Orthogonal Cutting Performance of Vegetable-Based Lubricants via Minimum Quantity Lubrication Technique on AISI 316L

Amiril Sahab Abdul Sani, Zubaidah Zamri, Shahandzir Baharom, Mugilan Ganesan, and Norfazillah Talib

Abstract In this research, the workpiece material used is AISI316L stainless steel, which has higher corrosion resistance and is also difficult to machine at high speeds. The objective of this study is to determine the machining performance of 316L stainless steel using minimum quantity lubrication (MQL) and dry machining. The effects of MQL lubricants and dry machining are then studied and compared in terms of cutting performance, such as tool chip contact length, chip thickness, and cutting force (N). The MQL lubricants used are a bio-lubricant: Crude Tamanu Oil (CTO), Crude Jatropha Oil (CJO), Synthetic Ester (SE) and Refined Bleached and Deodorized Palm Olein (RBDPO). The cutting insert used in this study is an uncoated tungsten-carbide insert (WC) SPGN120308 to ensure that the surface of the carbide insert is in direct contact with the stainless-steel disc. The cutting and MQL parameters are set to be the same for both MQL and dry machining. After machining, the micrographic representations of the chip and inserts are magnified by examination with a scanning electron microscope using energy dispersive X-ray spectroscopy (SEM–EDX) to identify any material adhering to the rake face of the tool. It is found that SE gives the best machining performance compared to the CTO, CJO, RBDPO and dry machining. Nevertheless, CTO and other crude vegetable oils are exhibiting high potential to be used as bio-based metalworking fluids following chemical modifications to improve their anti-wear and anti-friction capabilities.

Keywords Cutting performance · Orthogonal cutting · MQL · Lubrication · Plant-based oil

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1 Introduction

Machining, also called metal removal, is a subtractive manufacturing process in which material is removed from the workpiece layer by layer using cutting tools to achieve the desired shape and scale. The amount of heat flux flowing to the cutting tool during the cutting process has a major impact on tool wear as plastic deformation usually occurs in the shear zone of the metal being machined [1]. Metalworking fluids (MWF), also known as lubricants, are needed to reduce friction between worn parts on the surface, increase tool life, lower the cutting temperature, and improve machining efficiency and surface quality. They also act as lubricants, coolants, cleaning agents, and corrosion inhibitors when a protective lubricating layer is applied to metal-to-metal sliding surfaces. This is because the chemicals in the lubricant can reduce the friction between the two contact surfaces of the materials and thus reduce the heat produced when the surface interacts [2]. Excellent cutting performance is achieved through the ability of metalworking fluids to provide lubrication and dissipate the heat, resulting in less heat generated at the cutting edge of the object being machined. MQL or minimal quantity lubrication uses a combination of compressed air and cutting fluids, which produce mist. The mist is dispersed on the surface contact between the tool and the workpiece, thus resulting in lower temperature production, and helps to improve the flow of the chips across the tools by providing lubrication and cooling down the contact surfaces. Cutting fluid flow rates in MQL are significantly lower than the conventional machining methods [3]. In comparison to dry cutting, MQL provided lubricating and cooling effects that increased tool life [4, 5].

Mineral oil is the most typical form of lubricant however the usage of mineral oil-based lubricant causes a variety of health issues and pollution [6]. Researchers expect that demand for oil-based mineral metalworking fluids will rise because of increased demand from emerging markets. It is commonly known that global mineral reserves are depleting and that all resources will be extracted from the earth's crust one day [7, 8].

To deal with the issues, a new alternative has been explored to discover an alternative that can be the greatest option to replace the oil-based mineral metalworking fluids [9, 10]. The most suitable oil-based mineral alternative is vegetable oil; however, vegetable oil is a tricky non-toxic alternative making most research focused on how to utilize it as a metalworking fluid. It is due to vegetable oils having extremely high kinematic viscosity and viscosity index than mineral oil. However, vegetable oil does not emit poisonous gas during the machining, and more environmentally friendly. The fact that it is biodegradable and renewable is the most crucial element in selecting the oil as an alternative source for metalworking fluid [11].

Crude jatropha oil (CJO), Crude Tamanu oil (CTO), Synthetic ester (SE), and Refined Bleached Deodorised Palm Olein (RBDPO) are vegetable oils that were used in this experiment. In this research, the aim was to investigate the cutting performance of stainless steel 316L when employed with these lubricants via minimal quantity lubrication (MQL) techniques and comparing them with the dry machining.

2 Methodology

The workpiece material that is used in this research is AISI 316L stainless steel disc with a thickness of 2 mm. Stainless steel was chosen because of its great corrosion resistance and resistance to thermal oxidation. Due to its high yield strength, it has good energy absorption properties, and can sustain a high level of strength even at extremely high temperatures. AISI 316L has great manufacturing features. Because of the AISI 316L composition materials, the stainless steel has good chlorine resistance and corrosion cracking of stress resistance. Table 1 shows the composition of elements in AISI 316L.

2.1 MQL Lubricant Preparation

The MQL lubricants used to conduct this machining experiments are Crude Jatropha Oil (CJO), Synthetic Ester (SE), Refined Bleached Deodorised Palm Olein (RBDPO) and Crude Tamanu Oil (CTO) as depicted in Fig. 1.

2.2 Workpiece Preparation

The AISI 316L undergoes milling operations such as facing, centering, marking, patterning, pocketing, and island process to get the desired shape. Figure 2 shows the flow of the process for AISI 316L preparation in this experiment while Fig. 3 shows the specimen's dimension.

Table 1 AISI 316L disc specimen element composition [1]

Element present in AISI 316L disc	Composition (wt.%)
Carbon	0.025
Nitrogen	0.068
Sulphur	0.003
Phosphorus	0.025
Silicon	0.064
Manganese	1.680
Molybdenum	2.380
Nickel	10.120
Titanium	0.001
Niobium	0.045
Chromium	17.60

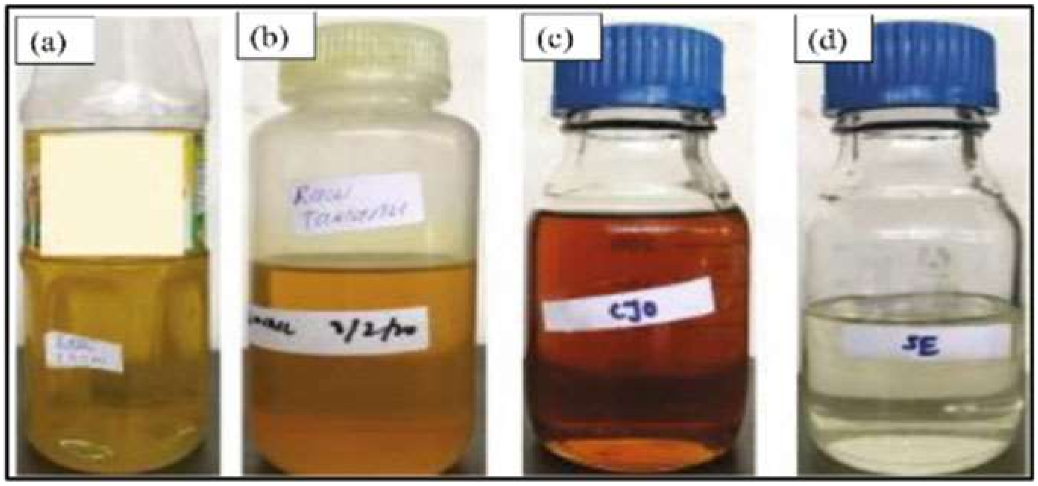


Fig. 1 MQL lubricant sample; **a** RBDPO, **b** CTO, **c** CJO and **d** SE

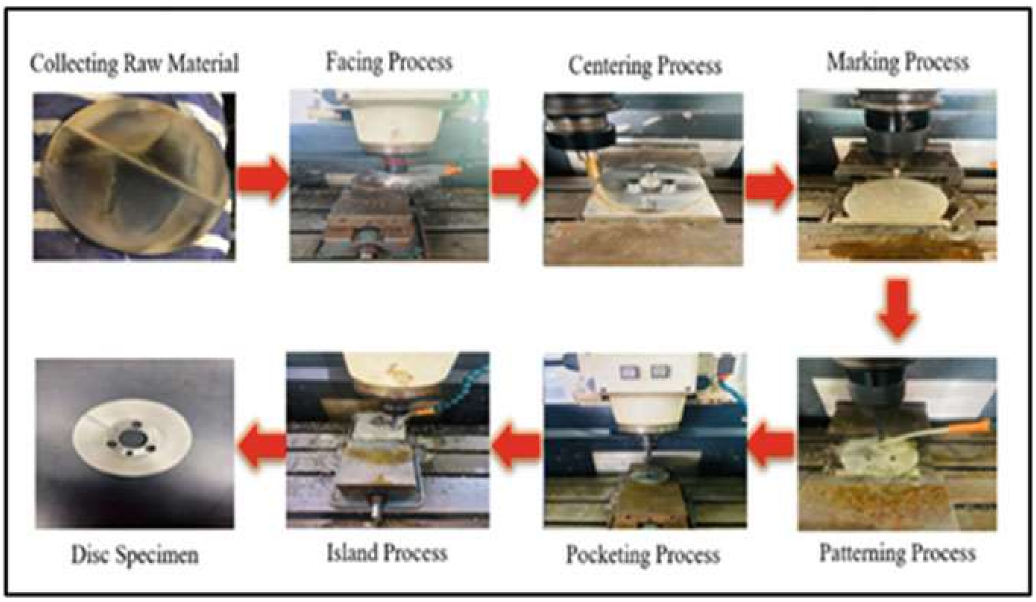


Fig. 2 The process of preparing workpiece sample

2.3 *Orthogonal Machining*

Orthogonal cutting process is a process where the cutting edge is perpendicular to rotation axis of the workpiece and was carried out on a CNC lathe machine ROMI C420. In this experiment, uncoated tungsten carbide (WC) inserts with the ISO number SPGN 120,308 are purchased. The indexable square shape of this insert has a positive rake angle of 5°. The inserts (brand: Korloy) are made of fine carbide grains that can withstand high-cutting tool edge wear indefinitely [12]. The distance between the nozzle orifice and the cutting insert is set to 8 mm. The angle of inclination of

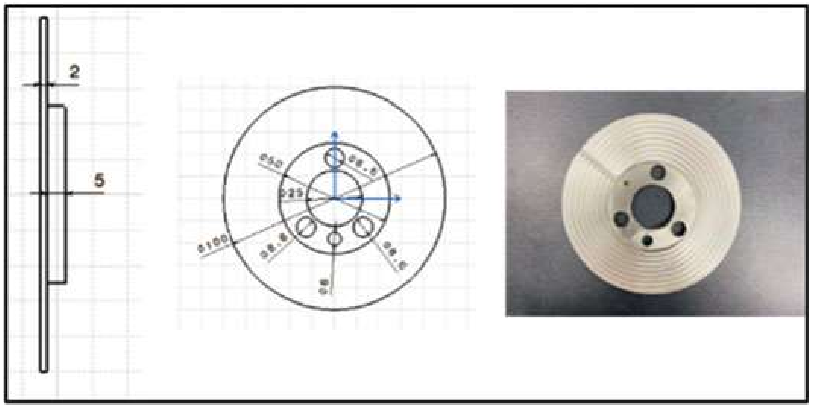


Fig. 3 The dimension of disc specimen

the nozzle should be 45° to make sure the dispersant of lubricant in contact with the insert and workpiece as depicted in Fig. 4 respectively [13]. After all the turning parameter was set, the MQL device's pressure was released, and the lubricant began to disperse to ensure that the lubricant dispersion was stable. The orthogonal turning procedure of the workpiece with the cutting parameter is as follows [14]. It is started once the lathe machine has been filled with fog [15]. When turning begins, the MQL device must first disseminate the lubrication. The suggested MQL parameter is listed in Table 2. After that, all the chip samples are collected and measured for their thickness.

3 Results and Discussion

3.1 The Viscosity for Each Lubricant Sample

The outcomes for each lubricant sample's kinematic viscosities and the viscosity index (VI) are shown in Table 3. CJO possesses the highest viscosity index (VI) which is 310 and followed by SE, which is 187, and RBDPO, 172. This clearly demonstrates that CJO, although in a crude state, it can be a good lubricating oil by nature while CTO possesses the lowest viscosity index which is 142. The high VI indicates that the lubricant may maintain its effectiveness of keeping the oil layer protection film even at high temperature conditions [16].

3.2 Cutting Force

Cutting force is one of the important characteristics in turning operations because it can determine the amount of power required for machining [17]. Shearing forces

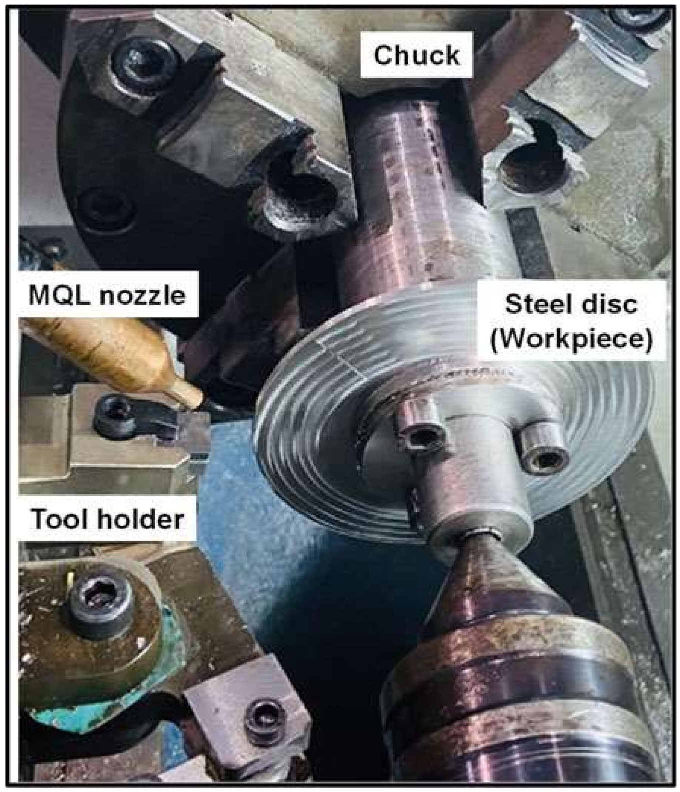


Fig. 4 Orthogonal cutting experimental setup

Table 2 Machining parameter setup

Parameter	Value
MQL outlet pressure	0.4 MPa
MQL spray flow rate	0.16 L/hr
Inner diameter of nozzle	2.5 mm
Tool edge-nozzle distance	8 mm
Inclination angle of nozzle	45°

Table 3 The viscosity value for each lubricants sample

Lubricants	Viscosity index (VI)	Kinematic viscosity at 40° (mm^2/s)	Kinematic viscosity at 100 °C (mm^2/s)
SE	187	21.50	5.20
CTO	142	68.99	10.62
CJO	310	30.71	9.30
RBDPO	172	40.24	7.89

distort the material being cut while machining a ductile material, generated plastic deformation and ductile fracture on the metal layer (chips). Large cutting forces indicate the formation of high shear strains on the shear plane [18].

Table 4 Cutting force generated for each lubricant sample

Lubricant sample	Cutting force (N)		
Cutting speed (m/min)	100	125	150
Dry machining	2452.4	3566.65	3394.93
SE	1891.31	2092.04	2612.88
RBDPO	2317.98	2598.86	2951.90
CJO	2388.09	3264.34	3265.99
CTO	2216.41	3119.73	3222.01

Table 4 depicts the increasing pattern of cutting speed and cutting force. SE had an especially significant contribution in reducing the resulting cutting force. SE has a good impact on the workpiece and tool during machining since the cutting force is lowest. In other words, SE is suited as a cutting fluid for AISI 316L machining. The CJO and CTO achieved nearly equal results. The cutting force for dry machining is the most severe, which indicates that the tool and insert contact is less successful when no lubricant is present than for CJO, CTO, SE, and RBDPO.

3.3 *Thickness of the Chips*

The type of metal being machined, whether brittle or ductile, as well as the temperature at the cutting zone, determine the chip thickness produced during machining. Friction between the insert and the workpiece causes this temperature to rise [19]. The fundamental impact on chip formation and thickness is high heat and stresses induced by high deformation resistance of cutting inserts and the material of the workpiece being cut [20]. The thickness of the chip is measured with a micrometer screw gauge. Table 5 shows that due to the lack of lubrication, Dry machining produces the highest average chip thickness while SE produces the lowest average chip thickness compared to CJO, CTO, and RBDPO. This is due to the greater friction and rubbing that happens during dry machining which affects the chip thickness and formation [21].

Table 5 The thickness of the chips for each lubricant sample

Lubricant sample	Chip thickness (mm)		
Cutting speed (m/min)	100	125	150
Dry machining	0.36	0.43	0.50
SE	0.25	0.34	0.38
RBDPO	0.26	0.35	0.43
CJO	0.26	0.39	0.47
CTO	0.24	0.27	0.32

Table 6 The chip contact length for each lubricant sample

Lubricant	Chip contact length		
Cutting speed (m/min)	100	125	150
Dry machining	6.53	5.55	4.45
SE	4.24	3.89	3.27
RBDPO	4.99	4.46	3.58
CJO	6.13	5.34	4.24
CTO	5.78	5.12	3.98

3.4 Tool Chip Contact Length

Tool chip contact is observed under an optical microscope. As depicted in Table 6, although SS 316L is a hard-to-machine material, SE lubricant able to reduce the tool chip contact length as the cutting speed increases from 100, 125 and 150. The lowest tool-chip contact length proves that the sticking and sliding region is smaller which mean the material removal rate is higher. Since no lubrication is used, dry machining produces the worst results in terms of tool chip contact length [5].

3.5 Tool Rake Surface

Tool rake surface can be defined as the chip-flowing surface which is when chips generated by the shearing effect during machining have flowed over the rake surface and out of the cutting zone. The flow of the chips over the rake surface causes intense rubbing, which raises the cutting temperature [9]. As shown in Figs. 5 and 6, CJO and SE still show the existence of an insert element which is the tungsten (W) element which shows that the material of workpieces does not adhere to the tool rake surfaces. Differing to CTO as depicted in Fig. 7, it has a highly adhered material at the insert surfaces. Dry machining also reveals adhered material at the insert surfaces, but not to the same extent as CTO machining as shown in Fig. 8. In addition, the wear at CTO's insert is obvious.

4 Conclusions

From the results, SE gives the best machining performance compared to CTO, CJO, RBDPO, and DRY machining. This is because SE possesses higher viscosity index than CTO and RBDPO. As a result, SE has the lowest cutting force, finest chip, and minimum tool chip contact length, resulting in longer tool life and fewer tool wear. Next, the CTO gives the worst performance compared to CJO, SE, and DRY machining. CTO and RBDPO's high kinematic viscosity values at low temperature

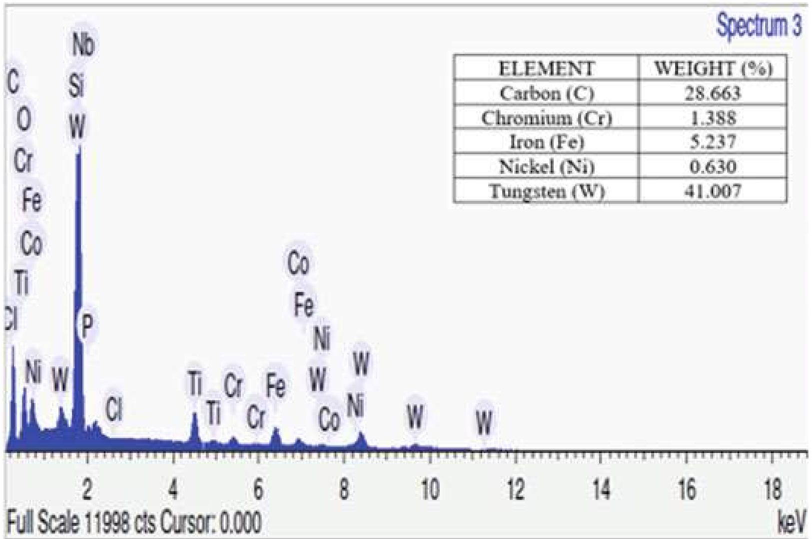


Fig. 5 Element graph for CJO-150

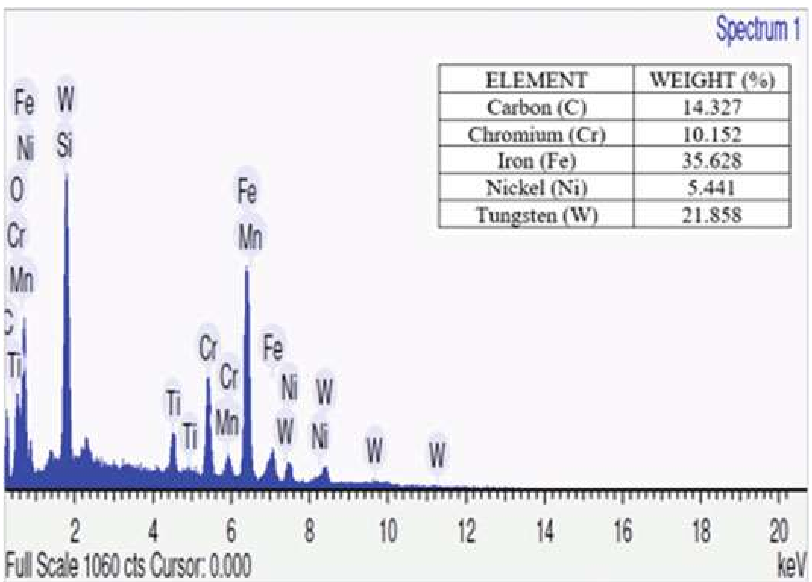
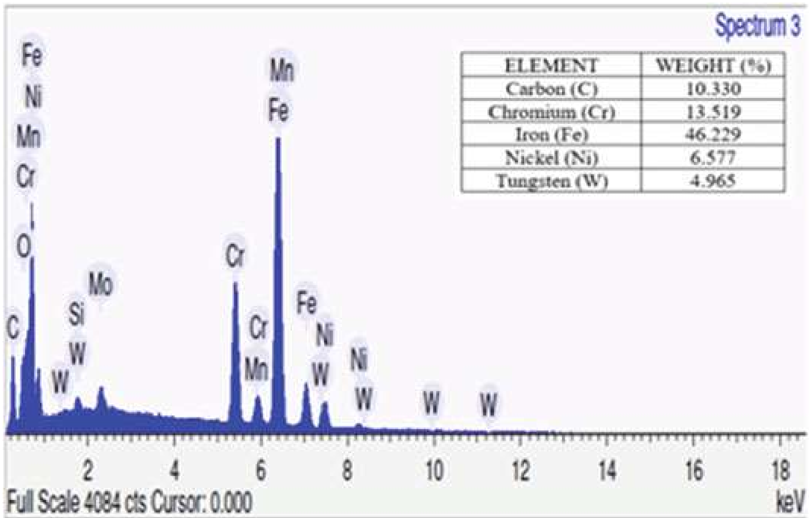


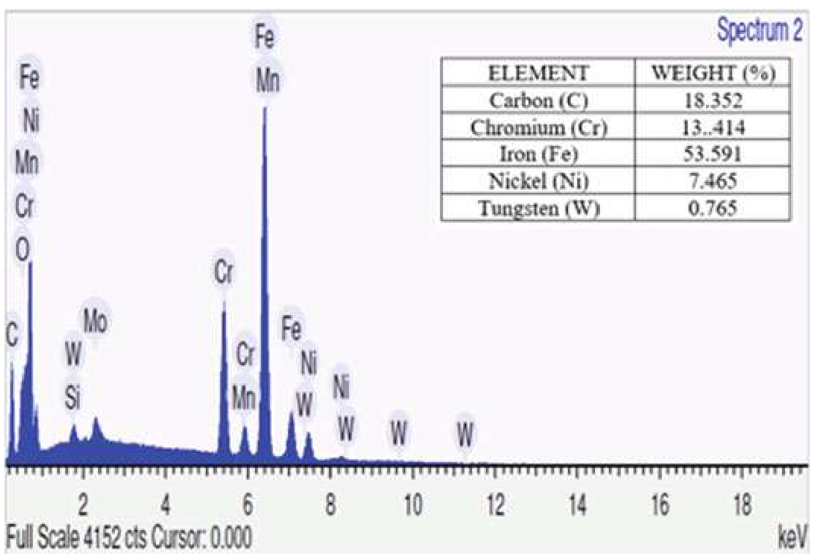
Fig. 6 Element graph of SE-150

may result in fewer atomization molecules being dispersed across the cutting zones. The thicker oil may not offer enough lubrication around cutting, exposing more dry surfaces to the tool insert [2]. Nevertheless, CTO and RBDPO can still be used as metalworking fluid however further research on chemical modification needs to be done to improve their properties such as their anti-wear and anti-friction capabilities. Finally, using dry machining at low cutting speed or below 100 m/min is not ideal because it will damage the cutting tool.



ELEMENT	WEIGHT (%)
Carbon (C)	10.330
Chromium (Cr)	13.519
Iron (Fe)	46.229
Nickel (Ni)	6.577
Tungsten (W)	4.965

Fig. 7 Element graph of CTO-150



ELEMENT	WEIGHT (%)
Carbon (C)	18.352
Chromium (Cr)	13..414
Iron (Fe)	53.591
Nickel (Ni)	7.465
Tungsten (W)	0.765

Fig. 8 Element graph of Dry machining-150

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