Influence of the Viscosity of Nanofluids on Surface Roughness in End Milling of Nickel Alloys with Minimum Quantity Lubrication

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Abstract. Minimum Quantity Lubrication (MQL) using vegetable oils is considered a sustainable lubrication method, particularly for machining difficult-to-machine materials like nickel and titanium alloys. Although a significant influence of nanofluid viscosity on lubrication has been observed in MQL machining, as evidenced by limited literature, the influence of viscosity on MQL machining of difficult-to-machine materials like nickel alloys is yet to be established. This research aimed to study the influence of viscosity on the MQL end milling machining performance of Inconel 718 alloy. Three representative nanofluids were prepared using metallic (Cu), ceramic (Al2O3), and non-metallic (CNT) nanoparticles and palm oil. It was found that the CNT had a significant influence on viscosity at the same concentration, resulting in the highest viscosity of 433.2cP at 30oC. When the machining performance was investigated under different lubricating conditions (dry machining, flood cooling, and MQL), the viscosity of the nanofluids was observed to have a substantial influence on the machining performance. The CNT nanofluid with the highest viscosity penetrated the machining zone producing the lowest surface roughness with improved lubrication by 65.4% and 30.18% when compared with dry machining and flood cooling, respectively. The surface topography study confirmed the superior lubrication performance of CNT nanofluid. Overall, MQL milling with 0.5wt% nanoparticle concentration demonstrated effective machining performance when compared with dry machining and flood cooling.

1. Introduction

Machining is a manufacturing process in which a product is made by removing excess material from the stock. Turning, milling, drilling, and grinding are a few conventional machining processes adapted by any manufacturing industry. Higher productivity, enhanced surface quality, and lower cost in the modern manufacturing industry are prerequisites. During machining, the temperature rises at the point of contact between the cutting tool and the workpiece. The increased temperature in the cutting zone caused by excessive friction at the cutting tool and workpiece interface is undesirable [1]. Excess heat generation during machining reduces the surface finish and tool life and increases tool wear, primarily at higher speeds with higher feed rates. This problem becomes critical for materials such as nickel-based superalloys that are difficult-to-machine [2]. When machining superalloys, cutting fluids reduce the amount of generated heat. The flood cooling strategy is predominantly used to reduce the temperature in the area machined. However, it causes environmental issues and increases disposal costs. Dry machining is environmentally friendly and has null health hazards. However, it cannot substitute the flood cooling system due to uneconomical behavior in processing superalloys at higher cutting speeds. Tool wear and heat generation problems on and inside the workpiece and tool can't be dismissed [3].

Minimum Quantity Lubrication (MQL) is a technology wherein a thin layer of lubricant delivered in an atomized spray is coated on the interface between the cutting tool and the workpiece. This thin lubricant layer is particularly effective at reducing friction-generated heat. The quantity of lubricant consumed is very low. MQL with vegetable oil is a friendly solution for the global environment and the people who use it. The performance of the machining, however, falls short of that of traditional flood cooling. Introducing nanoparticles into vegetable oils has proven to enhance heat transfer comparatively. The size, shape, material, and concentration of nanoparticles all help to improve machining operations [4]. The effectiveness of MQL is only as good as the chosen lubricant. Saturated fatty acids outperform unsaturated fatty acids in lubrication [5]. Cottonseed and palm oils are better suited as base fluids in MQL environments [6]. Various experimental results showed that applying palm oil under MQL conditions as the cutting fluid was more efficient as it improved the machining performances. A key parameter for measuring machining performance is the surface quality of the machined part. The irregularities on the machined workpiece are identified by surface roughness. A lower roughness value indicates a longer workpiece service life. As a result, the lower the surface roughness rating, the better the machining. Surface roughness is primarily influenced by feed rate, then by depth of cut. Surface roughness, however, is inversely correlated with cutting speed [7].

The material of nanoparticles plays an important role in machining performance. Most literature shows that ceramic nanoparticles are commonly used in nanofluid preparation because of their ability to disperse well and remain stable for a relatively long time due to their oxidation resistance. However, studies on the influence of nanoparticle material on viscosity and machining are inconsistent and unreliable. For example, in an experiment by Li et al. [8] involving CNT nanofluid in grinding nickel alloy, it was reported that higher thermal conductivity accompanied by higher viscosity promoted efficient lubrication. However, another study by the same author reported that CNT nanofluids having high viscosity resulted in poor flow on the machining surface interface and thermal conductivity, limiting the heat transfer of the nanofluid and producing surfaces with a poor finish [9].

Based on the literature review, a significant amount of research has been done to examine the impact of thermal conductivity on MQL machining. But the results from the experiments conducted so far to study the influence of viscosity are limited and inconsistent. Thus, the influence of viscosity on MQL machining of difficult-to-machine nickel alloys was identified as the research gap. This research aimed to study the influence of particle material on the viscosity of nanofluids based on vegetable oil on the MQL machining of nickel alloys.

2. Methodology

2.1. Preparation of Nanofluids

For nanofluid preparation, Al_2O_3 and Cu nanoparticles (20-30 nm size and 99 % purity) and CNT nanoparticles (L:3-10 um and D:10-15 nm, purity >97%) was used to prepare the nanofluids with a fixed 0.5 % concentration by weight. The nanoparticles were evenly distributed throughout the base fluid by magnetic stirring for 20 minutes. The nanofluid was sonicated intermittently for 20 minutes with an ultrasonic probe sonicator (400 W, 20 kHz) to break up the agglomerates. Figure 2.1 shows the palm oil-based nanofluids prepared using the processes mentioned. This research computed the experimental dynamic viscosity of the fluids used as lubricants using the Brookfield Viscometer (Model LV-DV2T). The viscometer gave results whenever the applied torque fell within the 10 % and 100 % range with different spindles and speed combinations [10]. Using the KD2 Pro Thermal Properties Analyzer, the thermal conductivity of the lubricants was evaluated at a room temperature of 30 °C [11].
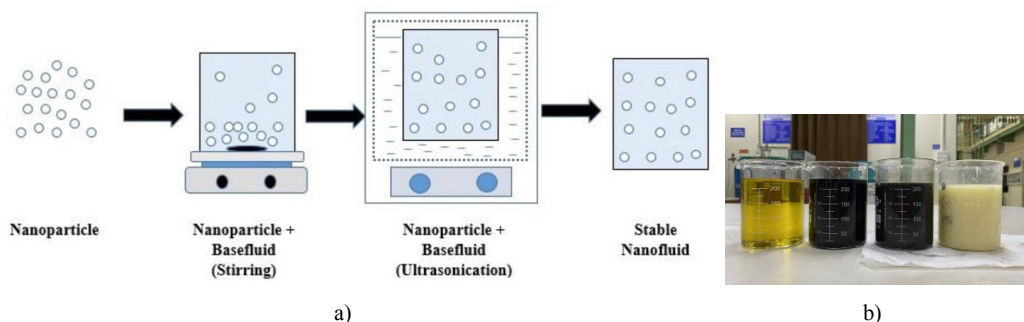

Figure 2.1: a) Preparation of nanofluid, b) MQL Lubricants (Pure Palm Oil, CNT nanofluid, Cu nanofluid, Al_2O_3 Nanofluid)

2.2. MQL End Milling of Inconel 718 Alloy

The workpiece selected for the experiment was Inconel-718 in 100×150×10mm size. All the experiments were conducted on a CNC Vertical Machining Centre (Figure 2.2a) at a constant cutting speed of 1250 rpm, 125 mm/min feed rate, and 0.5 mm depth of cut. Kenco's MQL system (Figure 2.2b) was used to provide the lubricant in the form of a jet spray of atomized lubricant using compressed air at a set pressure. The lubricant flow rate was kept constant at 50 ml/h and was atomized by a compressed air supply of a maximum of 7 bars of pressure. Nanofluids were sprayed at the machining zone through an MQL nozzle placed 30 mm away (Figure 2.2c). Experiments were conducted using three palm oil-based nanofluids as a lubricant in the end milling of the workpiece with MQL conditions. In addition, end milling with pure palm oil MQL, conventional flood cooling using Semitom CAS9001, and dry machining were carried out. After an experiment, the Surfcom 1400G was utilized to examine the roughness of the surface produced on the workpiece.
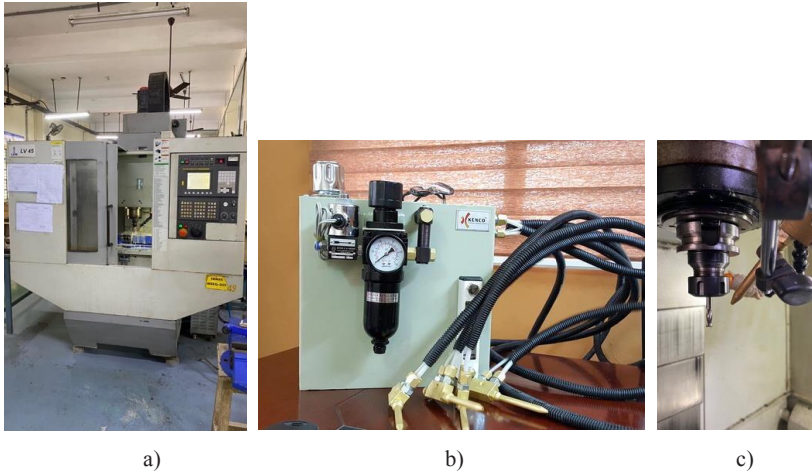
<center>a)   b)   c)</center>

Figure 2.2: a) CNC Vertical Machining Centre (Model LV45), b) MQL Setup, c) Nozzle Setup For MQL Milling

3. Results and discussion

3.1. Analysis of Thermophysical Properties

The dynamic viscosity of pure palm oil and the nanofluids prepared using it as base fluid with nanoparticles at 0.5wt% concentration was measured at room temperature of 30°C, and the values are given in Figure 3.1. Because nanoparticles were included in the base fluid, the three nanofluids had higher viscosities than the base fluid. This was in accordance with the established fact that as particle concentration increases, the viscosity of nanofluids increases [12]. As can be observed, the increase in viscosity was the highest for CNT nanofluids, followed by Cu and Al_2O_3 nanofluids. This indicated that the material of nanoparticles introduced into the base fluid had an influence on the viscosity of the nanofluid, even when the particle size and concentration were the same [13].
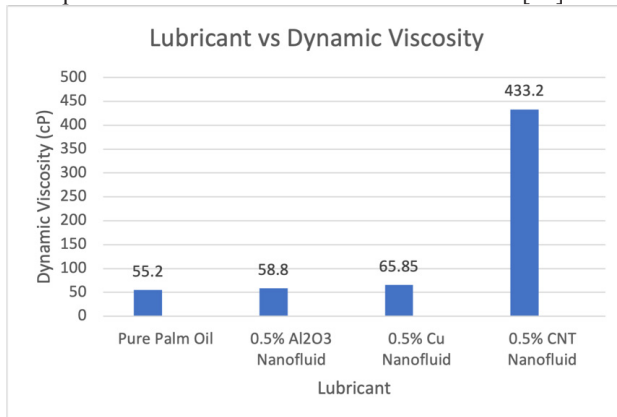

Figure 3.1: Lubricant vs Dynamic Viscosity

The thermal conductivity values of pure palm oil and the nanofluids are shown in Figure 3.2. At room temperature, pure palm oil has a thermal conductivity of 0.1218 W/mK. When 0.5wt% nanoparticles were added, the thermal conductivity of Al_2O_3, Cu, and CNT nanofluids changed. In general,

nanoparticles' thermal conductivity directly influences the nanofluids' thermal conductivity [14]. Despite the lower thermal conductivity values of Al_2O_3 nanoparticles, Al_2O_3 nanofluid has a greater thermal conductivity than Cu nanofluid. Al_2O_3 nanofluid was homogenous and stable for a longer period than Cu Nanofluid. This was attributed to ceramic nanoparticles being more stable in solution than metallic nanoparticles. Cu nanofluid agglomerated more and sedimented faster, thereby reducing the heat transfer. On the other hand, CNT nanofluids had a poorer thermal conductivity than pure palm oil. The higher viscosity hampered the heat transfer and increased the energy needed to circulate the nanofluid because of increased friction.
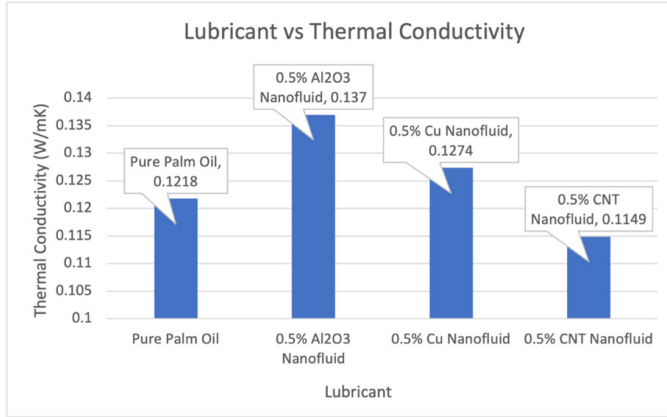
Figure 3.2: Lubricants vs Thermal Conductivity

3.2. Analysis of Surface Roughness

A surface with the lowest surface roughness rating and no nanoparticle adherence determines whether a produced product is "accepted" or "rejected". The lubricant's cooling and lubricating capacity are associated with the quality of the workpiece surface. This study measured the surface roughness at three locations to determine the average surface roughness. The surface roughness of the machined surface was also analyzed using SEM to evaluate the lubricating performance of the nanofluids. Figure 3.3 illustrates the surface roughness values obtained under various lubrication settings.
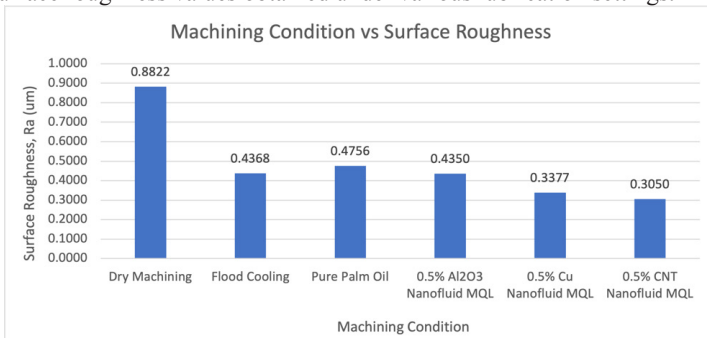

Figure 3.3Machining Condition vs Surface Roughness

As can be seen from Figure 3.3, MQL end milling with 0.5wt% CNT nanofluid provided the best surface quality, whereas the worst surface was produced by dry machining. When compared to dry machining and flood cooling, 0.5wt% CNT nanofluid MQL reduced the surface roughness by 65.43% and 30.18%,

respectively. Compared to Al_2O_3 and Cu nanofluid, CNT nanofluid MQL demonstrated better results by 29.9% and 9.7%, respectively. Because there was no effective transfer of the heat generated due to the absence of cooling and lubrication during dry machining, the surface produced was poor and had a lot of tool paths. SEM image of the surface produced by dry machining confirmed the same (Figure 3.4a). Compared to flood cooling with Semitom CAS9001, pure palm oil MQL created a rougher surface (Figure 3.4b&c). This was related to the fluid's weak thermal conductivity. This confirmed that while MQL with vegetable oil outperformed dry machining in terms of machining performance and durability, the viscosity of nanoparticles added to the base fluid played a role. Bright feed marks and material adhesion were noticed on the machined surface at 0.5wt% Al_2O_3 concentration. There was not much waviness on the workpiece from the SEM image. The spherical shape of Al_2O_3 nanoparticles allowed them to perform ball-bearing and anti-friction operations. Because of their ball-bearing function, the nanoparticles changed from sliding to rolling. The nanoparticles coated the surfaces in contact and formed an oxide layer, compensating for material loss through the mending effect (Figure 3.4d). The SEM analysis of the surface milled with Cu nanofluid MQL indicated that including Cu nanoparticles in palm oil formed a thin film with good anti-friction and lubricating on the workpiece surface and improved the surface quality. A smoother surface was obtained with 0.5% Cu nanofluid MQL than dry machining and flood cooling (Figure 3.4e). The lubricating capability of the nanofluid was linked to the quality of the workpiece surface. CNT nanofluid penetrated the machining zone with high viscosity, eliminating the frictional heat. The buildup of nanoparticles on the workpiece acted as an anti-wear mechanism, lowering shearing stress and increasing tribological qualities. As a result, there were fewer scratches on the machined surfaces (Figure 3.4f). A published study by Debnath et al. [15] also supported this outcome.
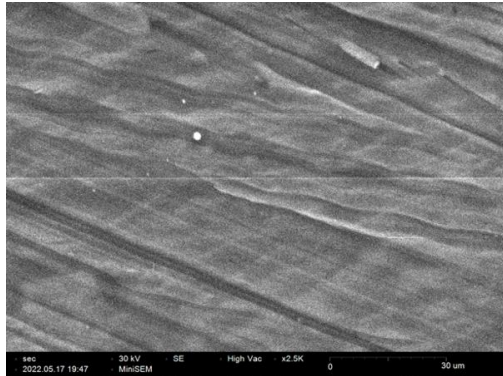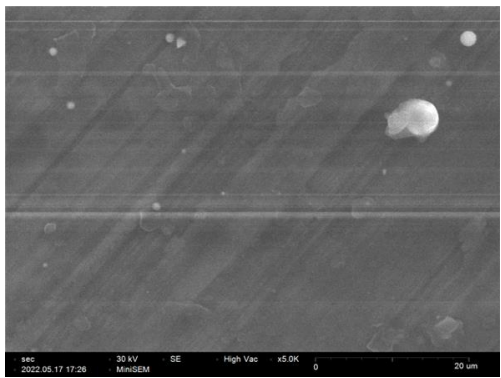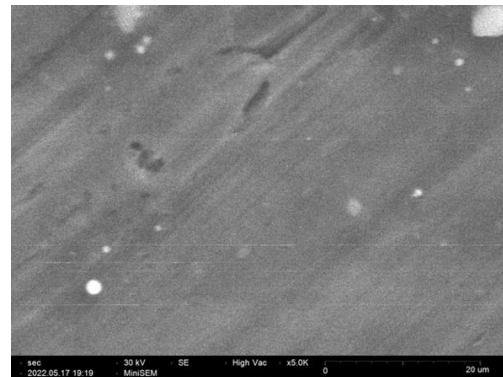
a) Dry Machining
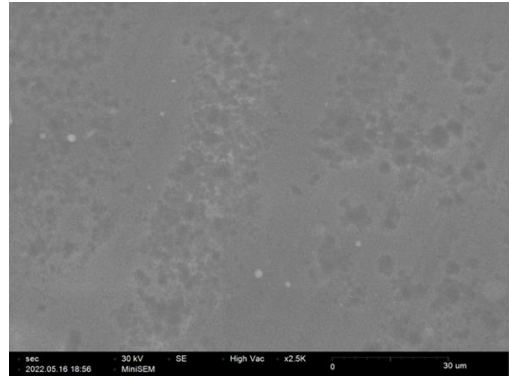
b) Flood Cooling
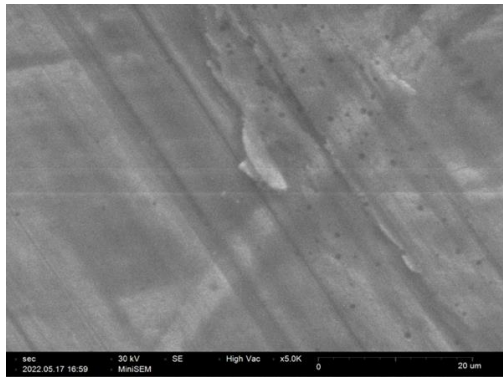
c) Pure Palm Oil MQL

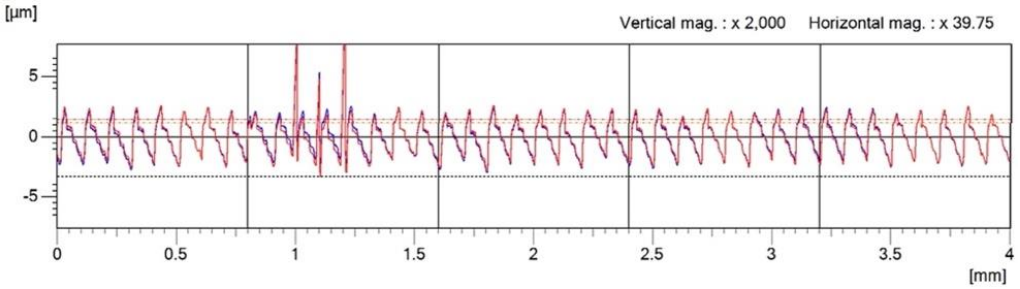d) Al_2O_3 nanofluid MQL

e) Cu nanofluid MQL
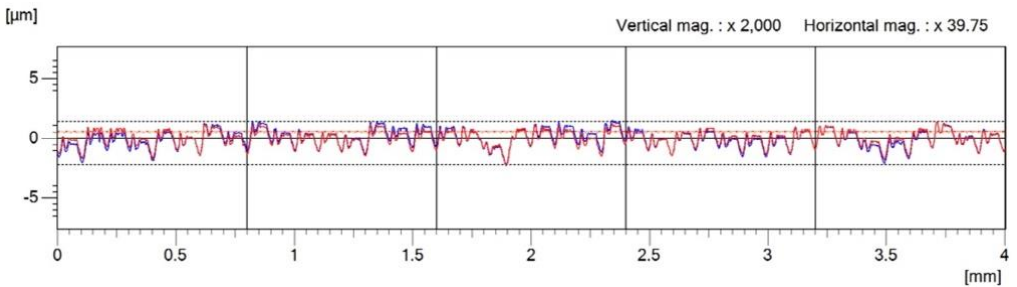

f) CNT nanofluid MQL

Figure 3.4: SEM Images of the milled surfaces

Feed marks were visible in dry machining, according to surface topography studies. However, these marks decreased in the MQL and nanofluid MQL machining. In dry machining, the peaks were higher,
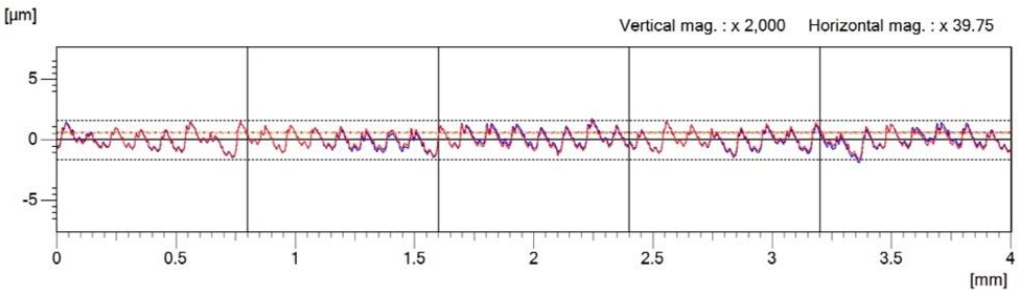
but their widths were smaller. The height of the peaks in pure oil MQL and nanofluid MQL fell dramatically while their width expanded, as seen in Figure 3.5.
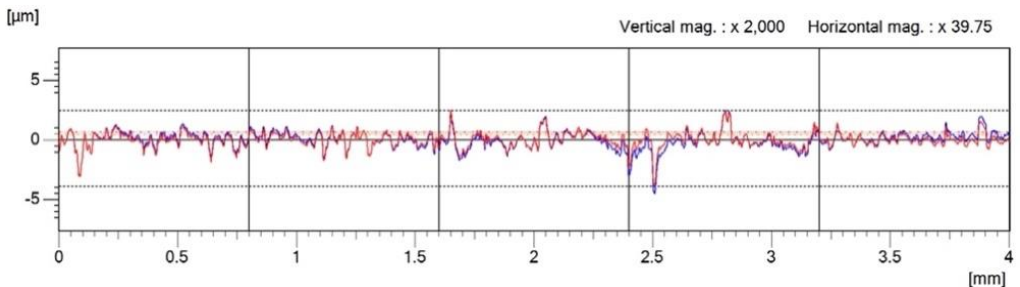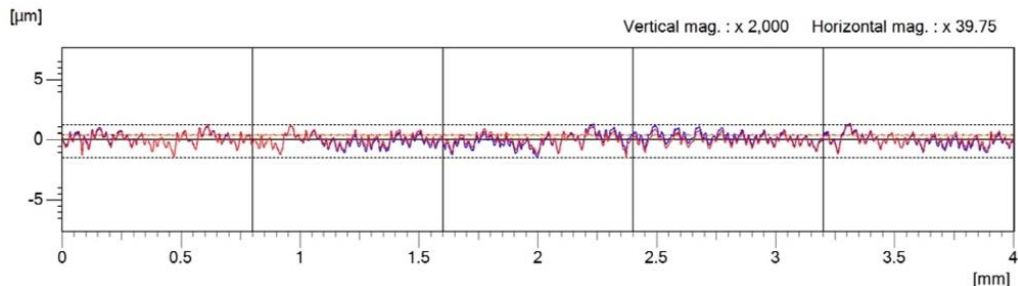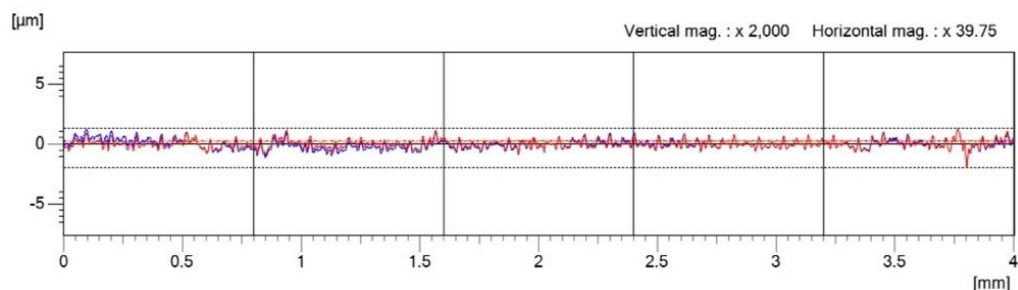

a) Dry Machining

b) Flood Cooling

c) Pure palm oil MQL

d) Al_2O_3 nanofluid MQL

e) Cu nanofluid MQL

f) CNT nanofluid MQL

Figure 3.5: Surface topography of the milled surfaces

4. Conclusion

Minimum quantity lubrication with vegetable nanofluids is one of the alternatives to conventional flood cooling to reduce cutting fluids consumption and promote sustainable manufacturing. This research aimed to study the influence of viscosity of vegetable oil-based nanofluids on surface roughness in end milling of nickel alloys with minimum quantity lubrication. This was done by preparing nanofluids using three nanoparticles. The concentration of the nanofluids prepared with these nanoparticles was held at a constant 0.5wt%. Also, the nanofluids were prepared with magnetic stirring for 20 minutes, accompanied by ultrasonication for 20 minutes. The viscosity of these nanofluids was determined to be the highest in CNT nanofluid, followed by Cu nanofluid, Al_2O_3 nanofluid, and pure palm oil. It was noted that nanoparticles of the same size had a different influence on the viscosity of nanofluids. Understanding the nanoparticle material was important in understanding the influence on the nanofluid viscosity. On the other hand, CNT nanofluids had a poorer thermal conductivity than pure palm oil. This was because higher viscosity hampered heat transfer and increased the energy needed to circulate the nanofluid because of increased friction. The performance of these nanofluids as lubricants was assessed by looking at the surface roughness. Results revealed that vegetable oil-based MQL milling was an ideal alternative to dry machining and flood cooling. CNT nanofluid with the highest viscosity during MQL machining produced the lowest surface roughness. This showed that studying nanofluids' viscosity and thermal conductivity together was important to understand their performance as effective

lubricants during machining. Hence, more research is needed to fully comprehend the relationship between nanoparticles' thermal conductivity and nanofluids' thermal conductivity.

Nomenclature

Abbreviation	Description
MQL	Minimum Quantity Lubrication
Al_2O_3	Aluminium Oxide
Cu	Copper
CNT	Carbon Nanotube
SEM	Scanning Electron Microscope

5. Acknowledgements

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