Characterisation, Performance and Optimisation of Nanocellulose Metalworking Fluid (MWF) for Green Machining Process

J. Kananathan¹, M. Samykano²*, K. Kadigama², A. K. Amirruddin¹, D. Ramasamy¹, and L. Samylingam³

¹College of Engineering, Universiti Malaysia Pahang, 26300 Gambang, Kuantan, Pahang, Malaysia
²Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
³Research Centre for Nano-Materials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, Bandar Sunway, 47500 Selangor, Malaysia

ABSTRACT – The present research attempts to develop a hybrid coolant by mixing alumina nanoparticles with cellulose nanocrystal (CNC) into ethylene glycol-water (60:40) and investigate the viability of formulated hybrid nanocoolant (CNC-Al₂O₃-EG-Water) towards enhancing the machining behavior. The two-step method has been adapted to develop the hybrid nanocoolant at various volume concentrations (0.1, 0.5, and 0.9%). Results indicated a significant enhancement in thermal properties and tribological behaviour of the developed hybrid coolant. The thermal conductivity improved by 20-25% compared to the metal working fluid (MWF) with thermal conductivity of 0.55 W/m°C. Besides, a reduction in wear and friction coefficient was observed with the escalation in the nanoparticle concentration. The machining performance of the developed hybrid coolant was evaluated using Minimum Quantity Lubrication (MQL) in the turning of mild steel. A regression model was developed to assess the deviations in the tool flank wear and surface roughness in terms of feed, cutting speed, depth of the cut, and nanoparticle concentration using Response Surface Methodology (RSM). The mathematical modeling shows that cutting speed has the most significant impact on surface roughness and tool wear, followed by feed rate. The depth of cut does not affect surface roughness or tool wear. Surface roughness achieved 24% reduction, 39% enhancement in tool length of cut, and 33.33% improvement in tool life span. From this, the surface roughness was primarily affected by spindle cutting speed, feed rate, and then cutting depth while utilising either conventional water or composite nanofluid as a coolant. The developed hybrid coolant manifestly improved the machining behaviour.

INTRODUCTION

Traditional machining plays a substantial role in the production process through the elimination of excess materials in the form of chips to develop shapes with high dimensional precision and surface finish [1, 2]. Cutting fluids, cutting tools, and machine tools are the three critical enablers in machining [3]. A cutting instrument is a tool that expels the extra materials by direct contact, while the machining tool delivers the essential movement within the workpiece and the cutting tool. Meanwhile, cutting fluid empowers heat removal and helps in flushing out the produced chip [4]. Over the past years, a significant increase in machining process demands from the manufacturing industry has been reported, implying that the manufacturers have to expand their production to meet the growing needs while retaining their products’ quality [5]. The challenge is to boost productivity while reducing costs [6]. Expanding productivity implies the utilisation of a higher value cutting parameter to speed up the process. However, using a higher value of cutting parameters leads to an increase in cutting temperature and energy. The rise in temperature and energy during machining changes the quality of the surface and the instrument lifespan [7].

Green machining is environmentally friendly and will become a requirement for manufacturing enterprises in the near future. Industries will be obliged to investigate dry machining to comply with environmental and health rules. Dry machining benefits include the following: no pollution of the atmosphere (or water); no residue on the swarf, resulting in lower disposal and cleaning costs; no harm to health; and it is non-irritating to the skin and allergy-free. Additionally, it provides cost savings in machining. The cutting liquid or coolant’s or MWF’s main objective is to expel the heat produced by friction between the workpiece and the cutting tool, which ultimately decreases the upsurge in temperature of the cutting tool [8]. Besides, cutting fluid also aids in the flushing of the produced chips during the machining process. The reduction in cutting equipment temperature will also decrease cutting power at the tool-work interface and further increase the cutting tool’s lifespan [9, 10]. Even though the traditional cooling method can improve the machining procedure’s performance, a substantial amount of the machining coolant such as oil-based and synthetic water-based coolant utilised in the process increases the manufacturing cost due to the large quantity used. The large amount used could also endanger the environment and humans [11]. As an alternative to the traditional cooling methods, low-consumption, highly efficient, and clean methods such as minimum quantity lubrication (MQL) and cryogenic cooling have been introduced. MQL is...
ultimately a green technology, and it is the most efficient, energy-saving, and environmentally friendly lubrication system available [12]. It is expected that the average lubrication consumption can be reduced significantly with the adaption of MQL. The coolant type will also further increase the efficiency of MQL, leading to improved lubrication and decreased environmental pollution [13]. It has been reported that MQL is currently one of the best cooling methods and has drawn immense attention from the research communities [14, 15]. MQL method supplies the cutting liquid in a mist state, delivered directly above the cutting zone interface. Since the low quantity of cutting fluid is utilised in the MQL method, the liquid’s heat-carriage capacity and lubricating properties should be at their optimum level. Thus, a cutting fluid possessing high thermal conductivity and lubrication properties is preferred and required for the system [16]. Hybrid nanoparticles are nanoparticles comprised of two or more distinct nanometer-sized components. Hybrid nanofluids are fluids produced using hybrid nanoparticles. Suspending tiny solid particles in energy transmission fluids may substantially increase their thermal conductivity, providing a cost-effective and novel method of dramatically improving their heat transfer properties. Nanofluids were identified as the suitable fluid that could satisfy this requirement [17]. Nanofluids are formulated by dispersing particles of size less than 100 nanometers in a base liquid [18]. There are two main approaches employed in developing nanofluids. The two techniques used are the two-step process and one-step process [19]. The addition of nanoparticles has been reported to improve the thermal properties of nanofluids [20] significantly. Nanofluid has also been categorised as a fluid with superior thermophysical and heat transfer properties [21, 22]. Nanofluid with different non-metallic and metallic nanomaterials demonstrated promising performance as an alternative for traditional MWF with the MQL method. The processing characteristics of nanofluids using the MQL technique were evaluated by Wang, Li [23] for three different workpiece materials. They reported that with Al₂O₃ nanofluid, the grinding ability of the hardened nickel-based alloy improved significantly. The grinding conditions minimised the force ratio (0.38), the real grinding energy (62.20 J/mm³) and increased the surface quality as compared to other grinding settings [23]. Wang, Li [23] concluded that Al₂O₃ nanofluids are ideal lubricants for high strength and tough machining materials. The research on hardened AISI 52100 steel MQL nanofluid (Al₂O₃/water) was carried out by Mao, Zou [24], and Mao, Huang [25]. Both groups of scientists decided to investigate the friction and grinding force by adding nanoparticles of Al₂O₃ into deionised water. Setti, Sinha [26] investigated the efficiency using MQL with Al₂O₃/water nanofluid and CuO/water nanofluid. They reported that compared to CuO nanofluid in both dry and wet conditions, Al₂O₃ nanofluid drastically reduced the friction coefficient. Sharma, Singh [27] prepared nanofluid for machining AISI1040 steel by adding 1 vol. % Al₂O₃ nanoparticles (45 nm size). Their effects on surface roughness, tool wear and cutting force in wet machining have been assessed and reported decreased by 5.27%, 28%, and 25.5%, respectively.

To further enhance the MQL method to reduce the cost and improve the effectiveness [28], nanofluids are prepared with the addition of nanomaterials obtained from natural resources like plants [29]. Cellulose Nanocrystals (CNC) are nano-structured cellulose obtained from various plants, mainly from Canadian Hemlock [30]. The obtained CNC was blended with alumina nanoparticles and ethylene glycol (EG) to formulate a nanofluid-based coolant for machining applications. It is believed that CNC and metal nanoparticles can absorb heat from the cutting tool during machining the workpiece excellently [31]. Due to the high thermal conductivity and optimum viscosity properties, it is believed that CNC-Alumina-based cutting liquid will have a better performance than conventional coolants while prolonging the cutting tool’s lifespan and providing a subtle surface finish on the workpiece. The present work aims to investigate the thermophysical properties (stability, thermal conductivity, and viscosity) of hybrid nanofluid for different volume concentrations and evaluate the machining performances compared to metalworking fluid (MWF) coolant in terms of tool wear, surface roughness, wear mechanism, tool life, and chip formation.

**MATERIAL AND METHODS**

The nanoparticles used in the present work are Cellulose Nanocrystals (CNC) and Aluminium Oxide (Al₂O₃). Both nanoparticles were purchased in powder form from Sigma-Aldrich Chemicals, USA. This nanoparticle has an average particle size of 20-100nm. Several parameters are surmised before blending the CNC with Al₂O₃ nanoparticles. The concentrations of the CNC and Al₂O₃ particles studied are 0.1, 0.5, and 0.9 vol %. The CNC nanoparticles were dispersed in the base liquid containing Al₂O₃ nanoparticles, ethylene glycol, and distilled water (60:40) according to Eq. (1). The volume concentration (φ) in this study is converted to weight concentration (ω) using Eq. (3).

The equation for volume concentration (φ) is given by:

\[
\varphi = \frac{\omega \rho_w}{(1-\omega)\rho_p+\omega \rho_w}, \text{ where } \omega = \left(\frac{m_w}{m_p+m_w}\right) \times 100
\]

The volume concentration is subsequently converted into weight concentration according to Eq. (3):

\[
\Delta V = (V_2 - V_1) = V_1 \left(\frac{\varphi_2}{\varphi_1} - 1\right)
\]

\[
\varphi = \frac{M_p}{M_p + V_{bf} \rho_p}
\]

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where, $M_p$ is the mass of nanoparticles, $\rho_p$ the density of nanoparticles, $V_{bf}$ is the volume of base fluid.

The study comprises two stages. The first stage is preparing a stable composite nanofluid and the assessment, including thermal conductivity and viscosity, of its thermophysical properties. The second stage is an analysis of the prepared nanofluid in machining and assessing the tool’s wear, the roughness of the workpiece surface, and the formation of the chip.

**Nanofluid Preparation**

The technique used to formulate the composite nanofluid is a two-step process. The production of nanofluids involves magnetic stirring and sonication processes. As shown in Figure 1. (a), a magnetic stirrer mixes the nanoparticles for 30 minutes until the CNC and Al$_2$O$_3$ powder is completely dispersed into the distilled water and ethylene glycol. The mixing speeds are also set at the appropriate pace to ensure that nanofluids blend not to sprinkled out from the measuring beaker during mixing. After the stirring procedure, the nanofluid is sonicated using an ultrasonic bath as shown in Figure 1. (b) for two hours at 50°C. The sonication procedure improves the stability and dispersion of nanoparticles in the nanofluid.

![Figure 1. Nanofluid preparation technique (a) magnetic stirring (b) sonication.](image)

**Nanofluid Thermophysical Property Measurement**

**Stability - sedimentation method**

After the sonication procedure, 10ml of nanofluid is filled into a test tube for every volume concentration for the stability observation method. The motivation is to observe the sedimentation process inside the nanofluid and estimate the composite nanofluid’s stability.

**Measurement of thermal conductivity**

Thermal conductivity is one of the domineering properties investigated in this research study. It is calculated to discern the fluid’s thermal behaviour through an analyser that relies on the transient hot-wire theory [32]. The KD2 Pro thermal property analyser developed by Decagon Devices, Inc., USA, is used to evaluate thermal conductivity. This thermal analyser quantifies thermal conductivity in the range of 0.200 W/m-K to 2.000 W/m-K with an accuracy of ± 5%. The estimations were executed in controlled temperatures extending from 30 to 70 °C using a Memmert water bath with a precision of 0.1 °C. The validation is performed using the manufacturer’s glycerine solution and base liquid 60:40 (EG: Water). The data obtained were compared to data released by the ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers). The experimental readings are recorded every 15 minutes for 20 readings to prevent experimental inaccuracy after the sample is immersed into the water bath. After completion of a collection of data, the mean value is calculated and used.

**Viscosity measurement**

Brookfield LVDV-III Rheometer combined with a temperature-regulated bath is used to obtain the composite nanofluids’ dynamic viscosity at different nanoparticle percentages. The instrument has an exactness of ±1.0%, and the temperature precision of 0.1 °C ranging from 20 °C to 100 °C. The DV-III Ultra Rheometer works based on a spindle rule located in an adjusted coil with a ULA spindle. The viscosity of the base liquid is measured and compared with values obtained by ASHRAE. In this study, the experiment was performed at the nanofluid temperature of 30 °C, 50 °C, and 70 °C.

**Physical Equipment and Material**

**Workpiece material**

Cylindrical mild steel (200mm length and 40mm diameter) bar was used to investigate the machining performances. The chemical composition and physical properties of the workpiece materials used are presented in Table 1 and Table 2.

| Material   | C  | Cr  | Ni  | Si  | Mn  | P  | S   | Mo  | V   |
|------------|----|-----|-----|-----|-----|----|-----|-----|-----|
| Mild steel | 0.15 | 0.013 | < 0.01 | 0.14 | 0.79 | 0.026 | 0.018 | 0.004 | 0.003 |
### Table 2. Properties of mild steel [33].

| Physical and chemical properties | Value                        |
|---------------------------------|------------------------------|
| Density                         | 7.75 - 8.08 g/cc             |
| Modulus of elasticity           | 183 - 213 GPa                |
| Tensile strength, ultimate      | 241 - 2450 MPa               |
| Tensile strength, yield         | 140 - 2400 MPa               |
| Poissons ratio                  | 0.250 - 0.300                |
| Fatigue strength                | 758 - 772 MPa                |
| Shear modulus                   | 70.0 - 80.0 GPa              |
| Electrical resistivity          | 0.0000142 - 0.000142 ohm-cm  |
| Specific heat capacity          | 0.450 - 0.486 J/g-°C         |
| Thermal conductivity            | 0.450 - 0.486 J/g-°C         |
| Melting point                   | 25.3 - 93.0 W/m-K            |

**Cutting tool material**

An uncoated carbide tool is used as the cutting device in this work. The cutting tool instrument is illustrated in Figure 2. The insert’s specifications are rake angle: 10 degrees, inscribed circle: 9.525 mm, insert thickness: 4.7625 mm, nose radius: 7.9502 mm, attached circle: 3.81. The lathe machine used for the turning test is the ERL-1330 lathe machine with a power 2.2Kw motor. The horizontal lathe system is 2000 mm × 965 mm × 190 mm in size, and the maximum speed of the spindle is 2570 rpm.

A metallurgical microscope instrument was used for metallurgical assessment. This microscope is utilised to extricate the wear type and measure the flank wear created on the cutter after the machining test. A low-weight portable surface roughness tester model Mahr Perthenometer S2 is used to measure the workpiece’s mean roughness depth, Rz, and arithmetic average surface roughness, Ra. Field Emission Scanning Electron Microscope (FESEM) and Energy Dispersive X-ray Spectrometer (EDX) are used to determine all the cutting tools’ defects and study the chip pattern after turning the operation. The TM3030Plus examines effective surfaces for compositional data. The Knoop/Vickers Tukon 1202 Hardness Tester was utilised to measure the cutting tool on tool wear. Figure 3 shows the turning process’s experimental setup using a lathe machine with metalworking fluid and nanofluids. Surface roughness values are measured by using Pethometer S2. A total of three measurements were taken to determine the average surface roughness of the turning surface. Flank wear is measured using the optical measuring device with the width from the original cutting edge to the limit of wear land. The flank wear measurement is taken after each pass of the machining process (as recommended by ISO 3685:1993, the wear criteria for steel are 0.3 mm).

**Figure 2.** Cutting device (a) rake face of insert (b) cutting tool (c) tool holder.

**Figure 3.** Experimental setup.
Scanning Electron Microscope and Transmission Electron Microscopes

Scanning electron microscope (SEM) is an electron microscope that generates clear micrographs of a sample by scanning the surface with a focused beam of electrons. It is used to determine all the defects on the cutting tool and to study the chip pattern after turning operation. Transmission electron microscopy (TEM) can produce pictures with much greater resolution than a light microscope by utilising electrons as the light source. The fundamental concept is that an electron beam travels through a very thin sample. After interacting with the sample’s atoms, some unscathed electrons reach a fluorescent screen, forming a picture. The picture is presented in various shades of grey to indicate the material density in various specimen regions. The picture is enlarged and may be seen immediately on the screen or captured with a camera for post-processing examination. In situ TEM enables the real-time study of nanostructures’ microstructural development in response to external active stimuli and their connection to their characteristics.

SEM that was utilised in this study was Hitachi TM3030Plus. This model has a superior SE detector which has been unified in FE-SEM and VP SEM. It can be operated successfully under low vacuum environments and enables fast SE observation without specimen preparation. The Energy Dispersive X-ray Spectrometer (EDX) for the Hitachi TM3030 series comes with the latest silicon drift detector (SDD), large detection area (30 mm²), and various elemental analyses such as point or area analysis, line scanning, and mapping. The TM3030Plus allows for effective imaging examination with double signals in one image, which is displayed as one collective SE signal provided that the surface has rich information and a BSE signal for compositional data.

Experimental Design and Selection of Cutting Data

The design of experiment (DOE) was utilised to obtain different cutting combinations comprising feed rate, cutting speed, and cutting depth. Additionally, the response surface method (RSM) was used to find the expected response from the combination of the different feed rates, cutting speeds, and cutting depth from the experimental value measured from tool wear and surface roughness, followed by a mathematical model development from the responses. There are essentially two main types of DOEs, Box-Behnken design (BBD) and central composite design (CCD). In this analysis, the Box-Behnken design was considered to evaluate first-order and second-order terms effectively. Besides that, it is cost-effective to operate compared with CCD with the exact number of factors.

Cutting speed, feed rate, and axial depth were the three factors that influence and should be considered in the analysis to explore their impact on surface roughness and tool wear. The designed variables and levels to be employed for the experiments are shown in Table 3. Table 4 shows the total of 15 experimental runs carried out in this study. Factor levels are coded as -1(low level) and +1(high level). The performance of the experimental design was analysed with Minitab 17 statistical software. The result was estimated using ANOVA with a 95% confidence level based on the p-value.

| Table 3. Selected parameter input for DOE. |
|-------------------------------------------|
| Parameter/ Coding level | -1 | 1 |
| Cutting speed (rpm)          | 425 | 990 |
| Feed rate (mm/rev)           | 0.05 | 0.18 |
| Axial depth (mm)             | 0.5 | 1.5 |

| Table 4: A 2³ Factorial design matrixes generated from Minitab 17. |
|---------------------------------------------------------------|
| Experiment | Cutting speed (rpm) | Feed rate (mm/rev) | Depth of cut (mm) |
|------------|---------------------|-------------------|------------------|
| 1          | 425                 | 0.1               | 1.5              |
| 2          | 707                 | 0.18              | 0.5              |
| 3          | 425                 | 0.1               | 1.2              |
| 4          | 425                 | 0.18              | 1.2              |
| 5          | 707                 | 0.05              | 1.5              |
| 6          | 707                 | 0.05              | 0.5              |
| 7          | 425                 | 0.05              | 1.2              |
| 8          | 707                 | 0.1               | 1.2              |
| 9          | 990                 | 0.1               | 1.2              |
| 10         | 425                 | 0.1               | 0.5              |
| 11         | 990                 | 0.05              | 1.2              |
| 12         | 990                 | 0.1               | 0.5              |
| 13         | 707                 | 0.18              | 1.5              |
| 14         | 990                 | 0.18              | 1.2              |
| 15         | 990                 | 0.1               | 1.5              |

RESULTS AND DISCUSSION

Sedimentation Observation - Qualitative Method

The common suspended particles’ problems are agglomeration and fast settlement of particles in a fluid [35]. Thus, high durability and enhanced suspension stability are required for optimum heat transfer enhancement. Although no surfactants were used during the preparation of nanofluids, the solution was found to be stable without any sedimentation
observed for up to one month, as shown in Figure 4. Based on the qualitative method (sedimentation observation) used for examining the nanofluid’s stability, it is noticed that the ethylene glycol-distilled water with CNC-based nanofluid has achieved good stability for a month. Ramachandran, Hussein [36] also found similar findings. They find that the ultrasonic process prolongs the stability of the nanofluid for up to 3 months. More in-depth investigations have been performed by Maheshwary and Nemade [37] using ZrO\(_2\)/H\(_2\)O nanofluid to study the sedimentation observation. Their findings showed only a small amount of sedimentation occurs for all base fluid due to the gravitational forces after more than one month of observation. Sundar, Singh [38], in their study, observed that Fe\(_3\)O\(_4\) nanoparticles dispersed in a water-ethylene glycol mixture is stable for up to one month. Sarafrz and Hormozi [39] stated that due to the powerful van der Waals interaction, sedimentation of nanofluids occurs. The particles accumulate due to high surface activity as time elapses [40].

![Figure 4. Nanofluid Al\(_2\)O\(_3\)/CNC samples at different concentrations.](image)

**UV-Vis Spectrophotometer Evaluation - Quantitative Method**

The UV-Vis spectrometer analysis was performed to investigate the structural, optical properties, and solution’s stability [42]. The absorbance is monitored and recorded every week to observe the three different prepared composite (Al\(_2\)O\(_3\)/CNC) nanofluid solutions stability. The data plotted in Figure 5 clearly shows that the three different concentrations’ absorbance has reached its stability within the 4-5 days after preparing the solution. From the investigated three concentrations, the 0.1% volume concentration achieved stability first, followed by 0.5%, and finally 0.9%. Furthermore, the stability of the samples over a month of observation was also seen to be stable. Habibzadeh, Kazemi-Beydokhti [41] also reported a similar stability state.

![Figure 5. UV-Vis spectrophotometer analysis for different concentrations for one month.](image)

Figure 5 shows the supernatant particle absorbance against the sedimentation graph for the studied three concentrations. It can be clearly seen that Al\(_2\)O\(_3\)/CNC hybrid nanofluids have been stable for more than a month. After a month, the absorbance was recorded within the range of 0.24 a.u to 0.31 a.u values, indicating that over 70% of these nanofluids’ relative concentration was maintained as initial. This pattern illustrates suspended nanofluids’ behaviour that
increases with the concentration volume [43]. The colloidal nanofluid’s stability is therefore preserved at the specific concentration volume. From this observation, it can be inferred that a lower concentration of nanofluids has the potential for faster sedimentation [44].

**Transmission Electron Microscopy**

A common method for acquiring an Al₂O₃ and CNC image at high magnification is by using transmission electron microscopy (TEM). The CNC and Al₂O₃ nanoparticles can be clearly seen in Figures 6(a) and 6(b). Meanwhile, Figure 6(c) shows the image of blended Al₂O₃/CNC. A good blending has been observed, which was anticipated for further studies.

![Figure 6. TEM images of (a) CNC, (b) Al₂O₃, and (c) Al₂O₃/CNC.](image)

**FESEM Observation**

The morphological and size characteristics of the prepared hybrid nanoparticles were analysed using FESEM. As illustrated in Figure 7, nanoparticles were found to be circular with a mean dimension of 13 nm. Hatami and Okhovati [45] observed round-shaped nanoparticles in a similar study but with dissimilar sizes. In a study conducted by Meriläinen, Seppälä [46], it was reported that small and circular shape particles significantly enhance the nanofluids’ heat transfer properties while maintaining the pressure effect.

![Figure 7. FESEM image of Al₂O₃/CNC nanoparticles (a) 15k, (b) 100 and (c) 50k magnification.](image)

**Thermophysical Properties Evaluation of Nanofluid**

*Thermal conductivity*

The thermal conductivity measurement was carried out at three different temperatures (30 °C, 50 °C, and 70 °C) for each volume concentration. The measurement was also performed for conventional machining coolant, MWF. Figure 8 shows the thermal conductivity reading of conventional machining coolant (MWF) and the nanofluid of various volume.
concentrations. Enhancement in thermal conductivity can be observed as the temperature and volume concentration increase. Similar results were also obtained by Chiam, Azmi [47] in their work examining the thermal conductivity for Al₂O₃ dispersed in water and EG.

Figure 8. Thermal conductivity with respect to temperature

The thermal conductivity results of Al₂O₃/CNC nanofluids with volume concentrations of 0.1 %, 0.5 %, and 0.9 % have been demonstrated in Figure 8. The thermal conductivity is seen to increase when the nanoparticle concentration increases in the nanofluids. In a study conducted by Acevedo-Fani, Salvia-Trujillo [48], the authors stated that the collision between particles escalates as the concentration increases. Vajjha and Das [49] reported the impact of the concentration of nanoparticles toward improving thermal conductance.

Based on Figure 9, the composite nanofluid containing Al₂O₃/CNC shows a better thermal property in comparison to CNC incorporated nanofluids. This is because Al₂O₃ has better thermal properties than other nanoparticles. Meanwhile, high collisions of particles lead to high kinetic energy [50]. Hence, the prepared composite nanofluid has higher thermal conductivity than CNC incorporated nanofluid. The presence of higher kinetic energy at high temperatures increases heat transfer rate as the particles can transfer heat directly from one to another at high temperatures [51]. Besides, it was observed that as the concentration of Al₂O₃ in the composite Al₂O₃/CNC incorporated nanofluid increases, the value of thermal conductivity increases as well. As shown in Figure 9, the composite nanofluid thermal conductivity value is greater than that of traditional coolant machining. It thus indicates that the tendency of the composite nanofluid containing nanocellulose to absorb heat produced during the machining operation is exceptionally high at the heat generation interface between the workpiece and the cutting tool. Nanofluid’s high thermal conductivity properties help remove most of the heat produced [52].

Figure 9. Composite nanofluid and single nanocelulose coolant thermal conductivity measurement with respect to temperature.

Effect on nanoparticles concentration on thermal conductivity

A linear relationship is seen between the concentration of nanoparticles in nanofluid and the thermal conductivity. The thermal conductivity of Al₂O₃/CNC hybrid nanofluid increases from 0.515 to 0.541 W/m K under the same
temperature as volume fraction increased. In the study by Hamid and Aiyelaagbe [53], it was reported that improvement in thermal conductivity of Al₂O₃/CNC water and ethylene glycol composite nanofluid was 13.8 % of every 1 % concentration and 22.1 % in 3 % concentration at the constant temperature. In another study conducted by Nabi, De Vriend [54], the enhancement was reported in thermal conductivity from 22.8 % out of 3 % concentration. In this study, an excellent improvement in thermal conductivity with a value of 150 % was accomplished at a 1.5 % volume fraction of (Al₂O₃/CNC) composite particles.

**Temperature effect on thermal conductivity**

At high temperatures, the Brownian motion of particles upsurges due to the high kinetic energy thus enhanced the thermal conductivity. The temperature increase is seen to improve the thermal conductivity of nanofluids. When the temperature raised from 30 ºC to 70 ºC, the composite nanofluid (Al₂O₃/CNC) thermal conductivity improved from 0.515 to 0.539 W/m K in 2 % volume concentration. However, high temperature in nanofluids leads to the agglomeration of nanoparticles and reduction of repulsive forces between them. This results in a reduction of thermal conductivity and stability of nanofluids. In a study by Farbod and Ahangarpour [55], it was reported that by increasing the temperature to 40 ºC, the thermal conductivity of Ag-MWCNTs incorporated composite nanofluid was improved. However, the value of thermal conductivity decreased by further increasing the temperature (above 40 ºC). In another study conducted by Esfahani, Zhang [56], it was indicated that the influence of dispersant could be prevented by increasing the temperature from 60 ºC to 65 ºC, leading to unsuspended nanoparticles and reduced thermal conductivity.

**Dynamic Viscosity of Nanofluids**

The viscosity measurement was initially taken with the base fluid to verify the correct steps and obtain accurate data. Previous studies that have been used as a benchmark are from Kulkarni, Crespo [57], and Vajjha, Das [58]. The measurements were then carried out after verification of the accuracy of the instruments. According to Vajjha, Das [58], the water and ethylene glycol mixture shows Newtonian behaviour. Based on Figure 10, it is observed that, as the volume concentration increases, the viscosity of nanofluid increases. This is in line with the fact that the fluid internal shear stress increases by increasing the nanoparticle concentration suspended in the base fluid, and therefore viscosity also increases [59]. This exhibits a more complicated behaviour and has a different relationship than simple linearity between shear stress and velocity gradient, following Non-Newtonian fluid behaviour. Previous literature such as Namburu, Kulkarni [60], and Fedele, Colla [61] found a similar effect of volume concentration on the viscosity. Figure 10 proves that as the temperature increase, the viscosity decreases. Li, Guo [62] elaborated that based on a molecular perspective, the temperature effect on nanofluid viscosity can be verified. They assert that the intermolecular gap becomes more significant as the temperature rises, leading to a decreased viscosity pattern.

**Selection of Nanofluid**

A coolant should exhibit lower viscosity and good thermal conductivity for optimum behaviour. Thus, nanofluids should meet or exceed those criteria to be considered a suitable replacement for conventional coolants. As shown in Figure 11(a), the present findings indicate that the investigated nanofluid containing CNC+Alumina exhibited a higher thermal conductivity than the conventional machining coolant. Figure 11(b) shows the residual plot for Ra RSM: MWF. A high viscous coolant will cause uneven material removal on the workpiece during metal cutting and require high pumping power to spray the coolant; thus, a major modification is required in the machining [63]. Considering both the thermal properties, the 0.5 % concentrated nanofluid was identified as suitable for performance investigation as it has low viscosity and high thermal conductivity value to avoid all major constraints. Therefore, 0.5% nanofluid volume concentration is used for turning operation to determine its machining performance relative to conventional metalworking fluid (MWF).

![Figure 10. Viscosity with respect to temperature.](image-url)
Response Model

The linear model shows the relationship between the turning responses and independent variables represented as the following expression Eq. (4) and Eq. (5).

\[ y' = (\text{cutting speed}) + (\text{Feed rate}) + (\text{Depth of cut}) + D \]  

(4)

Where a, b, c, and D are the constants. Eq. (4) can be stated in the following form:

\[ y'' = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \]  

(5)

Where \( y \) = turning response, \( x_0 = 1 \) (variable), \( x_1 = \) cutting speed, \( x_2 = \) feed rate, \( x_3 = \) cutting depth. \( \beta_0, \beta_1, \beta_2 \) and \( \beta_3 \) are the model parameter.

Development of linear surface roughness model: MWF and hybrid nanofluid

After the first pass of the turning experiment, set for 20 mm of cutting, the surface roughness reading result is used to produce a linear Eq. (5) model. To calculate this parameter, the response surface method is used with the aid of Minitab 17 Software. Linear equations used to predict the turning experiment’s surface roughness performed with metalworking fluid coolant and composite nanocellulose alumina-based coolant is expressed in Eq. (6) and Eq. (7).

Surface roughness using MWF coolant is:

\[ Ra = 2.465 - 0.001654 Cs + 4.37 Fr + 0.234 D \]  

(6)

Surface roughness using hybrid nanocoolant is:

\[ Ra = 2.057 - 0.001682 Cs + 4.80 Fr + 0.308 D \]  

(7)

From the ANOVA analysis for surface roughness using a conventional coolant and composite nanocoolant, the p-value was found to be less than 0.05, suggesting the importance of the independent variables (Table 5). According to the Pareto chart in Figure 11(a), in which the bar length is proportional to the absolute values of the estimated effect with a 95% confidence level, it is verified that cutting speed demonstrates the most significant effect on the surface roughness for both the conventional coolant and composite nanocoolant, as in Figure 12(c) — followed by the feed rate that almost half of the cutting speed effect. The depth contribution to the surface roughness was not significant as its effect is below the standardised effect of 2.201. The normal probability plot in Figure 12(a) shows that the point is aligned along the best-fit line. It can be said that the results obtained from the experiment fit and satisfy the mathematical model. Figure 12(b) shows the residual plot for Ra using RSM for hybrid nanocoolant. Comparing the ANOVA result for both the conventional and composite nanocoolant as in Figure 12(a) indicates that the cutting speed contribution to the surface roughness has been reduced when using the composite nanocoolant over conventional coolant. Table 6 represents the analysis of ANOVA for Ra using hybrid nanocoolant.
### Table 5. ANOVA analysis for Ra using MWF.

| Source         | Sum of squares | Contribution (%) | df  | Mean square | F-value   | p-value |
|----------------|----------------|------------------|-----|-------------|-----------|---------|
| Model          | 3.04           | 85.55            | 3   | 1.01        | 21.71     | <0.0001 |
| Cutting speed  | 2.25           | 63.50            | 1   | 2.25        | 48.18     | <0.0001 |
| Feed rate      | 0.66           | 18.73            | 1   | 0.66        | 14.22     | 0.0031  |
| Depth          | 0.12           | 3.33             | 1   | 0.12        | 2.53      | 0.134   |
| Error/Residue  | 0.51           |                  | 11  | 0.047       |           |         |
| Total          | 3.55           |                  | 14  |             |           |         |

\[ S = 0.22, \text{PRESS} = 0.986, \text{R-Sq} = 85.55\% , \text{R-Sq(adj)} = 81.61\% , \text{R-Sq(pred)} = 72.18\% \]

From the main effect plots Figure 11(c), it can be observed that to obtain a lesser worn out and increased tool life, the suggested cutting parameter is by reducing the cutting speed and raising the feed rate, which is also supported by the findings in Figure 12(c).

### Table 6. Analysis of ANOVA for Ra using hybrid nanocoolant.

| Source         | Sum of squares | Contribution (%) | df  | Mean square | F-value   | p-value |
|----------------|----------------|------------------|-----|-------------|-----------|---------|
| Model          | 3.33           | 78.96            | 3   | 1.11        | 13.76     | <0.0001 |
| Cutting speed  | 2.32           | 55.14            | 1   | 2.32        | 28.77     | <0.0001 |
| Feed rate      | 0.80           | 18.99            | 1   | 0.80        | 9.90      | 0.009   |
| Depth          | 0.20           | 4.82             | 1   | 0.20        | 2.52      | 0.141   |
| Residual       | 0.89           |                  | 11  | 0.081       |           |         |
| Total          | 4.22           |                  | 14  |             |           |         |

\[ S = 0.28, \text{PRESS} = 1.72, \text{R-Sq(adj)} = 73.22\% , \text{R-Sq(pred)} = 59.33\% \]

**Figure 12.** (a) Pareto chart plotted for Ra, (b) residual plot for Ra, and (c) main effect plot for Ra using RSM for hybrid nanocoolant.

**Analysis comparison on the experimental and mathematical model using MWF and hybrid nanocoolant for surface roughness**

After turning 20 mm for every 15 sets of metalworking fluid parameters (water coolant and composite nanofluid coolant), the mild steel surfaces’ roughness was measured three times at different steel surfaces to calculate the average value of the surface roughness, Ra.
Figure 13: Comparison of machining results for Ra using MWF and hybrid nanocoolant.

Based on the graph in Figure 13, it can be noticed that the average value of surface roughness, Ra for machining using composite nanofluid, has produced finer surface roughness compared to machining using water coolant. The differences significantly could be observed from the graph that machining using water coolant produce a rougher surface. It can be concluded that Ra decreases on the increasing of cutting speed. Hence it produced a better quality of the surface. On the other hand, the surface roughness tends to decrease with the escalation in cutting speed at a constant feed rate [64]. Lower surface roughness values or high-quality surface finish on the machined workpiece can be assumed due to lower cutting force and less heat lost to the workpiece during the machining process at higher cutting speeds during machining procedures [65].

Kumar, Singh [66] has stated that when the cutting speed is increased, the period of the chip stays in contact with the tool decreases, and the heat generated is removed and carried away by the chip. Moreover, when lubricants are used in flood conditions, a large quantity of coolant may not have reached the cutting zone and causing heat accumulation at the cutting area. In the MQL system, the cutting fluid is supplied at high pressure and high velocity directly to the interface of the cutting tool and chip that reduces friction force and increases tool life, leading to a better quality surface finish the workpiece [67]. The feed rate also influences the surface consistency. The experiment has shown that as the feed rate increases, surface roughness increases. This is because the heat produced in the cutting region increases as the feed rate increases due to the high material removal rate during the machining process [68]. Hence, it will increase tool wear, which reduces the sharpness of the flank face of the cutting tool, which will affect the surface roughness of the workpiece during machining [69]. ANOVA results have also revealed that the cutting speed and feed rate are significant factors affecting the quality of product surface. Therefore, the surface quality can be improved by decreasing the feed rate.

Adapting the MQL system, nanofluids are sprayed out like fog from the nozzle under the impression of high-pressure gas. Through precipitation or adsorption, the high polarity nanoparticles can bind to the tool-workpiece interface forming a layered film [70]. Nanoparticles in the layer film help to relieve the high pressure, thereby reducing the sliding machining force. It acts as a coolant lubricant to decrease the friction of the instrument and workpiece interface rather than to decrease the high heat generation in the cutting field [71].

Development of linear tool wear model with MWF and hybrid nanocoolant

Linear equations are used to predict the tool wear of the turning experiment performed with MWF, and hybrid nanocoolant is expressed as Eq (8) and Eq (9). To calculate this parameter, the response surface method is used with the aid of Minitab 17 Software.

Tool wear MWF =0.3172+0.000049 Cs-0.1609 Fr+0.0096 D

Tool wear hybrid nanocoolant =0.323-0.000049 Cs+0.063 Fr+0.0138 D

From the ANOVA analysis for tool wears using a conventional coolant and composite nanocoolant, the p-value of the main effects is smaller than 0.05 implies the significance of the independent factors for the conventional coolant. However, the p-value is more than 0.05 for the composite nanocoolant (in Table 7). According to the Pareto chart in Figure 14(a), the bar length is proportional to the absolute values of the estimated effect with a 95 % confidence level; thus, it is affirmed that cutting speed demonstrates the most significant effect on the tool wear for conventional coolant. However, when using composite nanocoolant (Figure 15(a)), no significant effect on the tool is wear caused by the cutting speed, feed rate, and depth of cut is observed. The three parameters show no significance as their effect is below the standardised effect of 2.201. The normal probability plot Figure 14(b) shows that the point is aligned along the best-fit line. It can be said that results obtained from the experiment fit and satisfy the mathematical model obtained. Comparing the ANOVA in Table 8, results for both conventional and composite nanocoolant show that the cutting speed and feed rate do not contribute to the tool wear when using the composite nanocoolant over conventional coolant. It can be said that the composite coolant helps (in Figure 15(b)) in reducing the high-temperature generation at the tool-work interface.
by providing high cooling during the high-speed cutting. The temperature generation during high-speed cutting has been reduced significantly; thus, no significant effect on the cutting speed. This increased cooling has reduced the high-temperature build-up at the cutting tool and promoted an enhanced cutting tool life [72]. From the main effect plots in Figure 14(c), it can be observed that to obtain a lesser warn out and increased tool life, the suggested cutting parameter is by increasing the cutting speed with reduced feed rate using the composite nanofluid. The findings from Figure 15(c) further support this conclusion. However, for lesser tools warn out using conventional coolant, the machining parameter is suggested to have lower cutting speed and increased feed rate.

### Table 7. Analysis of ANOVA for tool wear using MWF.

| Source       | Sum of squares | Contribution | df | Mean square | F-value | p-value |
|--------------|----------------|--------------|----|-------------|---------|---------|
| Model        | 3.078E-003     | 54.33        | 3  | 0.001026    | 4.36    | 0.03    |
| Cutting speed| 1.987E-3       | 35.07        | 1  | 0.001940    | 8.25    | 0.015   |
| Feed rate    | 8.94E-4        | 15.79        | 1  | 0.000897    | 3.81    | 0.077   |
| Depth        | 1.97E-4        | 3.47         | 1  | 0.000197    | 0.84    | 0.380   |
| Error/Residue| 2.58E-3        | 11           |    | 0.000235    |         |         |
| Total        | 5.66E-3        |              | 14 |             |         |         |

S = 0.0153, PRESS = 0.0049902, R-Sq = 54.33 %, R-Sq(adj) = 41.87 %, R-Sq(pred) = 11.92 %

### Figure 14. (a) Pareto chart plotted for tool wear, (b) residual plot for tool wear, and (c) main effect plot for tool wear using RSM: MWF.

### Table 8. Analysis of ANOVA for tool wear using hybrid nanocoolant.

| Source       | Sum of squares | Contribution | df | Mean square | F-value | p-value |
|--------------|----------------|--------------|----|-------------|---------|---------|
| Model        | 5.66E-004      | 10           | 3  | 1.89E-04    | 0.41    | 0.750   |
| Cutting speed| 1.8E-005       | 0.32         | 1  | 2E-05       | 0.04    | 0.840   |
| Feed rate    | 1.37E-004      | 2.43         | 1  | 1.36E-04    | 0.29    | 0.598   |
| Depth        | 5.08E-003      | 7.27         | 1  | 4.1E-04     | 0.89    | 0.366   |
| Error/Residue| 5.6E-004       | 11           |    | 4.62E-.4    |         |         |
| Total        | 5.051E+005     |              | 14 |             |         |         |

S = 0.02149, PRESS = 0.0049902, R-Sq =10 %, R-Sq(adj) = 0 %
Figure 15. (a) Pareto chart plotted for tool wear, (b) residual plot for tool wear, and (c) main effect plot for tool wear using RSM: hybrid nanocoolant.

Analysis comparison on the experimental and mathematical model of tool length of cut using: MWF and hybrid nanocoolant

Figure 16 shows the comparison of the cutting tool length of cut before it reaches the wear criterion of the experimental and predicted model using MWF and composite nanofluid. It shows that the predicted values satisfied the experimental findings with less than 10% of error. This validates the experimental work performed. Figure 17(a) and Figure 17(b) show the progression in flank wear distance with machining distance in turning cylindrical mild steel using water coolant and composite nanofluid. The mild steel workpiece of 20 mm in length will be cut by the cutting tool for each pass. The flank wear is assessed after each move, and the turning operation will be continued until the wear criterion is met according to ISO 3865:1977 (the flank wears ≥ 0.3 mm). It is also observed from Figure 17(a) that cutting parameter No. 9 (cutting speed = 990 rpm, feed rate = 0.1 mm/rev, and cutting depth = 1.2 mm) has the highest flank wear rate compared to other cutting parameters in the metalworking fluid coolant experiment. Flank wear meets the tool wear criterion with a total cutting length of around 45 mm for cutting parameter No. 1. Meanwhile, for cutting parameter No. 4 (cutting speed 425 rpm, feed rate 0.18 mm/rev, and cutting depth = 1.2 mm), the cutting tool has achieved wear criteria at a total cutting length of around 88 mm. This postulates the effect on flank wear of cutting speed and feed rate. Increased cutting speed and decreased feed rate increases flank wear, resulting in quicker tool wear [69]. These findings were further proved with the mathematical model analysis using surface response methodology, showing a similar trend from the main effect plots. According to Altin, Nalbant [73], the formation of flank wear on the cutting tool is affected by high heat generation at a higher cutting speed during the metal cutting process. Thus, the tool’s cutting edge is softened at high temperatures during the metal cutting process at the tool-chip interphase, which gradually causes gradual wear to occur [74].

Figure 16. Machining result for tool wear using water coolant and composite nanocoolant with the mathematical model prediction.
However, using the composite (nanocellulose+alumina) nanocoolant, the total length of cut was found to increase during the turning operation of mild steel workpiece at similar cutting parameters, as shown in Figure 17(b). Cutting parameters No. 9 and No. 4 significantly increase the overall cut duration to meet the wear criterion of ISO 3865:1977 under the same cutting conditions. For cutting parameters No. 9 and No. 4, respectively, flank wear meets the wear criterion of about 78 mm and 135 mm of the total cut length. Therefore, the composite has a significant flank wear rate enchantment. A similar result was also obtained by Vasu and Pradeep Kumar Reddy [75] on prolonged tool failure using nanofluid as a coolant. The superior nanofluid properties allow the hardness of the cutting tool to be maintained, and the time is extended to meet the wear criterion for failure.

![Figure 17](image)

**Figure 17.** Progression of flank wear by distance for turning with (a) MWF (b) composite nanocoolant.

**Analysis of chip formation on turning operation using MWF and hybrid nanocoolant**

The unwanted metal is removed during the turning process in the form of chips. The chip helps to remove the heat produced during the turning. Nonetheless, the pattern of the chip generated affects the processing results. As the cutting speed is increased, the output heat is also increased [76]. Therefore, the chip produced will be continuous, and the friction forces between the chip and the cutting tool will gradually increase [77]. This is because, as shown in Figure 18, the continuous chip would continuously move over the rake face of the cutting tool. The greater the impact of friction, the higher the heat produced by the cutting tool. Figure 18(a) shows the chip formation progression when using MWF coolant, and Figure 18(b) shows the discontinuous chip formed during turning operation using ethylene glycol/nano cellulose+ alumina-based nanofluid coolant. The enhanced higher thermal conductivity properties of composite nanofluid promote high heat transfer during machining, thus less heat generation at the tool-work interface along with reduced friction at the tool-chip interface providing better chip formation during turning operation [77].

During machining at high cutting speed, it can be seen that it leads to thinner chips' production. This is observed with the use of conventional coolant. The arc chip size gets longer without breaking due to the high heat generated from greater friction and cutting force, thus causing a continuous chip [78]. Conventional coolant does not effectively carries away heat generated due to the high cutting speed. Figure 19(b) demonstrates the chip created during the machining with the MQL system utilising composite nanofluid coolant. The arc chip size gets smaller resulting in discontinuous chip formation.
This proves that the hybrid coolant’s superior thermophysical properties can carry away heat generated and provide lubricity, resulting in less peeling off the cutting tool and longer tool life.

![Figure 18. The chip formation of MQL system (a) MWF (b) composite nanocoolant.](image)

**Analysis of tool failure on turning performance using MWF and hybrid nanocoolant**

A 20 mm cut length for the first pass for every experimental set is done to measure the tool life. The flank wear or major fracture obtained on the cutting tool will be measured using an optical microscope connected to a camera and computer. If the flank wear obtained did not reach 0.3mm, the experiment will be repeated with 20 mm length of the cut, and the tool wear measurement is repeated. This step is repeated until the flank wear reaches the range of about 0.3 mm to 0.35 mm. Every 20 mm pass, the time is recorded, and the total time taken to reach its wear criterion is tabulated. Table 9 shows the relationship between flank wear and the cutting instrument’s total time to achieve tool wear criteria.

**Table 9. Relationship between flank wear and total time taken to reach the flank wear criteria using MWF and hybrid nanocoolant.**

| Experiment | Flank wear (mm) | Total time taken (s) | Flank wear (mm) | Total time taken (s) |
|------------|-----------------|----------------------|-----------------|----------------------|
| 1          | 0.3178          | 198                  | 0.3729          | 254                  |
| 2          | 0.3128          | 32                   | 0.3482          | 53                   |
| 3          | 0.3252          | 226                  | 0.3694          | 311                  |
| 4          | 0.3407          | 63                   | 0.3273          | 94                   |
| 5          | 0.3488          | 230                  | 0.3371          | 307                  |
| 6          | 0.3528          | 269                  | 0.3364          | 384                  |
| 7          | 0.3681          | 452                  | 0.3407          | 678                  |
| 8          | 0.3397          | 96                   | 0.3139          | 134                  |
| 9          | 0.3663          | 24                   | 0.3421          | 36                   |
| 10         | 0.3116          | 226                  | 0.3126          | 395                  |
| 11         | 0.3502          | 97                   | 0.3136          | 97                   |
| 12         | 0.3657          | 36                   | 0.3568          | 48                   |
| 13         | 0.3348          | 32                   | 0.3629          | 53                   |
| 14         | 0.3436          | 13                   | 0.3316          | 20                   |
| 15         | 0.3724          | 24                   | 0.3621          | 36                   |

It is noted that the cutting tool achieves the ISO wear criterion faster under the MWF turning operation than the cutting tool under the nanofluid turning operation. This is because the enhanced viscosity properties of hybrid nanofluid providing good lubricity during machining reduced the friction at the tool-chip interface. Hybrid nanofluid also serves as a thermal barrier and decreases the amount of heat transmitted to the cutting device, workpiece, and chip [79]. The reduced heat influences the cutting tool’s material expansion, so the cutting edge’s hardness is maintained for the longer cutting length. Besides, the nanocellulose containing composite nanofluid forms the impermanent interfacial layer on the cutting tool and decreases the cutting tool’s wear.

**Analysis comparison of tool failure between MWF and hybrid nanocoolant**

Figure 19 shows that the tool life using hybrid nanofluid has shown a better result than using water coolant for every single parameter using the MQL system. The comparison graph shows that at machining parameter No. 7, hybrid nanofluid has significantly improved the cutting tool’s life. MQL composite nanofluid takes 678 seconds to reach its wear criterion at 0.3mm. Meanwhile, MWF took 452 seconds to get the same wear criterion. The study by Uysal, Demiren [80] found that the MQL method can decrease the wear of the tool because engraved cutting fluid could reach the interface between the cutting tool and the workpiece. Also, the MQL flow rate has a positive impact on tool wear. So, an increase in the engraved cutting fluid amount can decrease the tool wear.
CONCLUSION

In this study, a new class coolant of hybrid nanocoolant has been formulated to enhance the machining behaviour. A linear mathematical model was developed to predict turning parameters for cylindrical mild steel, using WC-Co uncoated carbide tool on two different machining experiments using two different coolants: MWF and hybrid nanofluid. The hybrid coolant’s thermophysical property was measured, and the performance was analysed by turning cylindrical mild steel using two different coolants (MWF and hybrid nanocoolant) utilising the MQL technique. The predicted linear model is used to get the best selection of turning parameters to reduce surface roughness, tool wear reduction, and improved cutting tool life based on RSM. Experimental results are compared with predicted results and the summarised findings as below:

i. Surface roughness is significantly affected by the spindle’s cutting speed, feed rate, and followed by cutting depth in both machining experiments using normal water coolant or hybrid nanofluid. Based on this experimental analysis, the surface roughness reduces when the feed rate decreases and the cutting speed increases.

ii. Based on the mathematical modelling developed using RSM, the cutting speed has the most significant effect on the surface roughness and tool wear, followed by the feed rate. It is seen the depth of cut does not significantly affect the tool wear and surface roughness.

iii. Based on the observation, flank wear is highest when turning the mild steel using MWF coolant. Besides, shorter tool life was obtained using the MWF coolant.

iv. Though, using the nanocoolant composite (nanocellulose + alumina), the total length of cut was found to increase during the turning operation of mild steel workpiece at similar. It shows that the predicted values satisfied the experimental findings with less than 10% of error.

v. The addition of the hybrid nanofluid has the lowest surface roughness and reduces the tool wear because it boosts the heat transfer rate and increases the thermal conductivity.

vi. The turning process using MQL hybrid nanofluid coolant has outperformed MQL MWF coolant in terms of surface roughness and tool life. The better surface roughness produced after using MQL hybrid nanofluid coolant is 1.026 μm while using MQL normal water coolant is 1.458 μm. Thus, the hybrid nanofluid has improved the surface roughness by 29.63%. Significant enhancement was observed in the longer tool total length of cut (39%) by utilising the prepared hybrid nano lubricant compared to MWF. The maximum tool life produced for the turning process until the wear reaches the ISO 3685:1993 wear criterion is 0.3 mm and 678 seconds by using MQL hybrid nanofluid coolant while using MQL normal water coolant 452 seconds. There is also an improvement in the cutting tool lifespan, which has increased by about 33.33% longer.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Malaysia Pahang (UMP) for the financial support under grants RDU192205 and RDU192208.

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