Thermophysical, Rheological and Wear Resistance of Canola Oil Biolubricant with Calcium Carbonate Additive Nanoparticle as Coolant in CNC Machining

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ABSTRACT

Vegetable oil-based cutting fluids are of great importance in supporting green and sustainable manufacturing. This research introduces a new groundbreaking vegetable lubricant formulated with canola oil as the base material, coupled with $CaCO_3$ nanoparticles synthesized from scallop shell waste and used as a cutting fluid in the AISI 1045 CNC machining process steel sprayed with minimum quantity lubrication (MQL). This investigation delves into the thermophysical, rheological, and wear resistance of the developed bio-lubricant. The results of this analysis show density value increased in the canola + $CaCO_3$ 0.15% sample by 3.28% of the pure canola sample, as did the viscosity value, an increase occurred in the canola + $CaCO_3$ 0.20% sample, at a temperature of 40°C it increased by 31% and at a temperature of 100°C it increased 42% of the pure canola sample. Thermal conductivity testing also showed an increase in the canola + $CaCO_3$ 0.15% sample by 1.8% compared to the pure canola sample. Optimal performance in reducing cutting tool wear was observed in the canola + CaCO3 0.15% sample, resulting in a 30% reduction compared to pure canola samples. This reduction also led to the smoothest chip surface and a silver-colored chip. This advancement positions our canola oil-based cutting fluid as a high-performance and environmentally friendly substitute for traditional cutting fluids. The findings underscore its potential for widespread adoption by the industry, promising a transformative change towards sustainable and environmentally friendly machining.

Keywords: *Biolubricant, canola oil, cutting fluid, calcium carbonate, minimum quantity lubrication*

I. Introduction

The machining process will not be separated due to friction between the work material and the tool, which allows wear on the cutting tool to reduce heat caused by friction during the metal forming process. Coolant is needed as a medium to minimize wear on the cutting tool [1]. In the cutting or machining process, the coolant's function is to lower heat, reduce friction on the surface of the workpiece, remove debris from cutting, and prevent corrosion of the workpiece [2], [3]. The use of coolants for the machining process still uses a lot of chemical coolants. This cooling liquid is not only not environmentally friendly but also has adverse effects on human health/machine operators [4]. Likewise, in the use of mineral oil-based flood cutting fluids with large amounts usually used in the machining and cutting

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process to reduce the cutting temperature figure so as not to overheat, however, only a small part can penetrate the grinding area and play a function in cooling and lubricating, and it cannot effectively transmit heat [2], [5]. Furthermore, the application of cutting fluid in huge volumes can cause the availability of mineral oil raw materials to be depleted [6]. So, an alternative solution is needed to address various existing problems to produce a more effective machining and cutting process.

It is known that the coolant that is widely used today comes from mineral oil [7]. The production of mineral oil in the world is very high and will continue to increase every year, so that the raw material has the potential to run out in the future [8]. With the rapid advancement of research, innovation, and technology, the significance of preserving the environment is becoming more widely recognized. Research on environmentally friendly and sustainable production, conservation of resources, and efficient use of energy is needed. Vegetable oils address these issues due to their excellent properties, such as non-toxicity [9], better biodegradability, very abundant raw materials in nature, and lower price [10]. Vegetable oils are also a clean energy source with relatively low environmental impact compared to petroleum. Therefore, the use of vegetable oil as an alternative cooling base material (bio lubricant) is a very appropriate solution [4], [11].

To enhance the effectiveness of cutting fluids during the process of machining, many researchers have developed nanoparticle-based cutting fluids and base fluids that enhance heat transfer capabilities [12]. The addition of additives can improve the characteristics of cutting fluids [11]. Nano-based base oils are new fluids in which nanoparticles of 100 nm or less are dispersed in the base cutting fluid [13]. Nanotechnology can be used to improve the properties of coolants, especially thermal, rheological, and tribological properties, especially through the formation of tribofilms that reduce wear and surface roughness, turn into a protective film, and rolling effect medium during friction procedures [14]. Nanoparticles are added to lubricants to improve friction properties, and can reduce the coefficient of friction and wear [11]. It has been demonstrated that vegetable oil, particularly canola oil, may be utilized as a base oil in a variety of machining applications when paired with MQL technology. These cutting fluids' cooling and lubricating qualities can be enhanced by the addition of nanoparticles [15]-[20].

In general, there aren't many studies comparing the qualities of different varieties of canola oil. Further development is still needed regarding the properties of vegetable oils, especially canola oil with different concentrations of nanoparticles added, so that it can provide various lubricating and cooling effects. To find the best mixture of canola oil with the advantage of the best cutting efficiency throughout the process of machining, we use canola oil with five concentrations milling process of AISI 1045 steel by studying the surface roughness, cutting tool wear, and wear debris produced throughout the milling process. Therefore, we also use calcium carbonate ($CaCO_3$) nanoparticle additives with five different concentrations, which will be mixed in the canola oil used. $CaCO_3$ is derived from leftover scallop shells (*Amusium pleuronectes*) that have been processed into powdered nanoparticles. The choice of $CaCO_3$ made from scallop shells aims to minimize waste from scallop shells, containing 98% $CaCO_3$, which is abundant in nature, making it more economical. $CaCO_3$ as a lubricant additive has the advantage of anti-wear properties [21], friction reduction, good chemical stability [22], load carrying capacity, and extreme pressure to produce good tribology [23]. The performance of $CaCO_3$ is evaluated experimentally, which is analyzed for its effect on the thermophysical, rheology, and tribology properties of vegetable oils used in CNC milling machining processes.

II. Material and Methods

1. Materials

Canola oil (Dougo, Indonesia) was used as the study's base oil and raw material. Regarding the substance that was added as an addition to the basic oil, specifically $CaCO_3$ nanoparticles made from leftover scallop shells. AISI 1045 steel was used for experiments when applying MQL (BPV Sprayer, China) cutting fluid samples to a milling machining process with dimensions of 50 mm x 50 mm x 20 mm (P, L, T). The machining procedure was carried out using a high-speed steel (HSS) endmill with an 8 mm diameter and four flutes (Toki, China).

2. Cutting Fluid Sample Preparation

A two-step procedure that included stirring and homogenization was used to prepare samples of nano-cutting fluid [24], [25]. The sample preparation process begins with mixing $CaCO_3$ nanoparticle additives into canola oil and stirring using a magnetic stirrer (Thermo Scientific, China) for 20 minutes with a rotation speed of 1250 rpm [26]. Followed by a homogenization process utilizing an ultrasonic homogenizer (Sonobio Homogenizer, China) for half an hour to create a cutting fluid sample with a high degree of dispersion [2]. The nano-cutting fluid sample preparation process is shown in Figure 1, and the experimental design for this investigation is provided in Table 1.

Fig. 1. Schematic of nano-cutting fluid sample preparation

Table 1. Research sample type specimen

No	Sample names	Nanoparticles content (wt%)	Lubricating condition
1.	Dry	0	Dry
2.	Dromus	0	MQL
3.	Canola Oil	0	MQL
4.	CO+0.05% $CaCO_3$	0.05	MQL
5.	CO+0.10% $CaCO_3$	0.10	MQL
6.	CO+0.15% $CaCO_3$	0.15	MQL
7.	CO+0.20% $CaCO_3$	0.20	MQL

3. Experimental Setup of CNC Milling

This research uses the CNC milling machining technique to identify and determine the performance of canola oil-based nano-cutting fluid samples with different variations in the mass fraction concentration of $CaCO_3$ nanoparticles to be sprayed using the MQL method, in addition to the various CNC milling machine components used for experiments, MQL preparation is also required, which consists of a mist-shaped spraying nozzle, a compressor to apply pressure to the nano-cutting fluid sample during the machining process, and a flow control to ensure constant air pressure. The CNC milling machining scheme with MQL is shown in Figure 2 with machining parameters as in previous studies [2].

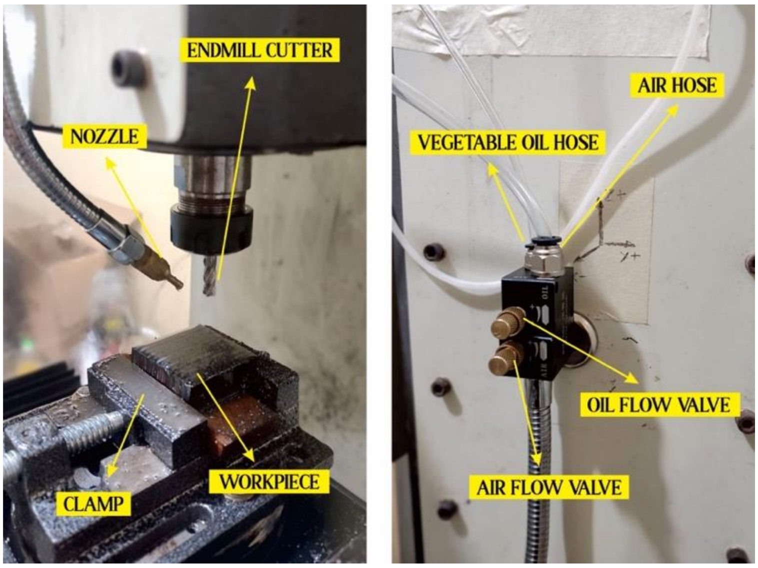

Fig. 2. Setup CNC milling with MQL

4. Thermophysical Test of Nano-cutting fluid

Density testing of nano-cutting fluid samples using analytical digital scales was conducted at room temperature. The mass value is obtained from the weight of the sample, while the volume is measured using a pycnometer [27]. Thermal conductivity testing was carried out using a thermal properties analyzer (KD2 Pro, USA) to assess the nano-cutting fluid sample's heat transfer performance [28]. Dynamic viscosity testing was conducted to analyze the viscosity level of the specified flow to use the viscometer (NDJ-8S, China) tool to determine the nano-cutting fluid sample's rheological value with variations in temperature and rotor speed [29], [30].

5. Rheological Test of Nano-cutting fluid

The flow type of the nano-cutting fluid that was analyzed established how shear rate and shear stress are related by the rheological properties. The outcomes of the nano-cutting fluid dynamic viscosity test are required in order to determine the shear rate and shear stress values [31]. Equation 1 determines the shear rate value, while Equation 2 determines the shear stress value.

$$\gamma = \frac{2\omega {R_c}^2 {R_b}^2}{x^2({R_c}^2 - {R_b}^2)} \quad (1)$$

Where γ is the shear rate (1/s); ω is the angular velocity (rad/sec); R_c is the container radius (cm); Rb is the rotor radius (cm); and x is the radius used to determine the shear rate (cm).

$$\tau = \mu \times \gamma \quad (2)$$

Where τ is shear stress (mPa.s); μ is dynamic viscosity (kg/m.s); γ is shear rate (1/s).

6. Tool Wear Measurement

HSS endmill tool wear was performed using a Sinher Binocular optical microscope type (XSZ-107 BN, China) to be able to determine the wear area at the interval of 4 HSS endmill flutes [32]. Then, the wear length was measured using ImageJ software to determine the edge wear length Vbmax. This cutting tool wear is measured on the edge side based on the length of wear that occurs on that side.

III. Results and Discussions

1. Density of Sample Nano-cutting Fluids

Figure 3 represents the density measurement results of the cutting fluid sample made with canola oil mixed with $CaCO_3$ nanoparticles. The density value rises in proportion to the basic oil as it is mixed with the mass fraction of nanoparticles. As the concentration of nanoparticles rises, so does the density. The phenomenon that occurs is that nanoparticles can act as reinforcements in the base material, increasing the hardness and strength of the processed material, so that it can produce a smoother and more durable machining surface. In fact, the mass of the cutting fluid sample rises in tandem with the concentration of nanoparticles [33]-[35].

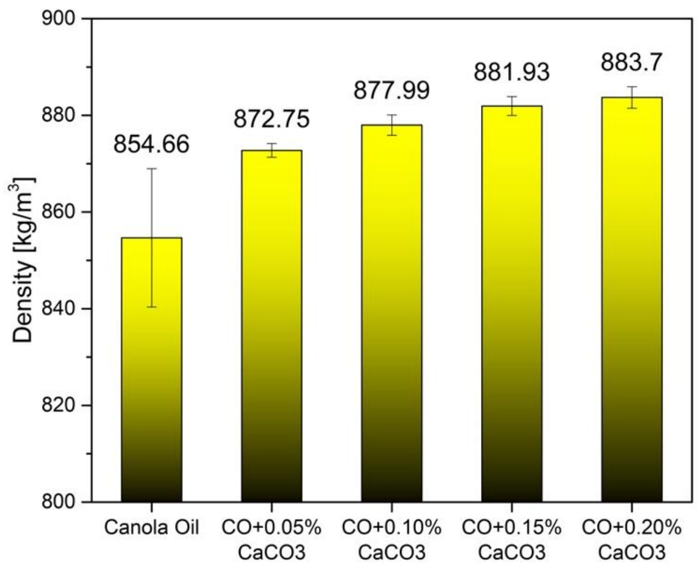

Fig. 3. The density of canola oil-based cutting fluid samples

The density value of nanoparticles contained in vegetable oil is higher, causing nanofluids to have a higher density value compared to basic liquids. The cutting fluid's performance is influenced by its density. The cutting fluid's ability to generate hydrostatic pressure increases with its density value. Therefore, increasing hydrostatic pressure can facilitate the cutting fluid's entry into the cutting zone throughout the machining operation.

2. Thermal Conductivity of Sample Nano-cutting Fluids

Figure 4 shows the value of thermal conductivity in cutting fluid samples using canola oil with variations in the fraction of $CaCO_3$ nanoparticles. Based on the results obtained, the fact that there is no discernible variation in each sample's thermal conductivity value can be explained. Canola oil, like other vegetable oils, has a relatively low thermal conductivity compared to canola oil with added nanoparticles due to the natural nature of the organic liquid. The addition of $CaCO_3$ nanoparticles can increase the thermal conductivity of canola oil. $CaCO_3$ nanoparticles generally have higher thermal conductivity than organic liquids. When these nanoparticles are dispersed in canola oil, they create pathways for more efficient heat transfer, so that the higher the concentration of nanoparticles, the more heat transfer pathways are available, and the higher the thermal conductivity.

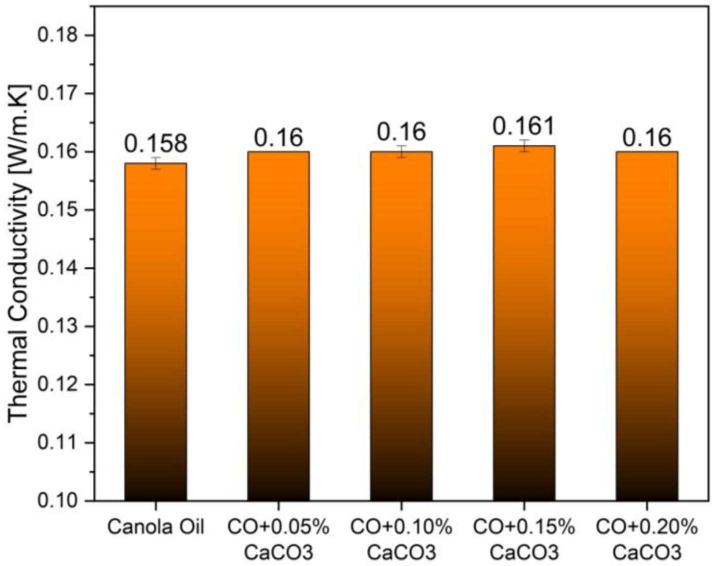

Fig. 4. Thermal conductivity of canola oil-based cutting fluid samples

The thermal conductivity value can be influenced by several factors, such as the kind of base oil, temperature, manufacturing method, concentration, form, and the nanoparticles' thermal conductivity [36], [37]. The difference in thermal conductivity values that are not too significant can occur possibly because the concentration impacts the Brownian motion force of nanoparticles, where the force is a random movement of particles in the suspension solution. Adding $CaCO_3$ nanoparticles to the base fluid should boost thermal conductivity, but if too much then there will be an agglomeration that reduces the nanoparticles' Brownian motion against the base oil [38]. In some cases, increasing concentration can increase thermal conductivity, but there is a limit where increasing nanoparticle concentration no longer provides a proportional increase in thermal conductivity [39]. Therefore, when nanocutting fluid was used, the addition of $CaCO_3$ nanoparticles showed higher thermal conductivity compared to canola oil. In addition, statistical analysis of the results showed that the data from experimental tests repeated three times for each type of variable showed validity, and the use of $CaCO_3$ nanoparticles showed the best results in increasing the thermal conductivity by one unit.

3. Viscosity of Sample Nano-cutting Fluids

Figure 5 displays the dynamic viscosity test results of canola oil with various fractions of $CaCO_3$ nanoparticles. Based on this, it shows that as the concentration of nanoparticle additives increases in canola oil, the viscosity rises. This is caused by the effect of increasing the density value of lubricant nanoparticles, causing an increase in viscosity [40]. In addition, the Van der Waals force is the cause of this phenomenon, which raises the lubricant's viscosity [41]. It was also observed that the decrease in the viscosity value of the cutting fluid samples was caused by the increase in temperature. This finding is consistent with earlier studies that explain how a fluid's decreased intermolecular interactions cause viscosity to drop as temperature rises [42]. The dynamic viscosity of the cutting fluid sample is important to analyze because during machining, the right viscosity will provide a thick layer in the bearing space, reducing wear and friction.

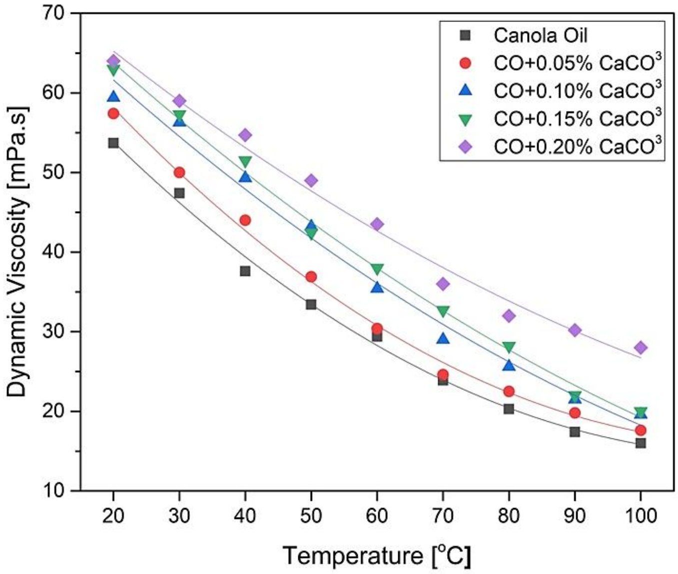

Fig. 5. Dynamic viscosity of canola oil-based cutting fluid samples

Table 2. Parameters of sample coolant

Value	Pure Canola	0.05%	0.10%	0.15%	0.20%
Density ρ (Kg m^{-3}) at 20 ºC	854.66	854.66	854.66	854.66	854.66
Kinematic viscosity v (mm² s^{-1}) at:					
40 ºC	4.40	5.04	5.62	5.84	6.19
100 ºC	1.87	2.02	2.23	2.27	3.17
Viscous Index	340.699	278.494	291.119	271.621	603.449

Table 2 displays the results of calculating the viscosity index for each sample using the ASTM D2270 standard. It is known that the viscosity index for the pure canola sample was 340.699, the 0.05% sample was 278.494, the 0.10% sample was 291.119, the 0.15% sample was 271.621, and the 0.20% sample was 603.449. The results of this calculation show that the viscosity values taken are different for each sample. The higher the viscosity index value, indicating that the viscosity of the liquid does not change much when the temperature rises.

4. Rheology of Sample Nano-cutting Fluids

Figure 6 demonstrates the contrast between the shear stress value and the shear rate of cutting fluids based on canola oil at 40°C and 100°C with the addition of $CaCO_3$ nanoparticles. The figure illustrates how pure canola oil exhibits Newtonian flow behavior when combined with additions of $CaCO_3$ nanoparticles [43]. Newtonian fluids can have consistent performance in lubrication, especially in cutting fluid applications where loads and speeds can change. This consistency can maintain surface separation to help prevent excessive friction and wear in the machining process [44].

Apart from that, the addition of $CaCO_3$ nanoparticles to canola oil has been proven to increase the shear rate and shear stress values. The highest shear stress values at temperatures of 40°C and 100°C were obtained from canola oil with the addition of 0.20% nanoparticles. Figure 6 also describes a decrease in shear stress after increasing the temperature from 40°C to 100°C, indicating a decrease in Van Der Waals forces at high temperatures. Nanoclusters arising from nanoparticle aggregation inhibit the relative movement of oil layers, thereby exerting a more significant influence on viscosity at lower temperatures. This happens because the temperature increases, allowing the particles to overcome the Van der Waals attraction force.

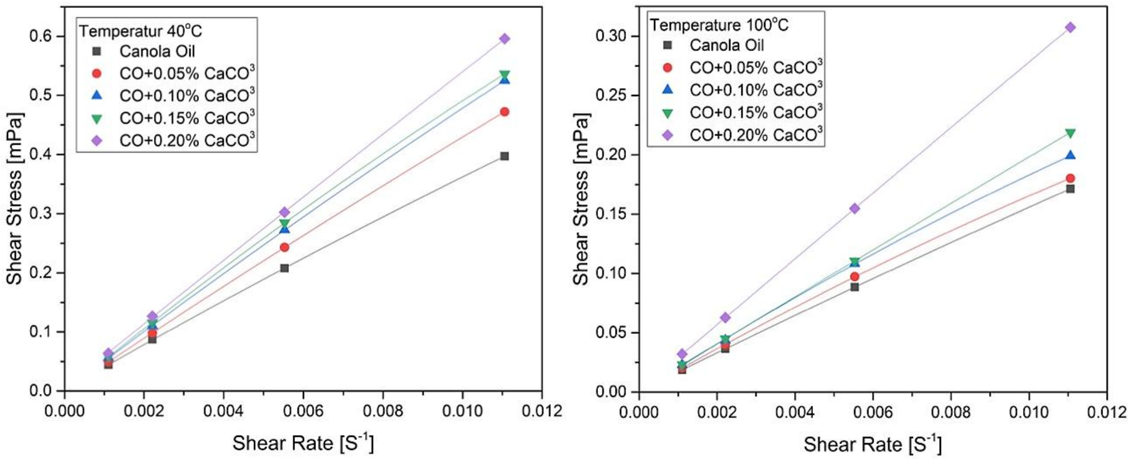

Fig. 6. Rheology of canola oil-based cutting fluid samples at (a) 40°C and (b) 100°C

5. Tool Wear

Tool wear affects a variety of metal cutting machining parameters, such as surface quality, machining efficiency, and tool life [45]. Figure 7 shows the endmill wear after being used in CNC machining using canola oil with $CaCO_3$ nanoparticle additive as cutting fluid. Tool wear can be decreased during the machining process by using a cutting fluid based on pure canola oil with $CaCO_3$ nanoparticles added [2].

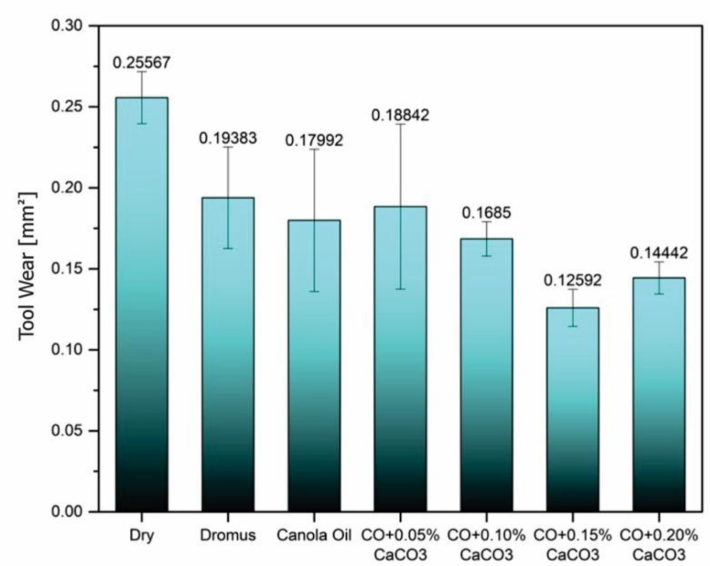

Fig. 7 Endmill tool wear measurement results after the CNC machining process

Research by Kazeem *et al.* [46] has demonstrated that cutting fluids based on vegetable oil can generate better surface smoothness and less tool wear than cutting fluids based on mineral oil. Research conducted by Tiwari *et al*. [47] explains that MQL nanofluids have the best performance in reducing cutting tool wear. When MQL is combined with nanofluids, it increases thermal conductivity so that it can provide excellent heat transfer effects and effective anti-friction pads that reduce abrasion wear on cutting tools compared to using other cooling methods. With nanoparticle engineering, it can improve the tribological properties of the cutting fluid, especially to form tribo-film [48].

The physical properties of nanoparticles also influence the tool wear value. The round shape of $CaCO_3$ nanoparticles can increase the flow ability of the cutting fluid, increasing its ability to lubricate the cutting zone. This can reduce friction between the tool and workpiece and minimize wear on the tool tip [2], larger crystal sizes can exert greater impact forces on the tool surface, thereby causing increased wear, smaller crystals generally have smaller impact forces and may be more easily dispersed in the cutting fluid, thereby reducing their abrasive effect on the tool. These results also show the great benefit of adding $CaCO_3$ to the cutting fluid to prolong the life of the tool. The ability of nano cutting fluid to preserve a very thin coating demonstrates its benefit. Wear will therefore be lessened when the test piece and the cutter come into contact.

Figure 8 demonstrates a photo macro of the endmill following the process of CNC machining in dry machining conditions, considerable cutting tool wear is obtained because the endmill and workpiece will come into immediate contact in the absence of adequate cooling media, resulting in high heat, and with it cutting tool wear will increase, at the same time, because chips produced during the cutting process will gather around the cutting zone, so this heat will be trapped and cause increased cutting tool wear in the absence of cooling under high temperature and pressure [49]. Meanwhile, in the conditions of the cutting fluid with a mixture of $CaCO_3$ nanoparticles, the wear value was lower than in other conditions. This was possible because the thin layer of the cutting zone produced lubricating oil containing small $CaCO_3$ particles as anti-friction and excellent load-bearing during the friction process. Besides that, $CaCO_3$ nanoparticles when used in the proper concentration, can help create a rolling protective layer that reduces friction and increases convective heat transmission. This allows the heat to be dissipated as efficiently as possible, which reduces tool wear [50].

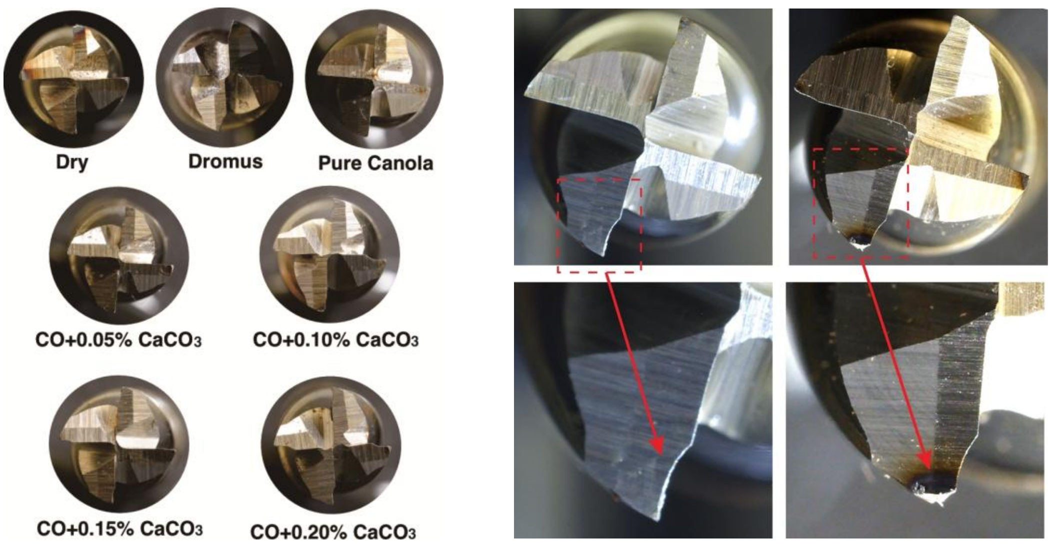

Fig. 8. Endmill photomacro after being used in the CNC machining process

IV. Conclusions

The addition of $CaCO_3$ nanoparticles from scallop shell waste to canola oil-based fluid with a mass fraction variation of 0%, 0.05%, 0.10%, 0.15%, and 0.20% has an impact on the nano-cutting fluid's thermophysical characteristics, specifically, the larger the mass fraction variation of $CaCO_3$ nanoparticles, the higher the value in the density, dynamic viscosity, and stability of nano-cutting fluid. The results of this analysis show density value increased in the canola + $CaCO_3$ 0.15% sample by 3.28% of the pure canola sample, as did the viscosity value, an increase occurred in the canola + $CaCO_3$ 0.20% sample, at a temperature of 40ºC it increased by 31% and at a temperature of 100ºC it increased 42% of the pure canola sample. Thermal conductivity testing also showed an increase in the canola + $CaCO_3$ 0.15% sample by 1.8% compared to the pure canola sample. Optimal performance in reducing cutting tool wear was observed in the canola + CaCO3 0.15% sample, resulting in a 30% reduction compared to pure canola samples. This reduction also led to the smoothest chip surface and a silver-colored chip. The results of the analysis of the rheological properties of nano-cutting fluid based on canola oil with variations in the mass fraction of $CaCO_3$ nanoparticles addition show a comparison of shear rate and shear stress values that, in all sample variations, have Newtonian flow behavior. The effectiveness of cutting fluid samples shows that the addition of $CaCO_3$ nanoparticles with a concentration of 0.15% indicates the most optimal performance with the lowest tool wear.

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