrates the potential of corn oil-based cutting fluids with the addition of GNPs to enhance surface quality (surface roughness) and machining performance (tool morphology and chip morphology). Machining was performed at a cutting speed of 110 m/min, a depth of 1.5 mm and a feed rate of 0.12 mm/rpm. MQL was applied with a spray angle of 45°, distance of 20 mm, pressure of 4 bar and nozzle diameter of 2 mm. Several conditions were used in the study, including dry, MQL with corn oil, and MQL with corn oil and added GNPs (0.10 to 0.30 wt. %). The results showed that the cutting fluid reduced surface roughness by 74 % compared to dry cutting conditions. The tool morphology showed a thin graphene layer, which can reduce friction and minimise built-up edge. This condition was also supported by examination of chip morphology, where a GNPs percentage of 0.25 wt. % produced C-shape chips, indicating high deformation.

## 1. Introduction

Milling machining is fundamental to the automotive, aerospace and electronics industries. This process can produce high-precision products with tight tolerances and excellent surface quality [1]. One of the most commonly used techniques in the manufacturing industry is high-speed CNC milling. This technique effectively machines hardened steel, reduces tool wear and improves the surface quality of the machined product [2].

AISI 1045 is a low-carbon steel that is often used in industrial machining because it has advantages such as good mechanical properties, toughness and strength. It has high tensile strength and good wear resistance, making it widely used in manufacturing mechanical components such as shafts, gears and cutting tools. Moreover, AISI 1045 steel is heat treatable, allowing its mechanical properties to be adjusted to meet industrial needs. However, AISI 1045 is susceptible to corrosion during machining, particularly when mineral oil is used as a cutting fluid in flood lubrication systems. Using mineral oil can accelerate surface corrosion, harm the environment and increase health risks for operators due to the release of toxic substances [3]. As an alternative, some industries implement dry cutting to reduce the risk of corrosion. However, this approach has a disadvantage: a significant rise in temperature in the cutting zone, which may accelerate tool wear and reduce manufacturing efficiency [4].

The use of vegetable oil-based cutting fluids has been researched to reduce environmental impact and improve surface quality. The surface quality of a component is essential in determining its performance and longevity, particularly in terms of fatigue, wear and corrosion [5]. Therefore, many studies focus on developing eco-friendly machining strategies. One promising approach is the use of bio-based cutting fluids, such as vegetable oil. Compared to mineral oil, these fluids are safer for both the environment and workers' health [6]. In addition to functioning as a lubricant and heat transfer medium, this fluid is more sustainable and has the potential to improve machining efficiency.

Corn oil is one of the bio-based cutting fluids that has gained significant attention. As a more sustainable fluid, corn oil is biodegradable and nontoxic. Additionally, its polyunsaturated fatty acid content, such as linoleic acid, provides excellent lubrication properties. However, pure corn oil still has limitations in fully optimising machining performance. Therefore, further modifications are necessary to enhance the required properties for machining applications [7]. In order to exceed the limit of corn oil in machining applications, this study explores the use of graphene nanoplatelets (GNPs) as an additive to enhance corn oil's thermal properties, lubrication and wear resistance [8]. In this context, a corn oil-based cutting fluid with the addition of GNPs presents a promising alternative. GNPs exhibit high thermal conductivity, superior lubrication properties and excellent chemical stability. This material is capable of reducing friction, minimising tool wear and enhancing machining performance [9]. Besides reducing environmental impact, adding GNPs to corn oil also enhances the surface quality of machined products and extends tool life, thereby supporting more sustainable machining.

Several previous studies have developed research related to cutting fluids containing nanoparticles. The study of Zhang et al. [10] comprehensively compared cutting fluids based on vegetable oils. Vegetable oils have limitations in thermal oxidation, which leads to degradation during high-temperature machining processes. Therefore, the method of adding nanoparticles such as graphene has been proven to minimise cutting forces (19.2 – 33.8 %) and tool wear (20 – 36 %) compared to base oil. Furthermore, Hu et al. [11] studied the improvement of cutting fluid using nanoparticles. The use of 0.2 wt. % of multi-walled carbon nanotubes in the turning process of Ti-6Al-4V material resulted in a 34 % reduction in tool wear, a 28 % reduction in cutting force and a 7 % reduction in surface roughness. These results were compared with those obtained using conventional cooling. Cui et al. [12] and Zhang et al. [13] studied MQL cooling using biolubricant in the grinding of aerospace materials. The results showed that with a high-viscosity biolubricant and the addition of nanoparticles with high thermal conductivity properties, machining temperatures can be effectively reduced by 15 – 25 %. Zhang et al. also indicated that the addition of nanoparticles to grinding cooling can reduce the temperature by 31.6 %. Furthermore, Liu et al. [14] analysed the temperature of cryogenic cooling air in relation to the physical properties of the lubricant. Numerical and experimental results show that at an air pressure of 0.4 MPa and a flow temperature of − 50 °C, the average droplet particle size reaches 133.5 µm, with an 8.2 % deviation from the theoretical model.

Based on previous research, the use of base fluids such as corn oil has long-term performance limitations, particularly in terms of thermal characteristics. Thermal characteristics can be improved by adding GNPs. They have good thermal conductivity characteristics and the ability to form a protective layer in tribological applications. Several previous studies have reported the use of GNPs, but their number is very limited for corn-based oils, particularly with CNC machine cooling systems using minimum quantity lubrication (MQL). This study is complementary, as it analyses rheological characteristics and more specific machining results, such as the morphology of chips produced during the machining process using corn oil enriched with GNPs. Thus, this study provides a new contribution to the development of biolubricant-based CNC machining cooling systems.

## 2. Materials and methods

### 2.1 Materials

This study utilises corn oil as the base fluid, modified with graphene nanoparticles to form a cutting fluid. Corn oil was chosen for this study because it contains higher levels of polyunsaturated fatty acids (PUFAs) than other types of vegetable oil. PUFAs act as temperature stabilisers during the machining process. The used graphene nanoplatelets (GNPs) were KNG-150 manufactured by Knano Graphene Technology (China), with a purity of 99 %, a thickness of 5–10 nm and a width of 10 µm (width measured horizontally across the layer). The used corn oil was obtained from a supermarket (Mazola, brand produced by ACH Food Companies, USA). This corn oil has no synthetic additives and has undergone a refining process. The workpiece material for machining was AISI 1045 steel, with dimensions of 50 × 50 × 20 mm. This steel has a tensile strength of 570 MPa, a hardness of 220 HB and excellent machinability, making it highly suitable for industrial applications. The general composition of AISI 1045 is presented in Table 1 [15].

**Table 1.** Chemical composition of AISI 1045 steel

| Element | C | Si | Mn | P | Fe |
|---|---|---|---|---|---|
| wt. % | 0.445 | 0.226 | 0.635 | 0.009 | balance |

## 2.2 Cutting fluid preparation

The cutting fluid mixture of corn oil and GNPs was prepared using a two-step method. First, the GNPs were accurately weighed using an analytical balance OPD-E204 (Optima, ± 0.1 mg) at various concentration levels. The GNPs concentration was set at 0.10, 0.15, 0.20, 0.25 and 0.30 wt. % of the corn oil. These concentrations were chosen because the optimum percentage is generally below 0.5 wt. %. Increasing the concentration will cause agglomeration. Furthermore, the concentration selection also aims to analyse the optimum increasing trend without the risk of agglomeration. Each GNPs concentration was then added to 200 ml of corn oil. The cutting fluid mixture was then placed in a beaker and stirred using a magnetic stirrer (Thermo Scientific) at 1250 rpm for 20 minutes to achieve initial dispersion. Next, the mixture underwent sonication using an ultrasonic homogeniser LUH-103 (Labocon) for 30 minutes to ensure dispersion stability and minimise graphene particle agglomeration. To avoid agglomeration, several steps need to be considered, namely: GNPs are dried first, then dispersed in corn oil for 30 minutes using bath sonication and after that, external cooling is carried out for 15 minutes using probe sonication, which aims to prevent agglomeration due to temperature increases. After preparation, the cutting fluid is directly used in the machining process to avoid precipitation.

## 2.3 Characterisation

Material characterisation aims to identify the properties of GNPs, including morphology, crystal size and chemical compounds, to understand the material's behaviour in specific applications. This analysis is particularly important for additive materials, as their composition, shape and size can influence the thermophysical properties and performance of cutting fluids in machining processes. In this study, the characterisation methods used include scanning electron microscopy (SEM) with a FEI Inspect S50, X-ray diffraction (XRD) with a PANalytical X'Pert PRO, and Fourier transform infrared spectroscopy (FTIR) with a Shimadzu IRPrestige-21.

The density measurement of the cutting fluid was conducted using a pycnometer according to ASTM D4052 standard at a temperature of 25 °C. Each sample was tested three times to ensure consistency in the results. After the sonication process, the samples were weighed using an analytical balance, and their volume was measured using a graduated cylinder or pycnometer. The cutting fluid density was calculated based on these measurements.

A viscometer NDJ-8S (Chongqing Drawell Instrument Co.) was used to measure the dynamic viscosity of the cutting fluid at temperatures ranging from 30 to 100 °C. Each sample was tested three times to ensure consistency in the results. The average dynamic viscosity of the samples was then calculated.

The thermal properties analyzer KD2 Pro was used to measure the thermal conductivity of the cutting fluid with the Modified Transient Plane Source method at a temperature of 30 °C. Each sample was tested three times to ensure consistency in the results. The average thermal conductivity value of the samples was then calculated.

## 2.4 Machining of AISI 1045

The machining experiments utilised a CNC milling machine SuperMill MK 2.0 (DTech-Engineering), equipped with a 4-flute high speed steel (HSS) tool and an AISI 1045 steel workpiece. This study employed several lubrication conditions (MQL lubrication with investigated cutting fluids), including dry machining (without lubrication). All machining were performed using the same parameters. The machining results were analysed based on worn surface morphology, surface roughness, and chip morphology using a SEM. The machining parameters are presented in Table 2, while the experimental setup is shown in Figure 1. The MQL parameters used an air pressure of 4 bar, a cutting fluid rate of 40 ml/hour. The distance and angle of the lubricant flow were 20 mm and 45°, respectively. These parameters are set as constants to indirectly examine the agglomeration of the cutting fluid.

**Table 2.** CNC machining parameters

| Parameter | Value |
|---|---|
| Spindle speed | 4000 rpm |
| Feed rate | 0.12 mm/rpm |
| Depth of cut | 1.5 mm |
| Cutting speed | 110 m/min |
| Spraying method | MQL |
| Spray angle | 45° |
| Spray distance | 20 mm |
| Air pressure | 4 bar |
| Nozzle diameter | 2 mm |
| Workpiece | AISI 1045 steel |
| Tool | HSS |
| Machining type | Facing |

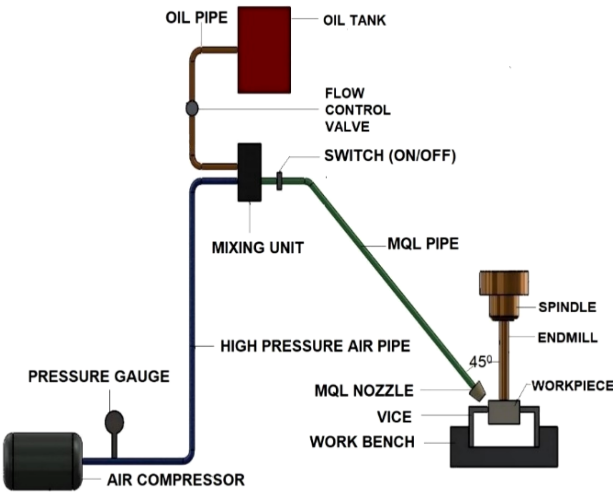



**Figure 1.** Experimental process of AISI 1045 steel milling with MQL

Surface roughness measurements were performed using a Surftest SJ-410 (Mitutoyo) on the surface of AISI 1045 steel after CNC machining. Surface roughness parameters included a stylus radius of 2 µm, a Gaussian filter, a cut-off length of 0.8 mm and a cut-off number of 5.

## 3. Results and discussion

### 3.1 Materials characterisation

Figure 2 presents the surface morphology of GNPs, captured through SEM imaging at magnifications of 20,000 and 50,000 ×. This analysis reveals that the GNPs exhibit a characteristic platelet-like structure [16]. Figure 2 illustrates the rough and irregular surface of GNPs, with some particles exhibiting wrinkled features, microindentations and an imperfect layered structure. These characteristics increase the material's specific surface area, which influences its mechanical properties. Additionally, the surface roughness affects interparticle friction and interlayer bonding strength, enabling more complex interactions through mechanical interlocking and van der Waals forces. The layered morphology of GNPs and their large surface area allow for the formation of tribological layers which can reduce friction.

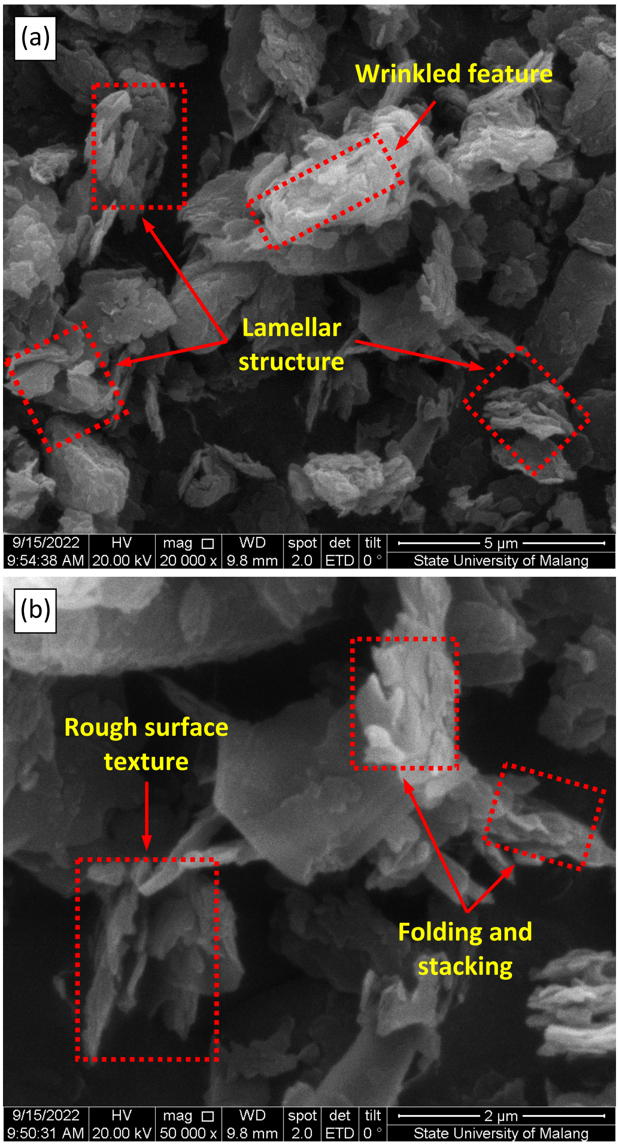



**Figure 2.** Graphene morphology at magnifications of: (a) 20,000 × and (b) 50,000 ×

GNPs were selected as lubricant additives due to their high surface area and unique platelet morphology. Their rough texture enhances the dispersion stability of the corn oil-based cutting fluid by strengthening interactions between the nanoparticles and the oil through mechanical bonding while also minimising particle agglomeration. Additionally, the layered structure of GNPs enables more efficient thermal conduction channels, resulting in improved thermal conductivity of the cutting fluid. In machining applications, corn oil-based cutting fluid with rough-textured GNPs improves lubrication, reduces friction and extends cutting tool life. The GNPs form a stable protective layer on the tool and workpiece surfaces, resulting in optimised machining efficiency and sustainability [17].

The crystal structure of GNPs was analysed using XRD, as shown in Figure 3. The XRD results show sharp peaks at 2θ = 26.4336° (plane (002)) and 2θ = 54.5347° (plane (004)), indicating the characteristic hexagonal crystal structure of graphene. The plane (100) is also seen as the peak at 2θ = 43°, indicating a structure typical for GNPs. These findings confirm that the used nanomaterial consists of high-quality GNPs.

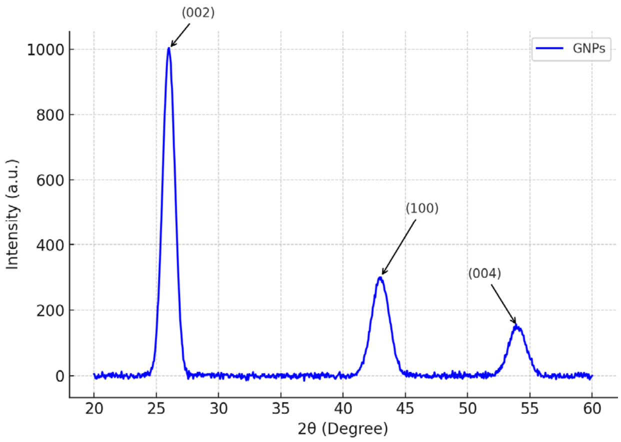



**Figure 3.** XRD analysis of GNPs

Additionally, the average crystal size was calculated using the Scherrer equation, yielding a value of 31.889 nm at 26.4336° with a Full Width at Half Maximum of 0.2558 [18]. The crystallite size in question is the average size of the stack of graphene crystallites perpendicular to the surface.

The FTIR analysis indicates complex interactions between corn oil and GNPs, as shown in Figure 4. The FTIR spectrum identifies hydroxyl groups in the 3600 – 3400 cm$^{-1}$ range, originating from free fatty acids and oxidation products of corn oil, which interact with GNPs through hydrogen bonding and electrostatic interactions. Peaks in the 3000 – 2800 cm$^{-1}$ range indicate shifts in $CH_2$ and $CH_3$ vibrations after mixing with GNPs, suggesting van der Waals interactions between the hydrocarbon chains of corn oil and the graphene surface. A strong peak around 1750 cm$^{-1}$, associated with C=O stretching vibrations from ester groups, shows intensity fluctuations, indicating π–π interactions between carbonyl groups and the graphene surface. Additionally, spectral variations in the 1500 – 500 cm$^{-1}$ range confirm modifications in the molecular structure of corn oil.

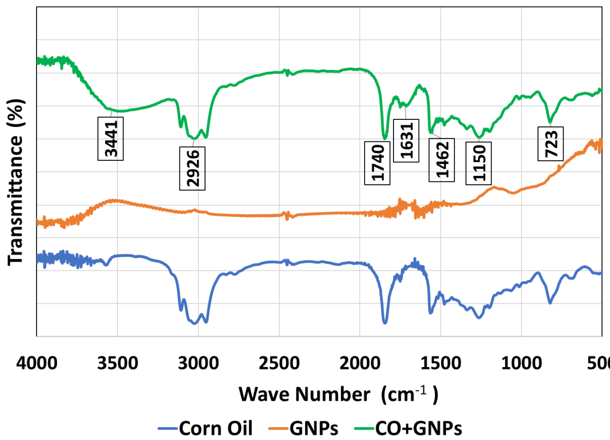



**Figure 4.** FTIR analysis of corn oil (CO), GNPs and cutting fluid (CO + GNPs)

The molecular interactions form a stable dispersion system with a uniform distribution of GNPs in corn oil. This stability is supported by hydrogen bonding between the hydroxyl groups in corn oil and oxygen-containing groups in oxidised GNPs, as well as dipole interactions with π-electrons in graphene. Kinetic and thermodynamic factors, such as hydrogen bonding and Gibbs free energy, influence the system's stability. The hydrophilic mechanism facilitates the formation of a cutting fluid layer during the grinding process, thereby improving the stability and distribution of particles in the cutting fluid-based lubrication, which enhances optimal performance.

A condensation reaction involving GNPs, hydroxyl groups and linoleic acid yields ester bonds. This reaction effectively couples the hydroxyl groups on the GNPs with the carboxyl groups of linoleic acid. GNPs interact with linoleic acid through ester bonds formed via a condensation reaction between hydroxyl groups on GNPs and carboxyl groups of linoleic acid. This process will release $H_2O$, which plays a role in improving the stability of GNPs in polar liquids. Increasing the stability of GNPs will be particularly beneficial in corn oil-based lubricants, providing improved lubrication efficiency and heat transfer properties. The ester bonds strengthen the interaction between GNPs and polar compounds, increasing their effectiveness in cutting fluid, lubricant and composite material applications.

### 3.2 Cutting fluid characterisation

The density measurement results of corn oil-based cutting fluid enriched with GNPs at 25 °C are presented in Figure 5. The graph shows that as the concentration of GNPs increases, the density of the cutting fluid also increases. However, the increase is not significant. This phenomenon occurs due to various factors, including the relatively low volume fraction of GNPs compared to corn oil. In addition, this can occur because the GNPs are well dispersed in the solution, which means there is no agglomeration in the cutting fluid, so that the average overall density will approach the value of the base fluid (corn oil) [19]. The relationship between density and GNPs content is linear, with the highest density noticed at a GNPs content of 0.3 wt. %. This increase in density is influenced by factors such as particle size, bond strength and particle packing density, as well as structural nonhomogeneities and the presence of graphene bubbles. Furthermore, effective dispersion further contributes to the increase in density.

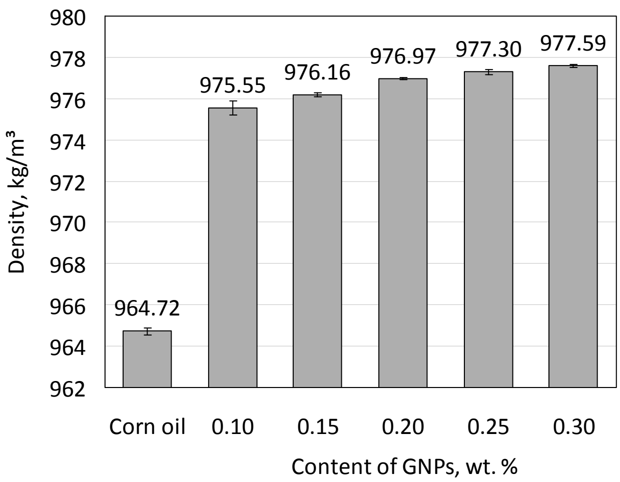



**Figure 5.** Density of the cutting fluid for various GNPs contents

Experimental viscosity testing was conducted at temperatures ranging from 30 to 100 °C. The detailed test results are presented in Figure 6. As the temperature increases, the viscosity of the cutting fluid decreases, thereby enhancing the efficiency of the cutting fluid, lowering the cutting temperature and increasing tool longevity. The highest viscosity at a GNPs content of 0.25 wt. % enhances lubrication by forming an effective lubricating film, which reduces tool wear and maintains machining stability. High viscosity minimises vibrations, preserves thermal stability and produces a smoother surface. This condition also improves cutting precision and surface quality by retaining heat in the cutting zone. Additionally, the inclusion of nanoparticles enhances the thermal performance of the cutting fluid. However, excessive viscosity can impede the flow of cutting fluid and reduce cooling efficiency [20].

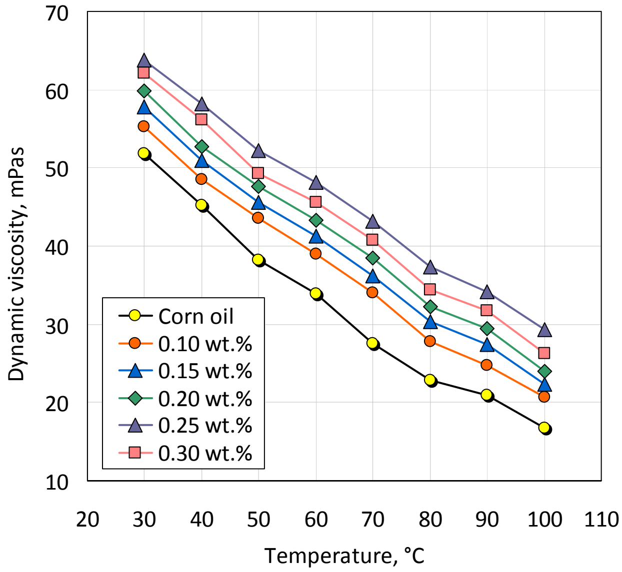



**Figure 6.** Dynamic viscosity of the cutting fluid for various GNPs contents

Viscosity decreases at contents above 0.25 wt. % due to several factors, such as particle agglomeration, dispersion stability and two-layer lubrication. Agglomeration occurs at high concentrations due to the effects of van Der Waals forces. This agglomeration reduces the molecular bond between GNPs and corn oil due to the reduced effective particle area. Furthermore, viscosity decreases because most GNPs at high concentrations form a rolling effect between molecules, facilitating fluid flow [21]. These results are consistent with previous studies indicating that the addition of nanoparticles to the base oil increases the viscosity of the mixture. The increase in cutting fluid viscosity due to the addition of nanoparticles occurs because of the interactions formed between nanoparticles within the base oil, which hinder the movement of fluid molecules [22]. These interactions create a network-like particle structure that restricts the movement of base oil molecules, resulting in increased viscosity [23].

The graphical analysis in Figure 7 shows that thermal conductivity increases from 0.1610 to 0.1620 W/mK, reflecting an increase of approximately 1.24 %. This increase demonstrates a positive correlation between nanoparticle concentration and thermal conductivity, despite a slight decrease at a content of 0.15 wt. % (0.1612 W/mK), which is commonly noticed in cutting fluid systems. The addition of nanoparticles enhances heat transfer by expanding the surface area, although it also increases fluid viscosity. However, the improvement in thermal conductivity remains within an acceptable range without significantly hindering fluid flow. Overall, the thermal conductivity of the cutting fluid is influenced by several factors, including nanoparticle concentration, nanoparticle material type and temperature [24].

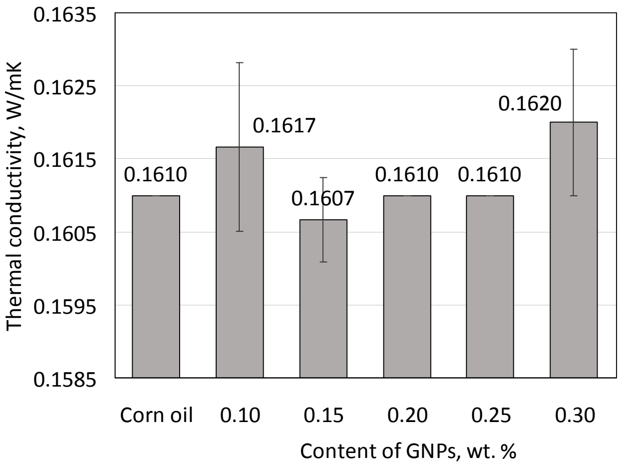



**Figure 7.** Thermal conductivity of the cutting fluid for various GNPs contents

A decrease in thermal conductivity occurred at a GNPs content of 0.15 wt. %. This condition occurs due to micro-agglomeration, which significantly reduces the effective surface area of the molecules and increases thermal resistance [19]. Furthermore, the effects of non-monotonic conditions, where dispersion and interfacial resistance influence, prevent thermal conductivity from increasing significantly with particle addition [25]. Nanoparticles with high thermal conductivity are more effective in enhancing the thermal conductivity of cutting fluid. Additionally, an increase in nanoparticle concentration within the fluid correlates directly with improved thermal conductivity. The moderate enhancement of thermal conductivity in GNPs-enriched corn oil provides benefits in improving cooling efficiency during machining processes. Cutting fluids with high thermal conductivity are more effective in transferring heat away from the cutting zone, thereby reducing cutting temperatures and preventing tool wear more efficiently [26].

### 3.3 Machining performance test

SEM image analysis of worn surfaces morphology indicates that adhesion and abrasion mechanisms have a significant impact on tool wear. Figure 8 presents the tool wear and surface morphology analysis for CNC milling of AISI 1045 under dry cutting conditions and using the MQL method with corn oil and cutting fluid containing GNPs at contents ranging from 0.10 to 0.30 wt. %. Dry cutting conditions surface appears as quite thick adhesion flakes, and wear also extends to the sides, with microcracks present. This condition occurs due to the occurrence of high temperatures between the tool surface and the workpiece. Cooling with corn oil appears to reduce wear on the side, but there is an appearance of built-up edge (BUE) on the tool surface. The presence of cutting fluid with GNPs contents ranging from 0.1 to 0.2% wt. % shows a layer of GNPs on the tool surface, which is smoother than in corn oil and dry cutting conditions, and microcracks begin to decrease. The GNPs content of 0.25 wt. % wt is the optimal because the layer of GNPs formed on the tool surface looks more homogeneous, the wear area is reduced and the tool surface looks clean. The GNPs content of 0.3 wt. % shows a slightly nonhomogeneous GNPs layer when compared to 0.25 wt. %.

Morphological analysis indicates significant differences between new and used tools, particularly under dry cutting conditions, where flank wear, microcracks and chip adhesion are noticed. The application of cooling fluid containing GNPs at contents ranging from 0.10 to 0.30 wt. % reduces tool wear by forming a GNPs layer on the tool and workpiece surfaces due to adhesion forces and electrostatic interactions. High pressure and elevated temperatures during machining enhance the mobility of GNPs, enabling uniform dispersion in the contact zone. This layer acts as a protective barrier, reducing friction and preventing direct contact of the surfaces. Its presence significantly improves tool life, surface quality and machining efficiency. The morphological examinations of the worn surface when the GBPs content was 0.25 wt. % showed better results compared to dry cutting. This is indicated by less chip adhesion, a more even distribution of the thin film of GNPs on the tool surface and the absence of scratches or fractures. While dry cutting accelerates tool wear, the use of cutting fluid not only mitigates wear but also lowers cutting temperatures and minimises BUE formation. These findings align with existing literature, confirming the effectiveness of cutting fluid in improving tool longevity.

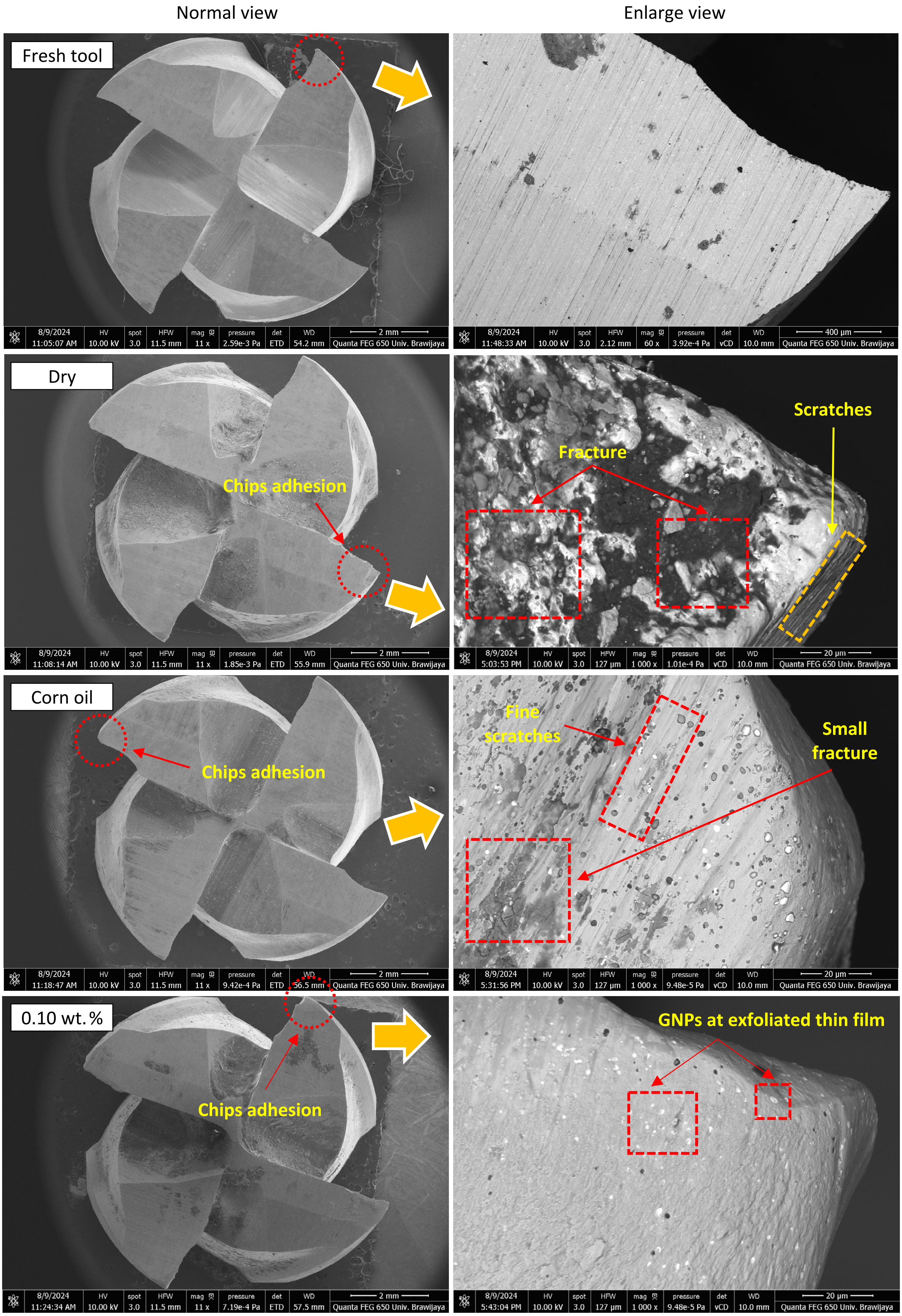



**Figure 8.** SEM images of worn surfaces morphology for various GNPs contents

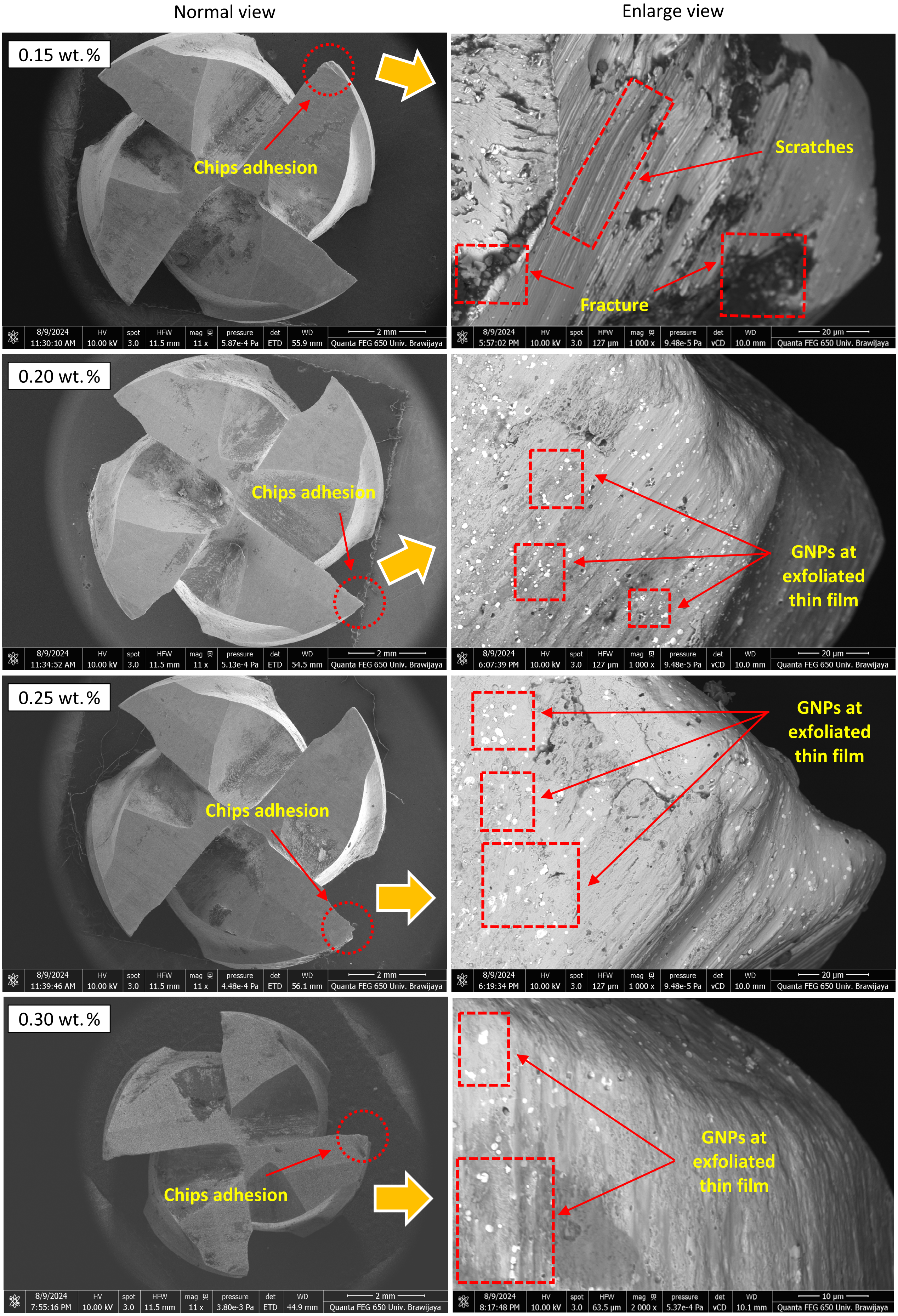
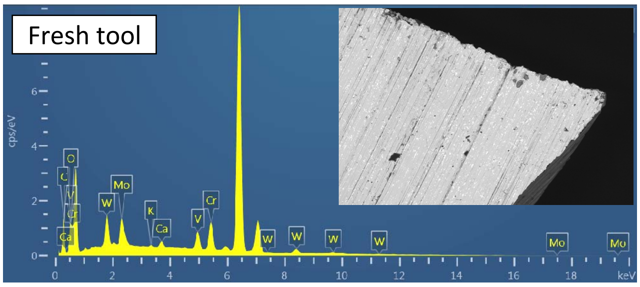
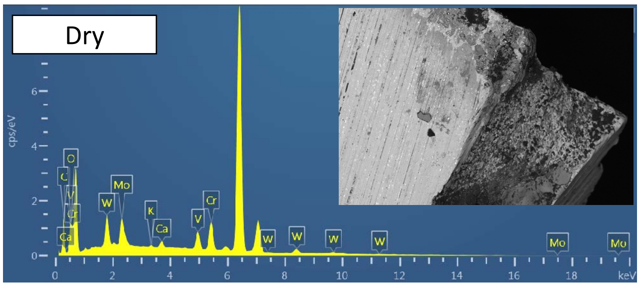


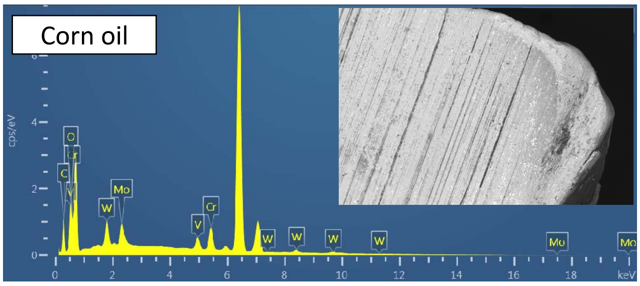

**Figure 8.** *Continued*



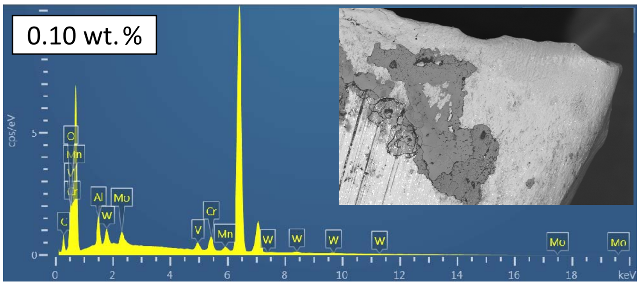

| Element | Fe | C | O | Cr | Mo | W | V | Ca | K |
|---|---|---|---|---|---|---|---|---|---|
| wt. % | 58.07 | 19.87 | 5.66 | 3.77 | 4.07 | 5.64 | 2.30 | 0.47 | 0.13 |



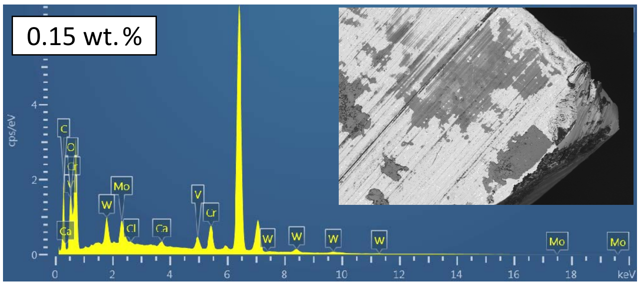

| Element | Fe | C | O | Cr | Mo | W | V | Ca | Al |
|---|---|---|---|---|---|---|---|---|---|
| wt. % | 38.64 | 34.32 | 17.79 | 2.24 | 2.03 | 2.50 | 1.00 | 0.27 | 1.22 |



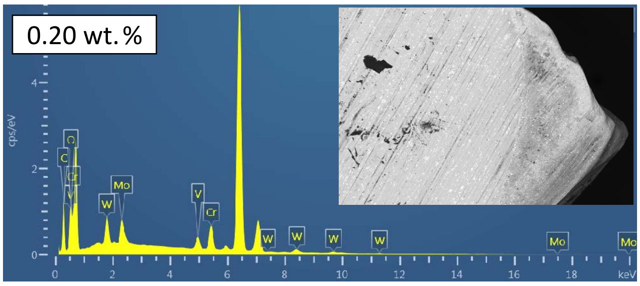

| Element | Fe | C | O | Cr | Mo | W | V |
|---|---|---|---|---|---|---|---|
| wt. % | 61.38 | 16.55 | 9.38 | 3.29 | 3.32 | 4.49 | 1.60 |



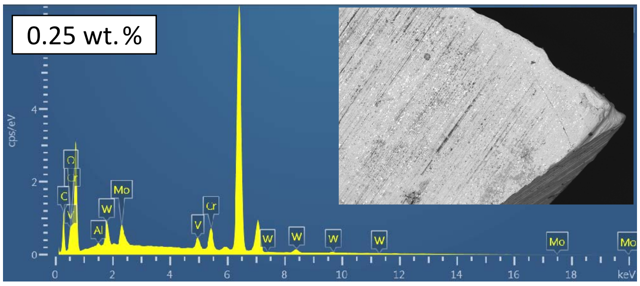

| Element | Fe | C | O | Cr | Mo | W | V | Mn | Al |
|---|---|---|---|---|---|---|---|---|---|
| wt. % | 69.47 | 10.96 | 8.15 | 2.13 | 2.24 | 2.43 | 1.11 | 0.58 | 2.93 |



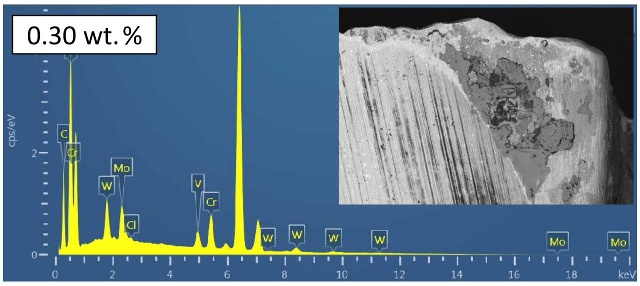

| Element | Fe | C | O | Cr | Mo | W | V | Ca | Cl |
|---|---|---|---|---|---|---|---|---|---|
| wt. % | 52.15 | 26.02 | 10.31 | 3.01 | 3.04 | 3.61 | 1.37 | 0.36 | 0.13 |




| Element | Fe | C | O | Cr | Mo | W | V |
|---|---|---|---|---|---|---|---|
| wt. % | 57.23 | 22.13 | 8.11 | 3.38 | 3.59 | 4.08 | 1.49 |




| Element | Fe | C | O | Cr | Mo | W | V | Al |
|---|---|---|---|---|---|---|---|---|
| wt. % | 62.31 | 20.30 | 4.38 | 3.12 | 3.25 | 4.76 | 1.58 | 0.29 |




| Element | Fe | C | O | Cr | Mo | W | V | Cl |
|---|---|---|---|---|---|---|---|---|
| wt. % | 40.06 | 21.57 | 26.09 | 3.31 | 3.45 | 3.88 | 1.48 | 0.16 |

**Figure 9.** EDS results of worn surfaces for various GNPs contents

Figure 9 presents the EDS analysis results. CNC milling with cutting fluid containing GNPs shows a higher percentage of C and O elements on the tool surface compared to machining with cutting fluid without GNPs. The use of MQL in CNC milling increases the concentration of C and O elements, indicating the presence of graphene from the cutting fluid. Consequently, the nanographene lubricant forms a thin lubricating layer that reduces friction and enhances the performance of CNC milling. The concentration of carbon appears to increase with increasing content of GNPs. The highest peak is obtained at a GNPs content of 0.3 wt. %, with a value of 35 wt. %. This increase indicates that the GNPs layer acts as a protective carbon layer on the tool surface. Conversely, a decrease in oxygen occurs at high GNPs contents, leading to oxide reduction and a decrease in cutting area heat during the machining process.

The element distribution graph in Figure 10 shows that GNPs-enriched cutting fluid enhances lubrication by increasing carbon content and reducing oxidation, as indicated by a decrease in oxygen levels. At a GNPs content of 0.30 wt. %, the lubrication effect is the most significant, where the carbon content reaches 35 wt. %. Therefore, the use of cutting fluid enriched with 0.25 – 0.30 wt. % GNPs is recommended to minimise tool wear and improve cutting performance.

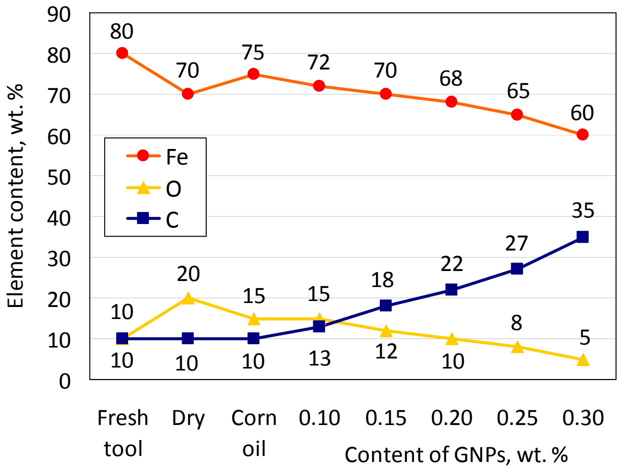



**Figure 10.** Element distribution on the tool surface for various GNPs contents

Surface roughness measurements of surfaces machined under dry cutting conditions and with cutting fluid with various GNPs contents are shown in Figure 11. Machining conditions influenced the surface quality in CNC milling. The reduction in surface roughness is attributed to the enhanced lubrication properties of corn oil-based cutting fluid with the addition of GNPs. A refined surface enhances the product's visual quality and reduces the risk of moisture or corrosive substance accumulation, which could accelerate corrosion. Additionally, a smooth surface lowers stress concentration points, resulting in an extended lifespan and improved strength of the machined components.

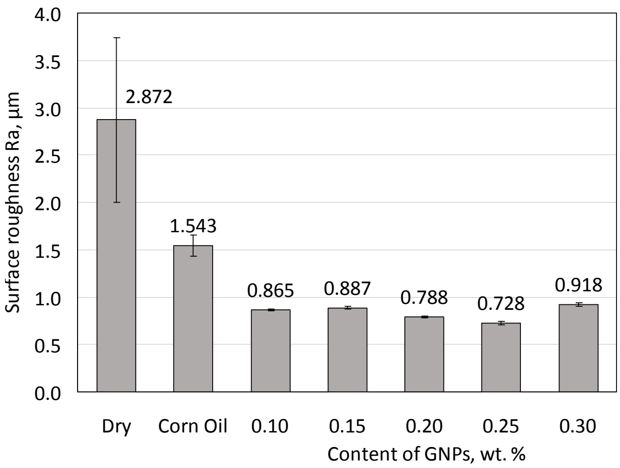



**Figure 11.** Surface roughness of the machined surface for various GNPs contents

The test results indicate that the addition of 0.25 wt. % GNPs to corn oil reduces the workpiece surface roughness by up to 74 % compared to dry machining. These findings align with previous studies, which state that a vegetable oil-based cutting fluid can enhance the surface quality of machined components [27]. According to Manikanta et al. [28], nanoparticles increase the durability of both tool and workpiece surfaces compared to oil-based cutting fluids without nanoparticles, although the effect also depends on the concentration and dispersion stability.

Surface roughness also shows a slight increase for a cutting fluid containing 0.3 wt. % GNPs. This phenomenon is attributed to a reduction in viscosity, which causes the lubrication between the workpiece and the tool to become unstable. In addition, according to SEM morphology examinations, the GNPs layer on the tool surface is not homogeneous. Areas not coated with GNPs will increase friction, resulting in increased tool wear and higher surface roughness. According to recent research by Manikanta et al. [25], increasing the concentration of nanoparticles in cutting fluids results in a decrease in surface quality. Research by Abellán-Nebot et al. [29] also shows that if the shape/size of nanoparticles is not optimal, it will affect surface quality.

The analysis of chip morphology reveals details about the tool wear mechanisms during machining. Figure 12 presents the morphology of the chips, illustrating variations in chip shapes and surface structures based on experimental conditions. SEM examinations identified two primary types of chip morphology: C-shape chips and comma-shape chips. C-shape chips, which have a curved shape resembling the letter "C", indicate significant plastic deformation during cutting. These chips form when the machined material exhibits high plasticity, allowing continuous bending without fracturing. In contrast, comma-shaped chips, which are shorter and sharper, form when the material is more brittle or when higher cutting forces are applied, leading to rapid material fracture [30].

The examinations indicate that machining conditions influence chip formation. In dry machining, the chips are rougher due to the high friction that occurs in the absence of lubrication. In contrast, the use of corn oil/GNPs-enriched cutting fluid significantly alters chip structure, with an increasing dominance of C-shape chips as the GNPs content increases. This suggests that the addition of GNPs enhances the material's plastic

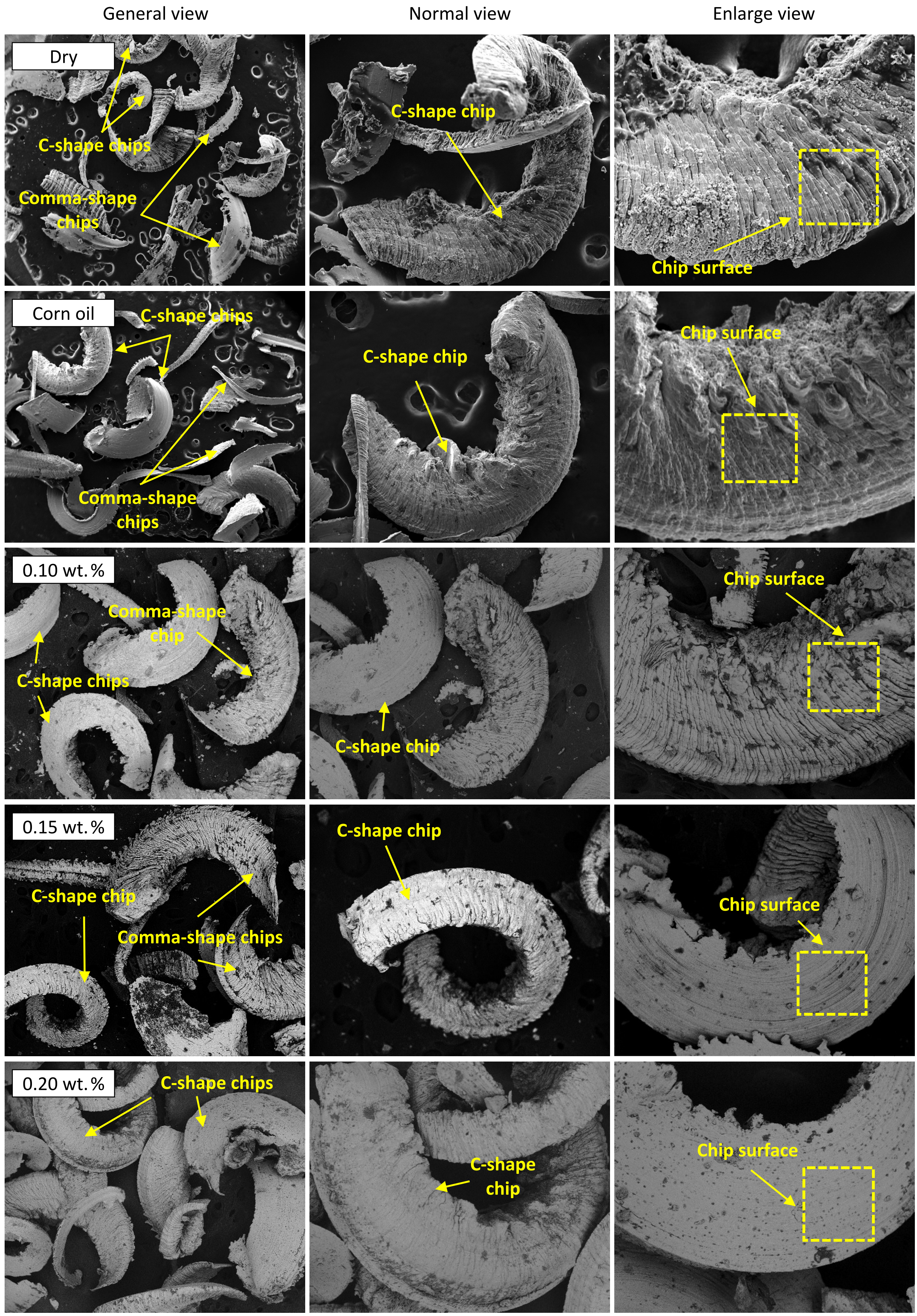



**Figure 12.** SEM images of chips morphology for various GNPs contents

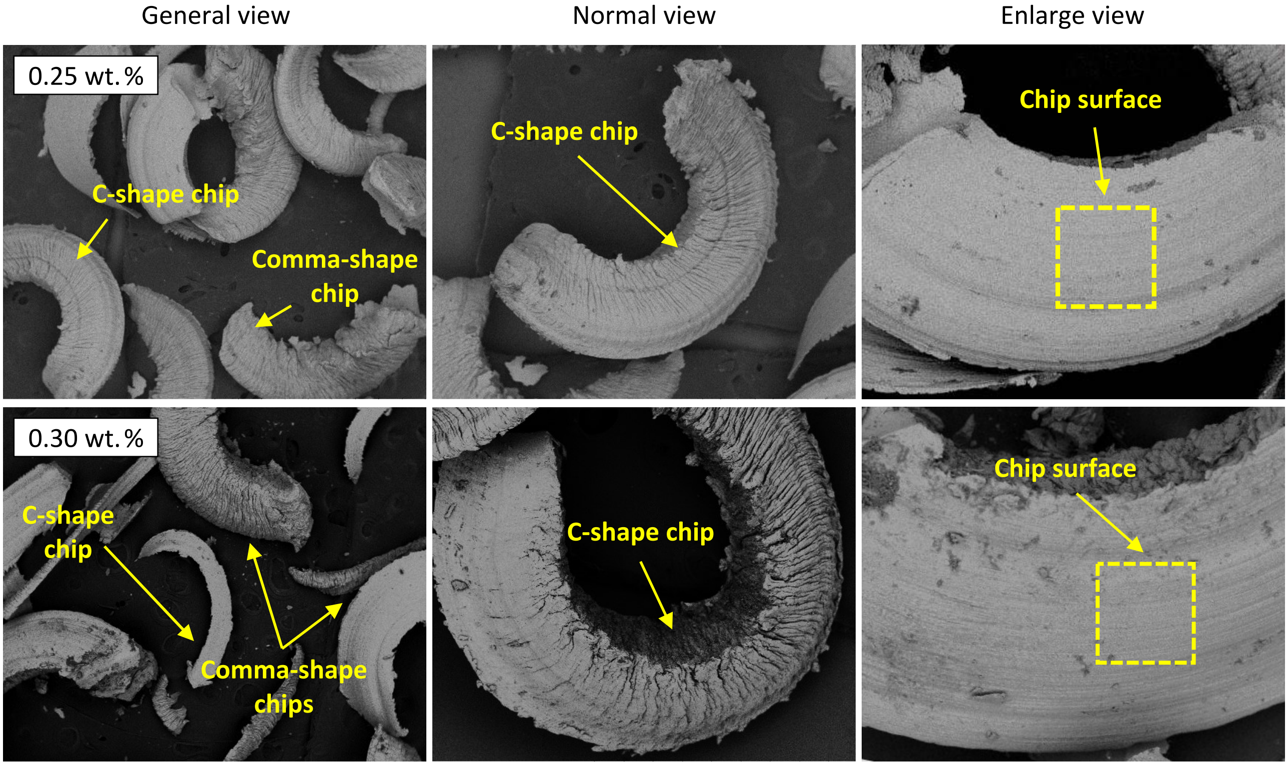



**Figure 12.** *Continued*

deformation and reduces friction, resulting in the formation of specific chip morphologies. Plastic deformation significantly influences chip formation, while the use of GNPs in a cutting fluid reduces friction, temperature and cutting forces. Optimal lubrication better controls plastic deformation, resulting in smooth chips, such as C-shape chips. In contrast, without lubrication, high friction causes irregular plastic deformation, leading to rough or fractured chips, such as comma-shaped chips.

## 4. Conclusion

The MQL CNC milling of AISI 1045 steel results were significantly improved by the addition of GNPs to corn oil. The optimal GNPs content in a cutting fluid was 0.25 wt. % because the results of the tool morphology examinations showed a more homogeneous distribution of the GNPs layer, and the EDS results also showed an increase in the carbon content.

The resulting surface roughness also decreased by 74 % compared to dry cutting conditions. However, at a higher GNPs content of 0.30 wt.%, agglomeration caused a slightly higher surface roughness, indicating optimal loading. In addition, chip morphology examinations confirmed that the addition of GNPs encourages the formation of smoother C-shaped chips and a protective layer on the tool surface.

Future work on this topic will involve further studies to determine the long-term optimal GNPs content, considering dispersion stability. Stability is needed to overcome agglomeration in a cutting fluid with 0.25 wt. % GNPs. Testing on different workpiece materials such as stainless steel, Inconel superalloys and titanium alloys as a generalisation of machining results is also planned, as well as further applications to machining for more specific products such as automotive, industrial and aircraft components.

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