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Evaluating the chip formation process and machining performance during orthogonal cutting using bio-based metalworking fluids

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KEYWORDS

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Metalworking fluids
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Quick-stop device

ABSTRACT

Metalworking fluids (MWFs) serve to cool and lubricate tools, but commercial MWFs harm the environment and pose health risks due to mineral oil content. Vegetable-based MWFs are being researched as alternatives for their superior properties and biodegradability. A Quick Stop Device (QSD) is used to monitor chip formation during metalworking processes that are lubricated with vegetable-based minimal quantity lubrication (MQL) to evaluate the efficiency of the lubricant. Experimental comparison between vegetable oils and synthetic esters during stainless steel turning showed MQL, combining air and cutting fluid, as a better alternative to flood coolant systems. Crude Tamanu Oil (CTO), Crude Jatropha Oil (CJO), and palm olein (RBDPO) led to Build Up Edge (BUE) development, indicating less effectiveness compared to Synthetic Ester (SE). Lubricant application reduces friction, improving surface quality and formed short continuous chips during turning.

1.0 INTRODUCTION

Metalworking fluids (MWF) are commonly used as lubricants and coolants in the machining industry. To enhance productivity and quality in machining operations, cooling and lubrication are employed as essential requirements throughout metal machining and cutting processes. Government restrictions and public awareness have pushed industrialists to decrease the use of mineral oil-based metalworking fluids as cutting fluid due to the rising concern about environmental and health implications of industrial activities (Abdul Sani et al., 2024). Moreover, MWFs also contribute to a significant percentage of production expenses. Manufacturing

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processes that focus on economic, environmental, and health benefits are crucial and feasible study areas, making MWF ideal candidates for sustainable manufacturing research (Sustainable Development Goal (SDG) 7, 12, 13). Modern manufacturing processes now use minimal quantity lubrication (MQL) instead of dry machining and as a substitute for flood cooling. This study will assess the effectiveness of bio-based oil as metalworking fluids (MWFs) when used with minimum quantity lubrication (MQL) in machining processes.

The main adverse effect of mineral oil is due to its low biodegradability, which can lead to prolonged environmental contamination. Manufacturers in the machining sectors have been encouraged to explore new technologies that can replace mineral oil-cutting fluids. Inadequate coolant flow and lower pressure can cause negative consequences when working with challenging materials like titanium and hard alloys. Palanisamy et al. (2009) have identified several negative consequences of thermal stress and abrasion, which can lead to early tool failure and severe tool chipping.

With the growing need for energy, the depletion of fossil fuels, and the rising global concern for the environment (SDG 12 & 14), there has been an important shift towards researching and developing renewable and sustainable energy sources, due to the impact of fossil fuels. Unlike traditional petroleum-based lubricants, bio-based lubricants are characterized by their chemical structure of fatty acids, making them a cleaner alternative (Abdul Sani et al., 2023). Vegetable oil consists mostly of triglycerides, esters formed from glycerol molecules, and three long-chain fatty acids. Fatty acids can create a variety of compounds by reacting with any of the three hydroxyl groups and there are three primary categories of fatty acids: (i) saturated, (ii) monounsaturated, and (iii) polyunsaturated (Srikant & Rao, 2017). The carbon chain of a fatty acid is typically connected by single, double, or triple carbon-carbon bonds. Saturated fatty acids consist of carbon atoms connected by single bonds in their chain, resulting in strong resistance to oxidation. Unsaturated fatty acids may be classified into two types: monounsaturated and polyunsaturated. Monounsaturated fatty acids, like oleic acid, have a single double bond in their chain. On the other hand, polyunsaturated fatty acids, such as linoleic acid, have many double bonds in their chain. The presence of double bonds in the chain will affect the oxidative stability of the fatty acids (Reeves et al., 2015). An increase in the amount of double bonds in the chain might lead to a decrease in oxidative stability until now, quite a bit of vegetable oils from both edible and inedible sources have been implemented in producing bio-based lubricants. However, the use of inedible materials is particularly appealing as it avoids the consumption of valuable edible nutrients that could otherwise be used for food production. The determination is significantly influenced by climatic and geographical factors (Zainal et al., 2018). Vegetable oils like rapeseed, canola, soybean, and coconut have been widely recognized as promising candidates for biodegradable lubricants. They are easily broken down by nature and are more affordable than synthetic base stocks. They demonstrate satisfactory performance as lubricants (Zulkifli et al., 2016).

To determine the effectiveness of the lubricant in the machining process, a Quick Stop Device (QSD) is developed in-house (Abdul Sani et al., 2024). QSD is a device used to capture chip development during the machining process (Satheesha et al., 1990). Throughout the machining process, QSD will freeze the metal chip and it has a mechanism to retract the cutting tool while in use (Mousavi Azam & Ahmadloo, 2016). The QSD device helps to maintain the chip formation on the workpiece as the frozen chip will retain its geometrical and metallurgical features, making it suitable for assessing the lubricant's performance (Yeo et al., 1992). Analyzing the frozen chip can provide information about the tool's lifespan, as well as the level of friction and heat generated.

An in-house Quick-Stop Device (QSD) is used in this research work to evaluate the effectiveness of vegetable-based lubricants through the analysis of chip root development (Satheesha et al., 1990 & Abdul Sani et al., 2022). Most QSD utilize a 'shear-pin' design to withstand cutting pressures during regular machining operations. During separation, the shear pin breaks off by a rapid impact, enabling the tool and workpiece to detach and halting the cutting process. Subbiah & Melkote (2008) designed a hammer blow type QSD where the top of the tool holder breaks the shear pin at a notch, allowing the tool holder to revolve quickly due to the spring's action and the hammer's velocity separating the cutting tool and the workpiece. This halts the cutting process, causing the chip to stay connected to the workpiece.

During machining, the material ahead of the cutting tool deforms first in the primary and secondary shear zones. The material that exists in these areas is referred to as the 'chip root'. The cutting process is intervened abruptly by separating the tool quickly from the rotating workpiece, resulting in a partially generated chip (known as a 'frozen chip') that remains rooted on the workpiece end (Amini et al., 2017). In this study, the objective is to assess the effectiveness of Bintangor Laut / Tamanu oil (Calophyllum Inophyllum) as a metal cutting lubricant in comparison to synthetic ester oil (SE) while machining AISI316L stainless steel by turning operation. The QSD is designed to detect the formation of chips during milling by freezing it. The lubrication method selected is MQL, which combines air and lubricant and formed spray particles that are precisely delivered to the cutting zone at high pressure (4 bar). Utilizing the four lubricants, the research methodology entails conducting the orthogonal cutting procedure at three distinct cutting speeds (100 m/min, 125 m/min, and 150 m/min).

2.0 EXPERIMENTAL PROCEDURE

2.1 Lubricant Preparation For Machining Operation

This study uses four distinct types of lubricant: a commercial MQL lubricant, the Synthetic Ester (SE), crude Tamanu oil (CTO), crude Jatropha oil (CJO), and refined bleached deodorised palm olein (RBDPO). The SE, CJO and RBDPO are commonly available for purchase, but CTO is cold-pressed in-house from Calophyllum Inophylum fruits that are found in Universiti Malaysia Pahang Al-Sultan Abdullah. CTO is a recently developed lubricant that may be used as a replacement to conventional vegetable oils in metalworking fluids as shown in Figure 1 below.

Figure 1: Lubricant used in the experimental study.

2.2 Experimental Procedure of Orthogonal Machining

The experiment involved testing several lubricants in minimal quantity lubrication (MQL) including CTO, CJO, RBDPO, and SE as previously stated in section 2.1. Figure 2 depicts the whole setup assembly of the machining tests. The machine conditions recommended by the tool manufacturer remain constant throughout the tests and are detailed in Table 1. During the experiment, the workpiece will be positioned perpendicular to the cutting edge of the rotating axis at 100 m/min, 125 m/min, and 150 m/min. The disc has an initial thickness of 2 mm and a diameter of 100 mm. The machining method utilizes a quick-stop device (QSD) set up to get a frozen chip (Chern, 2005). The material that was implemented in this experiment is uncoated carbide. The tool insert was installed at the QSD. The nozzle is mounted 8 mm apart from the cutting edge of the tool insert. The nozzle should be inclined at a 45° angle to properly distribute lubrication on the insert and workpiece, as Abdul Sani et al. (2018) recommended and depicted in Figure 2.

To learn about the chip development of stainless steel AISI 316L, the chip is kept intact at the workpiece utilizing the QSD. The arrangements of QSD are shown in Figure 3. While maintaining all other cutting parameters constant, the cutting speed must be decreased to 150 metres per minute to obtain the frozen chip, as QSD is incapable of operating at a higher speed when cutting stainless steel material. Ozcatalbas (2003) asserts that to get the desired chip formation, the material must be cut at a cutting speed of 150 m/min. During the turning operation, the tool turret will move in the Y direction while the workpiece rotates anticlockwise. As depicted in Figure 4, the user will activate the pneumatic valve when the tool begins to cut the workpiece; thus, the tool holder will be pulled by a pneumatic cylinder. Subsequently, the insert will fall slightly, causing it to separate from the workpiece.

As depicted in Figure 5 the ECOSAVER KEP-R MQL device was utilized to implement the MQL method. The mixing chamber of this device was responsible for combining the lubricant with the compressed air. The lubricant's input pressure was set at 0.4 MPa and the flow rate at 0.16 l/h. The MQL mist was sprayed through the nozzle at the tool-workpiece interfaces in the cutting zone. Before the experiment, the oil flow rate was determined by spraying oil from a nozzle which orifice is 2.5 mm in diameter. The oil gauge measurement was recorded both before and after the spraying procedure. The experiment was conducted three times, and the mean value was documented.

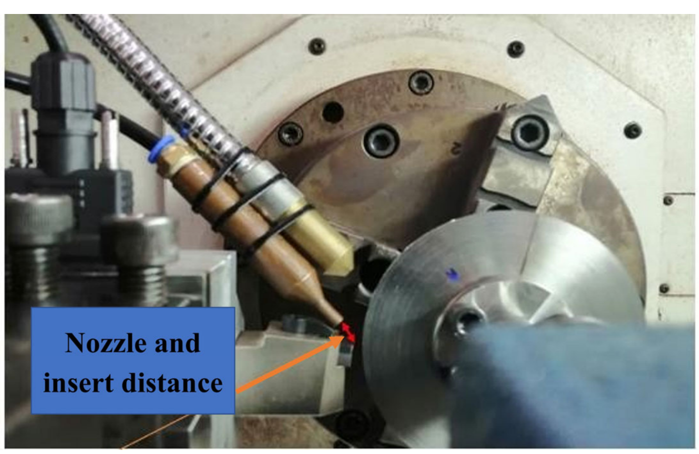

Figure 2: The setup of orthogonal cutting process.

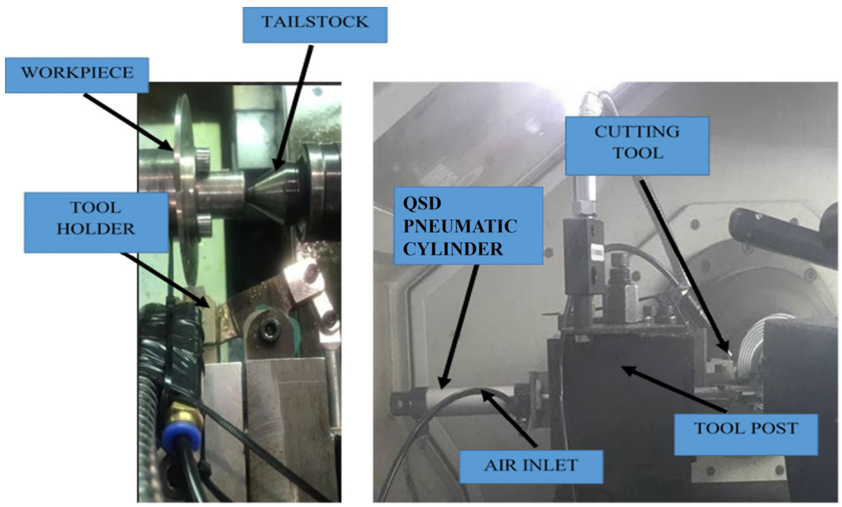

Figure 3: The QSD arrangement.

Figure 4: Pneumatic valve 5/3 hand lever valve manual return.

Table 1: The machining conditions recommended by the tool manufacturer

Description	**Value**
Cutting speed, v_c	100, 125, 150 m/min
Feed, f	0.12 mm/rev
Depth of cut, d	2 mm
Tool inserts model	SPGN120308 (uncoated carbide)
Tool corner radius	0.8 mm
Tool rake angle, α	+5°
Tool holder	CSDPN2525M12
Workpiece material	AISI 316L (Cr. 16.0-18.0 %; Ni. 10.0-14.0 %; Si. 1 %; Mo. 2.0-3.0%; Mn. 2.0%; N. 0.1%)
Initial workpiece diameter, D_o	65 mm
Workpiece thickness, t_o	2 mm

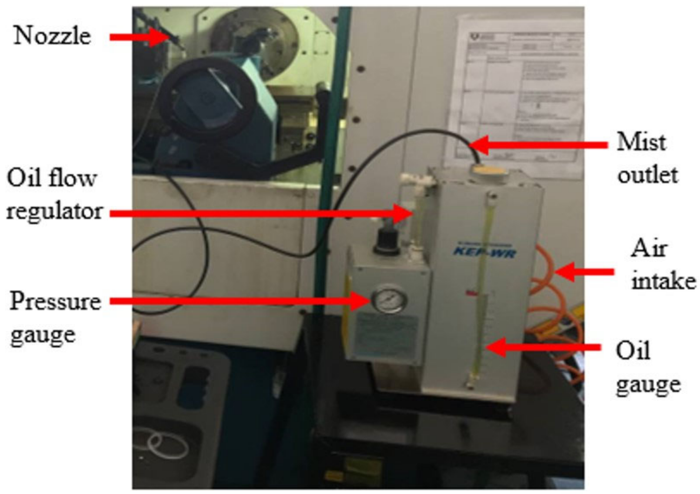

Figure 5: ECOSAVER KEPR MQL device.

2.3 Cutting Force Data Collection

A real-time cutting force monitoring device dynamometer called Neo-MoMac, which is also known as a strain gauge-based dynamometer, is attached to the machine tool to measure the cutting force. The system consists of a small data collector with a user-friendly graphical interface (GUI) and a dynamometer for measuring the cutting forces. The dynamometer could track primary feed force (F_x), thrust force (F_y), and cutting force (F_z) throughout the machining phase. To measure cutting force accurately, maintaining a suitable setup by positioning the MQL nozzle accurately on the turning machine, attaching a dynamometer to the machine, and connecting it to a multi-charge amplifier as shown in Figure. 6 The sensor signal is sent to the amplifier, and the resulting cutting forces are then shown on the screen.

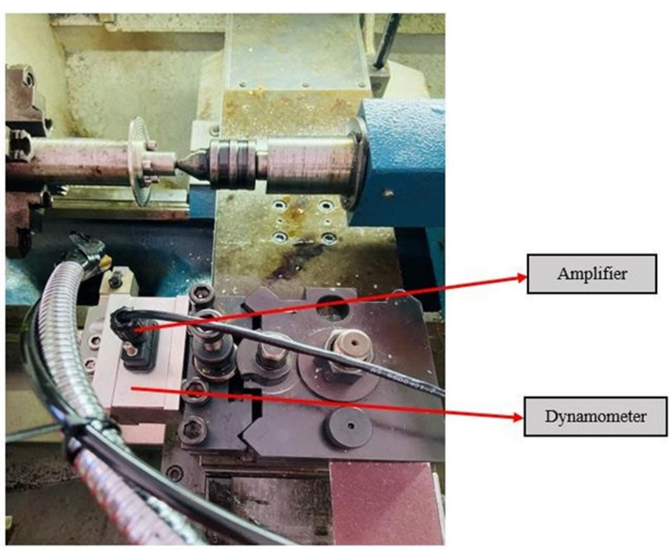

Figure 6: The dynamometer and amplifier position during machining.

2.4 Chip Surface Morphological Structure Analysis

Metallography is the examination of the composition and structure of metals and alloys. Etching is used to prepare the specimen prior to revealing the microstructural features under the microscope. Cold mounting requires resin powder and a hardener to create the mounting compound in a 1:2 ratio, consisting of 1 part hardener and 2 parts resin. The compound undergoes polymerization to create the block (cf. Figure 7). The specimens are grounded with increasing grit sizes of 320, 600, 800, and 1200 before being polished with diamond suspension to reveal scratch-free surfaces before advancing to the cleaning processes as shown in Figure 8. The sample must be cleaned and well dried, thus Aqua Regia is used as the etchant for the AISI316L steel. The concentrated hydrochloric acid (HCl) to concentrated nitric acid (HNO_3) molar ratio is 3:1. The Aqua Regia combination requires 6g of HCl and 2g of HNO_3. This combination is often prepared in limited amounts and utilized immediately due to its instability. When nitric acid (HNO_3) is added to hydrochloric acid (HCl), the solution changes to a yellow liquid after a few minutes. Successful etching requires a time frame between 10 and 20 seconds. The sample is swiftly cleansed with running water, washed with alcohol, and let dry in the air before moving on to the microscopic observation step.

The AISI316 chip is examined using an Olympus BX51M metallurgical microscope. To analyse steel at a microscopic level, the specimen is illuminated with frontal brightness, causing it to reflect onto the specimen. The microscope is focused on the chip pattern and deformation zone. The microscope's findings are analysed and compared for each lubricating oil. Scanning Electron Microscope (SEM) with Energy Dispersive X-ray Spectrometry (EDX) of brand Hitachi TM3030 Plus is used in this investigation to examine the impact of different MQL lubricants and dry cutting on the chip specimen in the orthogonal cutting condition. SEM analysis was conducted to examine the sawtooth structure on the chip. EDX analysis is incorporated to evaluate the adhesive wear present on the tool rake surface.

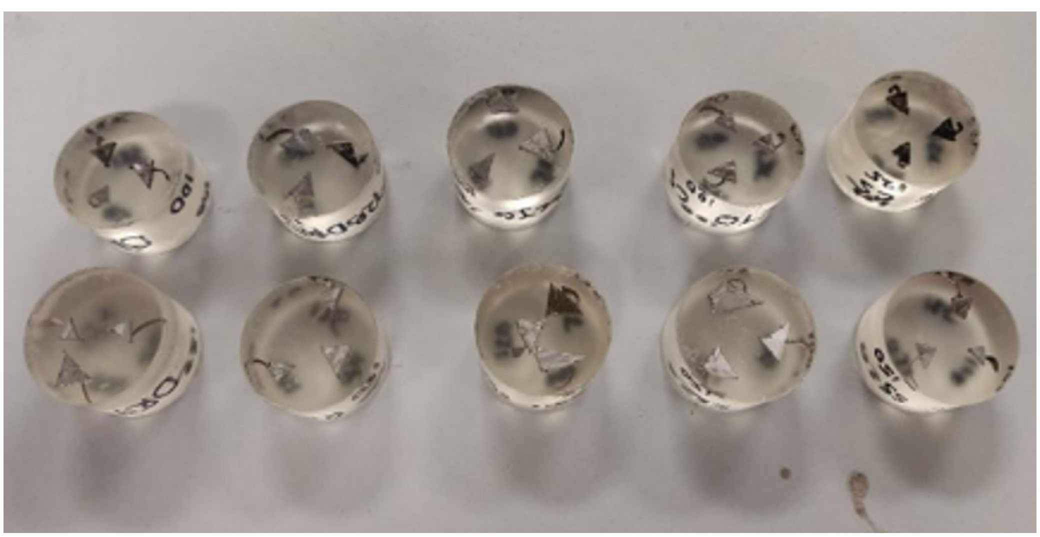

Figure 7: Cold mounting the frozen chip.

Figure 8: Polishing process.

2.5 The Analysis of Chip Thickness

Next, the chips collected from the machining experiments are assessed for thickness measurement. The measurement of chip thickness is conducted using the micrometre screw gauge depicted in Figure 9. The chip thickness undergoes 10 measurements at the centre of each single chip for each lubricated samples, which are then subsequently averaged to calculate the mean thickness.

(a) (b)

Figure 9: (a) Micrometer screw gauge to measure chip thickness and (b) The chips sample for the thickness measurement test.

3.0 RESULTS AND DISCUSSION

3.1 Cutting Force Data

The cutting forces in turning operations are crucial since they define the power needed for the machining process. The cutting forces that were collected from the dynamometer are transferred to spreadsheet data for analysis. Based on the results obtained from Figure 10, it can be shown that there is a direct correlation between the cutting speed and the cutting force, where an increase in cutting speed leads to a corresponding rise in cutting force. SE had the greatest influence in minimizing the cutting force that occurred. Due to its minimal cutting force, SE has a beneficial impact on the machined surfaces throughout the machining operation. Therefore, SE is suitable to be used as a MWF for the process of machining AISI 316L. CTO achieved very similar outcomes compared with CJO. Highest cutting force implied an inefficient lubrication or lubricant starvation between the tool's cutting edge and the workpiece surfaces as compared to CJO, CTO, SE, and RBDPO. Abdul Sani et al., (2017) pointed out that the generation of substantial shear stresses on the shear plane is shown by the presence of high cutting forces. The lubricant minimizes the resistance caused by friction between the tool and the chip. During the process of machining a ductile material, the application of shearing forces leads to the deformation of the material being cut. This movement results in the development of plastic deformation and the creation of ductile fractures in the metal layer, which are commonly referred to as chips.

3.2 Analysis on Chip Patterns (Shape, Form And Thickness)

The chip shape and forms are examined for each lubrication oils on the AISI 316L stainless steel workpiece (Figure 11). At cutting rates of 100 m/min and 125 m/min, the AISI 316L specimen exhibits a segmented chip or saw-tooth chip formation during dry machining as depicted in Figure 11. This chip is produced because of poor heat conductivity at a moderate speed and due to adiabatic shear, that occurs during the milling process. Adiabatic shear occurs when the cutting speed is escalated, leading to a significant rise in segment separation, eventually resulting in full segment detachment (Grzesik, 2016).

However, when cutting at a speed of 150 m/min, the chip transforms and becomes a continuous chip with a built-up edge (BUE). The Built-Up Edge (BUE) phenomenon arises when the temperature at the cutting edge or workpiece interface is low and there is a significant level of friction (Srikant & Rao, 2017). As a result, the workpiece material adheres or welds to the cutting edge. Built-Up Edge (BUE) on the outer shear zone of the uncut chip is obvious during the dry-cutting process at cutting speeds of 100 m/min and 125 m/min. However, when the steel disc is cut at a speed of 150 m/min, it results in the development of a continuous chip. Therefore, raising the cutting speed can decrease the BUE during the shearing process (chip formation).

While machining with RBDPO lubrication, the chip formed as a continuous chip type while cutting at speeds of 100 m/min and 150 m/min, respectively. Hence, the use of lubricant during the machining process can effectively diminish the friction between the cutting edge and the workpiece, resulting in better chip production. When employing CTO, CJO and SE (cf. Figure 11), all specimens demonstrate the formation of BUE at the secondary shear zone. Consequently, these three lubricants are less effective in reducing the built-up edge (BUE) for this machining process as compared to RBDPO.

The specimens are being observed on the SEM-EDX to explore the saw-tooth topographic structure (cf. Figure 12). A saw-tooth chip is created because of either thermoplastic shear instability or adiabatic conditions (Grzesik, 2016). This is a phenomenon that commonly arises during dynamic plastic deformation processes. The requirement is that the material's thermal softening effect as temperature rises is strong enough to counteract any deformation-induced strengthening. According to the adiabatic shear theory, the main reason for the creation of saw-tooth chips is a severe thermo-plastic instability. This instability occurs when the drop in flow stress, caused by an increase in strain, is more significant than the corresponding strain hardening. The amplitude of the saw-tooth pattern diminishes when the cutting speed is raised. The usage of MQL lubricant can effectively minimize the occurrence of saw-tooth chips by minimizing the friction that arises during the machining process (Srikant & Rao, 2017).

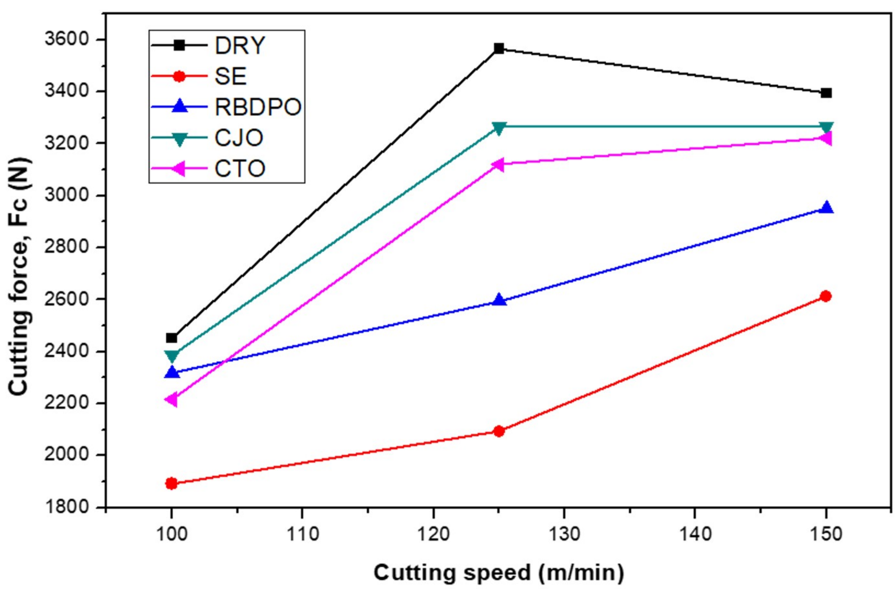

Figure 10: Orthogonal cutting force for AISI 316L steel disc.

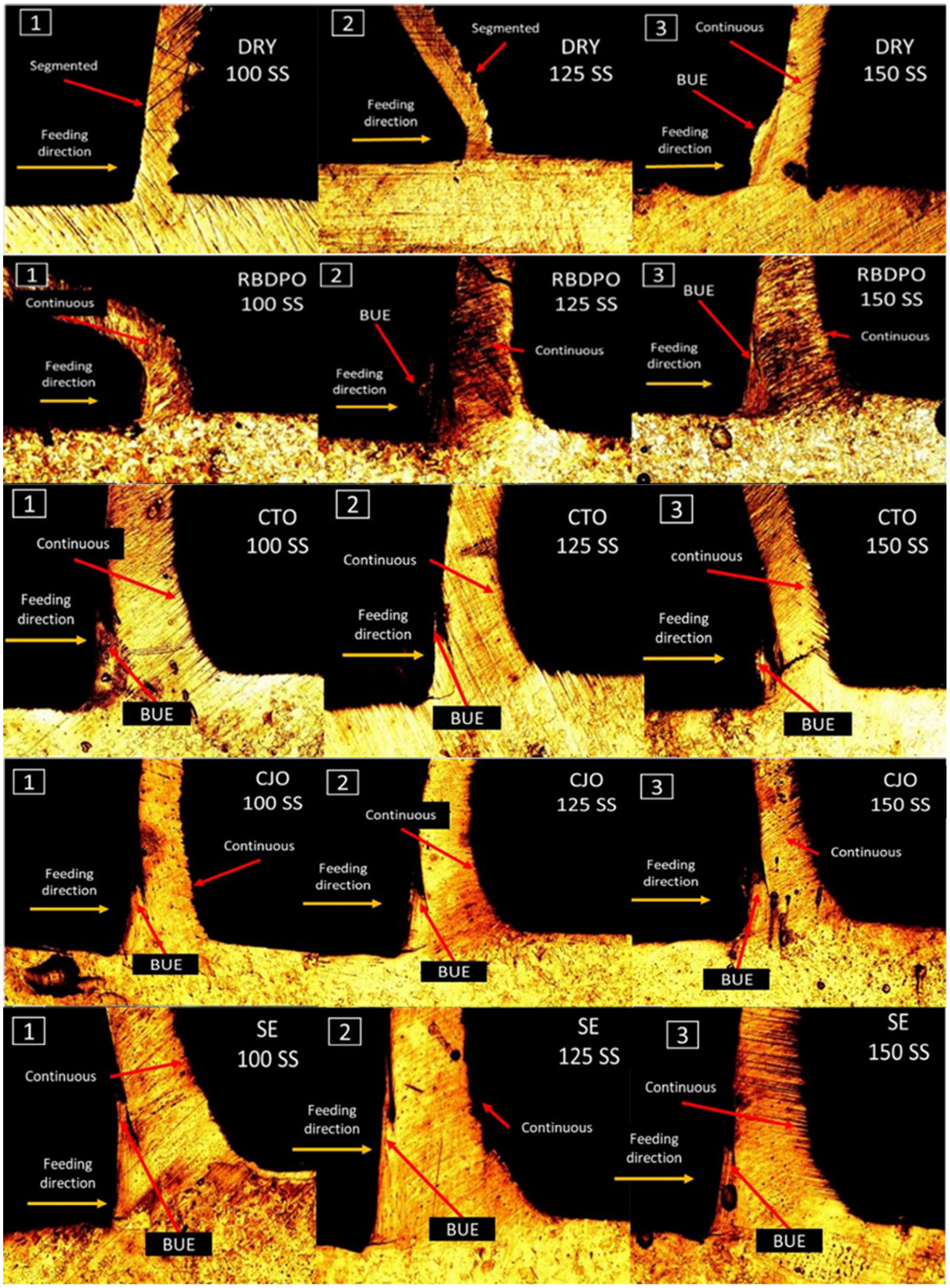

Figure 11: Chip formations at dry, RBDPO, CTO, CJO and SE cutting conditions on the AISI 316L stainless steel disc workpiece respectively.

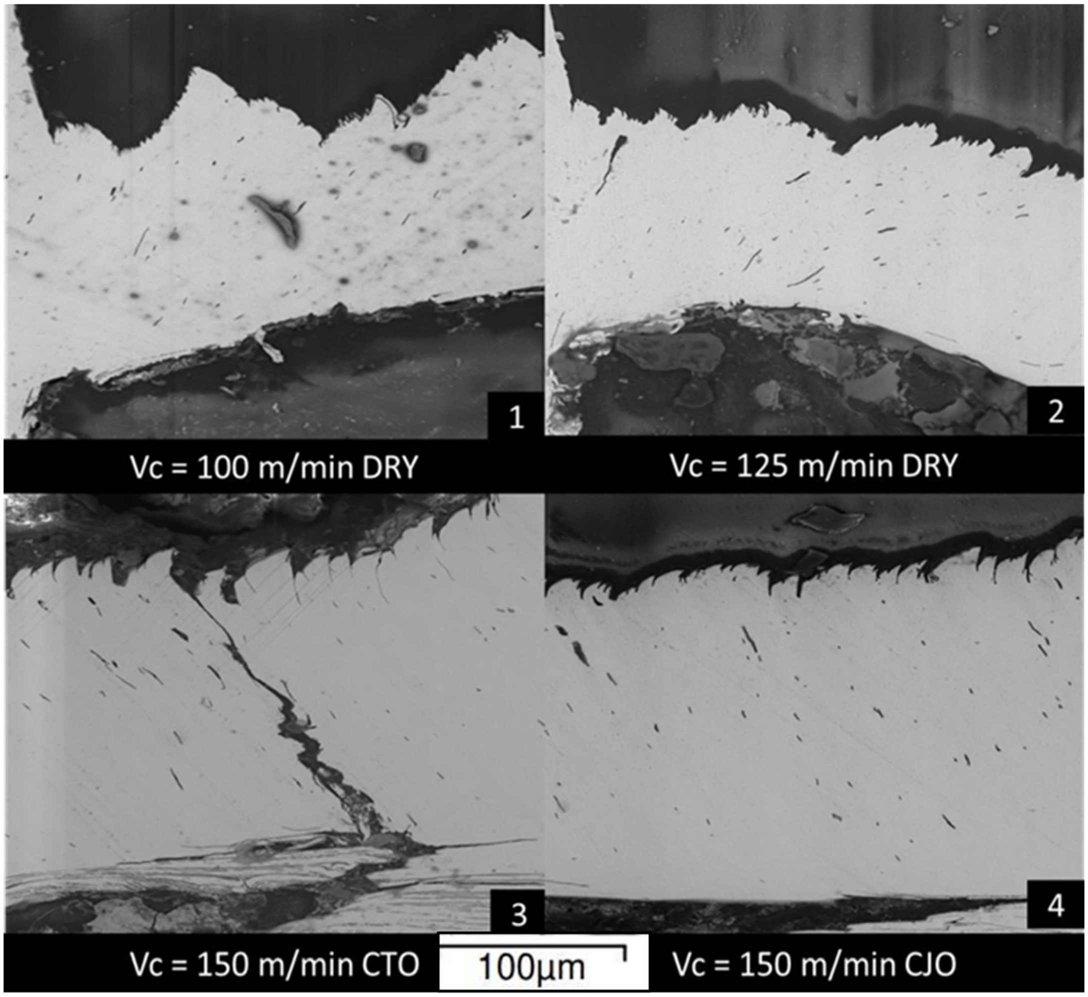

Figure 12 : Saw-tooth chip formation images for dry, CTO and CJO lubrication samples.

According to the graph shown in Figure 13, dry machining results in the greatest average chip thickness because of insufficient lubrication at the cutting zone, while SE yields the thinnest mean chip thickness when comparing against RBDPO, CJO and CTO lubrication conditions. This is attributed to the increased friction and abrasion that occur during dry machining, which impacts both the thickness and generation of the chips (Amiril et al., 2019). The chip thickness created during machining is determined by the strength of the metal being cut, which can be either ductile or brittle, and the amount of heat generated at the cutting zone. The temperature rise is caused by the friction between the insert and the workpiece. The primary influence on chip forming and its thickness formation is the significant heat and pressures caused by the strong resistance to deformation of tool inserts and the workpiece's bulk substances from being sheared apart (Grzesik, 2016). In conclusion, the chip thickness also increases as the cutting speed increases.

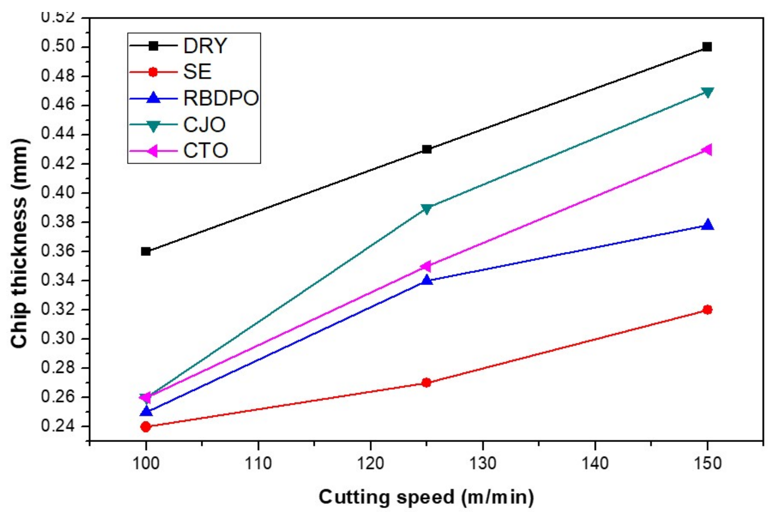

Figure 13 : Chip thickness graph.

3.3 Tool Chip Contact Length

An optical microscope is used for examining tool-chip relations. Despite the challenging machinability of SS 316L, the use of SE lubrication may effectively decrease the contact distance during the chip landing on the tool insert's surfaces as the cutting speed increases to 100, 125, and 150 m/min. (cf. Figure 14). The minimal tool-chip contact duration indicates a smaller sticking and sliding zone, resulting in a greater material removal rate. Due to the absence of lubrication, dry machining has the most unfavorable outcomes in terms of the length of contact between the tool rake surface and the cut material to form the metal chips, which is the longest as presented in Figure 14. Increased contact duration results in greater heat buildup within the tool. However, reducing the contact length might result in a decrease in both heat and friction force (Huang et al., 2015). It is feasible to deduce that the tool chip contact length reduces as the cutting speed rises.

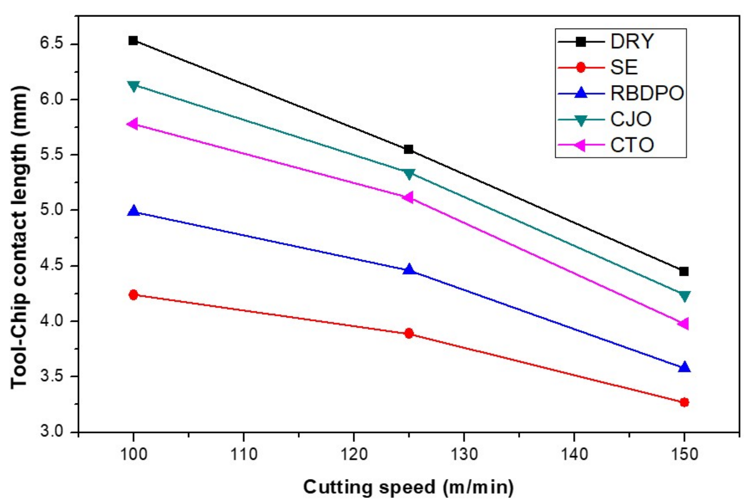

Figure 14: Tool-chip contact length graph.

CONCLUSIONS

A comparative study was carried out to evaluate the cutting performance of CTO, RBDPO, CJO, and SE as cutting oils. The findings indicate that the present formulation of SE outperforms the other bio-based lubricants in terms of cutting force, chip thickness, and tool chip contact length. Despite having the second lowest viscosity compared to the other two crude vegetable oils (CJO and CTO), RBDPO performs second best in the orthogonal turning process. From the results obtained at various cutting speeds, the average chip thickness was the lowest for RBDPO at feed 0.12 mm/rev and cutting speed of 100 m/min. The results obtained for the chip thickness tally with the results of the cutting forces. CJO and CTO outperformed dry machining in terms of reducing the chip thickness and tool-chip contact length. The results obtained from the chip thickness also relate to the previous study conducted by the author in 2022, where SE averaged the thinnest chips compared to the other tested lubricants. This can be attributed to its good lubricity, which reduces the cutting forces and hence also lowers the friction. CTO produces the least favorable results partially due to its low VI rating. In addition, the high cutting forces generated also accounts for this factor, which concurrently relates to high deformation resistance of the workpiece material.

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