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Oil viscosity effects on lubricant oil film behaviour under minimum quantity lubrication

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Abstract. Minimum Quantity Lubrication is a great alternative to flood coolant in many perspective such as economic perspective, safety and health perspective and others. In addition, natural biodegradable oils have been widely used as lubricant oil to meet the environmental-friendly machining environment. The study of lubricant oil fundamental nature during MQL machining is highly important to really identify how the lubricant oil behaviour does affects the lubricating process. Nevertheless, the study is still scarce probably due to the complexity of experimental setup and the natural flow of the lubricant oil cannot be disrupted during the machining operation. To cater this issue, the behaviour of MQL lubricant oil was investigated so a non-intrusive method called as Laser-induced Fluorescence method is applied onto Al6061 workpiece .This research was operated by different oil viscosity represented by different oil type i.e. mixed esters oil, sunflower oil, olive oil and calophyllum inophyllum oil to analyse the lubricant oil film thickness. Overall study showed that, the average of lubricant oil film thickness were significantly decreased as the oil viscosity increased affected by the spreadability of lubricant oil onto the milled surface. At all conditions for oil viscosities, the lubricant oil film showed similar downturn trend due to rise up of built-up edge formation and chips accumulation towards the milling point. Hence, the effects of MQL system parameter on the machining performance has been clarified in details through the observation on the MQL lubricant behaviour.

1. Introduction

Minimum Quantity Lubrication (MQL) technology is a great alternative to flood coolant in many perspective such as economic, occupational safety and health, environment and many more. MQL also has proven to be efficient in reducing the friction effects raised in the tool-workpiece interfaces, improving the surface quality of workpiece, lengthening tool life as well as lowering cutting temperature during the machining operation (Mark Benjamin, Sabarish, Hariharan, & Samuel Raj, 2018). Lower consumption of cutting fluid can help to reduce the occupational health hazards such as variety of respiratory disorders involving occupational asthma, loss of lung function and skin disease when operating the machine. This has made MQL as an environmental-friendly machining process. Moreover, the little usage of oil in MQL also helps to minimize the environmental impact as the need for oil treatment and disposal is no longer required (Hood, Morris, & Soo, 2016). With a flow rate of 30 mL/h being applied onto the cutting zone, MQL has been an outperform alternative lubricating method despite its minimal usage of oil (Sharma, Singh, & Sørby, 2015).

In recent years, it has been reported that MQL provides a better lubrication cooling system compared to conventional flood coolant with better surface roughness and longer tool life being achieved. For instance, a research of MQL milling process to enhance machinability of AISI 4140 steel has been conducted and slight improvement of surface finish was achieved (Al, Mozammel, Nikhil, & Dhar, 2018). Reduction of the flank wear has been observed which subsequently prolong the tool life. A similar finding also has been found where a better surface quality of Inconel 718 alloy were attained under 90 mL/hr MQL flow rate (Oliveira, Fonseca, & Araujo, 2017). This work also proved that tool life can be expanded due to its better cooling and lubrication performance at the tool-chip and tool-work piece interface. MQL operation in the milling process also has been reported to reduce formation of burrs at the edge of workpiece (K. Li & Chou, 2010). Hence, lower surface roughness ranging between 0.1 µm and 0.2 µm were achieved with flow rate as low as 7.5 mL/h from vegetable oil droplet penetration into the cutting zone. Depletion of tool flank wear were also found to improve the tool life progression in this study.

Although very little amount of lubricant oil being sprayed during the machining process, MQL technology has been proven to be efficient in minimizing the surface roughness of the work material for turning operation (Yazid, Ibrahim, Said, CheHaron, & Ghani, 2011). In addition, another result of surface roughness improvement with MQL implementation has been reported where surface roughness as low as 0.91 µm were achieved with medium cutting speed and feed rate (Kumar, Singh, & Kalsi, 2017). Apart from improving the surface finish quality, MQL turning application has been also proven to helps reducing the cutting temperature and cutting force application (Patole & Kulkarni, 2018).

In drilling process, the utilization of MQL application has been found to minimize the burr formation at the exit hole surface for the drilled holes as a result of heat transfer enhancement of the cutting fluids into the contact area (Niketh & Samuel, 2018). In conjunction with that, build-up edge formation at the cutting edge and tool wear efficiency were proven to develop better surface quality. Further analysis on the creation of burr in exit hole surface has been conducted where the burr formation and burr height was found to decrease significantly due to reduction of torque and drilling thrust force as well as enhancement of tool wear rate (Rahim & Sasahara, 2011). Furthermore, the results of better surface quality of drilled holes surface has been reported to be achievable with if high flow rate and pressure were applied during MQL drilling process as thrust force could be reduced (Mathew & Vijayaraghavan, 2017).

In grinding process, MQL is proven to be proficient in developing wheel life and improving the surface quality of the ground parts in grinding machining (Tawakoli, Hadad, Sadeghi & Daneshi, 2009). This can be explained by the enhancement of abrasive grains slipping at the tool-workpiece interface by the efficiency of lubrication and cooling effects from MQL lubricant oil which reduced the tangential grinding forces. Apart from that, lower power consumption in grinding process as well as lower surface roughness were successfully achieved by the competency of MQL technique (Rabiei, Rahimi, Hadad, & Ashrafijou, 2015). Furthermore, low friction conditions under MQL grinding operation has been found to influence the reduction in cutting temperatures which then lead to a reasonable specific material removal rate (Barczak, Batako, & Morgan, 2010).

To meet the environmental-friendly machining environment, natural biodegradable oils have been widely used as an alternative to traditional lubricant oil in MQL operation. Since different types of natural biodegradable oil which provide different viscosity can give different cooling effect and surface finishing of the workpiece, there is no doubt that the cutting oil type plays a major part in intensifying workpiece surface finish quality. A study has been conducted to examine the relation of oil viscosity and its impact on the cutting force, tool life and surface roughness where different types of natural biodegradable oil categorized as traditional canola oil, sunflower oil, high oleic sunflower oil, castor oil and ECO-350 recycled oil were used (Pereira & Calleja, 2017). The results revealed that cutting force was reduced and tool life was strengthened along with the improvement of surface finish of workpiece as a result of friction coefficient increment and oil viscosity decrement. This can be attributed by the better penetration of lubricant oil on workpiece executed at a lower friction between the cutting tool and workpiece. Moreover, a better spreadability of cutting oil on the contact area and competent diversion of heat in conjunction with tool life enhancement have been achieved by applying oil with lower viscosity (Junior, Falco, Batista, & Silva, 2017). On the other hand, application of synthetic oil compared with fatty alcohol type of oil to ensure a better surface quality of steel alloy has been achieved with high flash point of lubricating effect which was actually benefited by the use of greater oil viscosity under low cutting speed (Werda, Duchosal, Le, Morandeau, & Leroy, 2016). At the same time, cutting forces between cutting tool and the workpiece also was found to be reduced. However, application of oil with lower viscosity under high cutting speed could provide outstrip cooling effect which leads to a good surface roughness and better tool life.

Although there are many machining parameters such as feed rate, depth of cut, cutting speed in MQL milling process need to be controlled to achieve the great performance of MQL technology, the parameters from MQL system itself such as lubricant oil type, oil mist flow rate, nozzle distance from cutting zone and atomization angle still cannot be abandoned as the most challenging part in applying the MQL technology during machining process is to properly supply the lubricant oil to the cutting zone for sufficient lubricating effects. Among the main factors that affects this matter, the characteristics of the lubricant oil is the most important. MQL is only efficient when an adequate amount of oil droplets can successfully penetrate the cutting zone and thus can uniformly spread on the workpiece (Duchosal, Werda, Serra, Courbon, & Leroy, 2016).

To date, most of the experimental study of MQL technology were entirely focused on the relation between the machining parameter effects to the machining performance. However, the study of the fundamental nature of lubricant oil during MQL machining process is still deficient. This issue is important to really identify how does the lubricant oil behaviour affects the lubricating process. The study is still scarce probably due to the complexity of experimental setup during the machining process is on-going. On top of this, the natural flow of lubricant cannot be disrupted to maintain the machining process. To cater this issue, the behaviour of MQL lubricant oil during the milling process will be investigated in this study. Here, a non-intrusive method will be applied to observe the behaviour of MQL lubricant oil. The effects of lubricant oil viscosity to the oil film thickness aggregated on the milled surface by MQL application will be analysed.

2. Experimental Setup and Procedure

2.1 MQL Milling Process

In this experimental work, the milling operation was performed on a 2001 MAKINO KE55 CNC Verticall Mill machine equipped with Kuroda Ecosaver KEP-WR MQL generator. The MQL generator utilized internal delivery systems, where cutting fluid can be distributed precisely onto the cutting zone area. An uncoated carbide end mill with 10 mm-diameter was used to mill the workpiece materials, i.e. Al6061 with dimension of 100 mm × 100 mm × 100 mm. Four different types of lubricant oils, i.e. olive oil, sunflower oil, calophyllum inophyllum oil and mixed esters oil were employed as the working oils. The properties of working oil was categorized in table 1.

The experimental setup for milling process and laser-induced fluorescence (LIF) operation to measure the lubricant oil film thickness during MQL milling process in this study was illustrated in figure 1. During the milling process, a diode laser was irradiated on the milling path. The Neutral Density (ND) filter was used to cut wavelength of diode laser while the green filter was used to allow only the fluorescent light emitted from the lubricant oil to pass through recording video. The optical flat which was the probe for calibration procedure was also placed on the laser irradiation path to cancel its effects during the experiment. Concurrently, the video camera recorded videos of emitted light intensity formed on the workpiece. The recorded videos were transformed into images using video-to-JPG-converter software. The fluorescence light intensity from the lubricant oil were then quantified by using ImageJ software to obtain the lubricant oil film thickness. Upon experiment, the lubricant oil was sprayed onto the machining region by the nozzle of MQL generator which was positioned at 45° laterally in the direction of the feed. The nozzle distance was set as 3 mm away from the cutting tool edge. Table 2 shows the summary of experimental conditions and parameters applied throughout this study.

Table 1. Properties of working oil.

Oil types	Kinematic viscosity, *nu* [mm^2/s]	Dynamic viscosity, η [cSt]	Density, ρ [g/cm^3]
Mixed esters oil	11.954	11.075	0.9265
Sunflower oil	33.383	30.224	0.9054
Olive oil	39.216	35.260	0.8991
Calophyllum inophyllum oil	67.871	63.223	0.9315

Table 2. Experimental conditions and parameters.

Property	Value
Workpiece material	Aluminium alloy 6061
Workpiece dimension	100 mm × 100 mm × 100 mm
Cutting tool material	Uncoated carbide end mil
Cutting tool diameter	10 mm, 4 flutes
Feed per tooth, f_z	0.0893 mm/tooth
Axial depth of cut, a_p	0.5 mm
Cutting speed, V_c	29.514 m/min
Table feed, V_f	315 mm/min
MQL flow rate	116.667 mL/hr
MQL nozzle distance	3 mm from cutting tool edge, parallel with feed direction
MQL lubricant oil	Mixed esters oil, sunflower oil, olive oil, calophyllum inophyllum oil

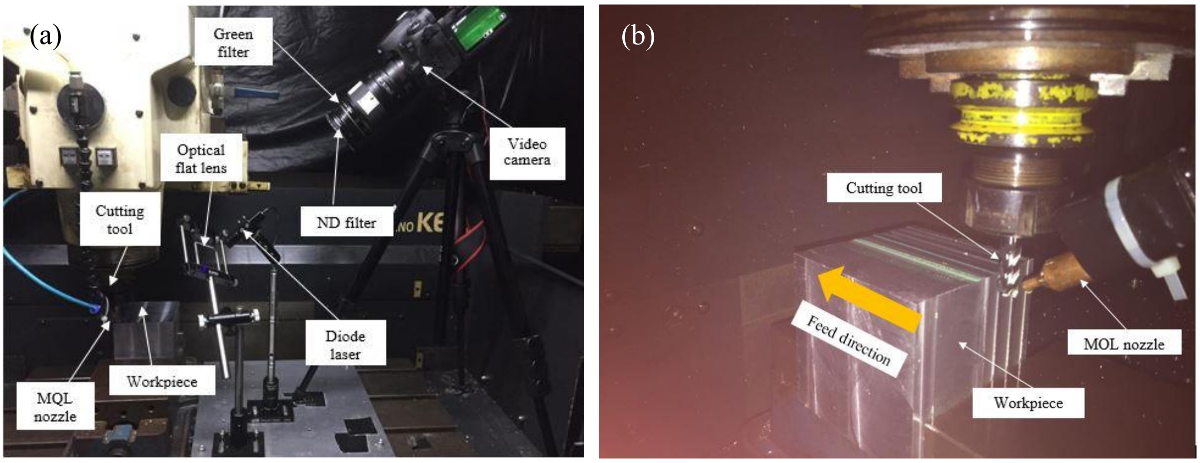

Figure 1. (a) Experimental setup for milling process and LIF operation and (b) image of machining operation.

2.2 Laser Induced Fluorescence

Laser Induced Fluorescence (LIF) is a non-intrusive method being applied in this study to measure the thickness profile of lubricant oil. This method utilizes the fluorescence effects of fluorescent dye dissolve in the working oil when being irradiated by a specific laser to represent the amount of oil exist on the workpiece during the milling process. In this study, the diode laser with 407 nm-wavelength was used to excite the fluorescent dye, i.e. Coumarin-153. All the working oils were dissolved with 0.03 wt%-concentration This method is LIF technique has been conducted to evaluate the film thickness profile of liquid flow around horizontal tube (Chen, Shen, Wang, Chen, & Zhang, 2015). To avoid the disruption with the flow field of liquid film in downward gas-liquid annular flow, LIF method has been utilized to examine the thickness measurement and flow evolution analysis (Xue, Yang, Ge, & Qu, 2015). In this study, liquid film thickness was measured depends on the fluorescence light intensity which theoretically computed as Equation (1) (X. Li, Zhengpeng, Sichao, Xiaoyu & Ruiqi, 2019) below:

$$I_i = \beta_c \emptyset I_i \,(1\text{-}e^{-\varepsilon b C}) \quad (1)$$

where Ii is defined as fluorescence light intensity. Quantum efficiency and incident irradiance for liquid film thickness are denoted as βc and $\emptyset$. C is dye concentration in working oil whereas ε and b is molar absorption of the fluorescence dye and absorption path length, respectively. In order to obtain the relation between fluorescence light intensity and oil fil thickness, a calibration procedure was conducted by placing an optical surface flat onto the raw workpiece where a known-thickness board was inserted in between to create spaces to be filled by the working oil, as exhibited in figure 2. The diode laser with laser beam in line shape was irradiated to the calibration probe. Therefore, the fluorescence light intensity from the thinnest oil at the bottom to the thickest oil near the known-thickness board can be quantify. Thus, the relation between the fluorescence light intensity and the oil film thickness can be obtained.

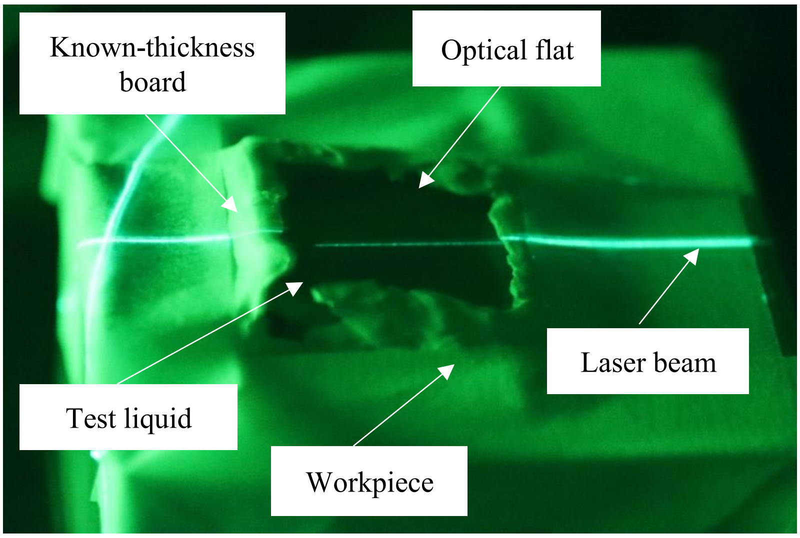

Figure 2. Actual view of calibration procedure.

Figure 3 presented the proportional correlation between the fluorescence light intensity and oil film thickness attained from the calibration procedure for all type of oil. It shows that the lubricant oil film thickness was found to increase with increasing fluorescence light intensity. The linear equation obtained from the results is depicted in table 3.

Table 3. Linear equation of calibration

Oil types	Linear equations
Mixed esters oil	$I = 2.4731\delta + 4.7994$
Sunflower oil	$I = 0.3234\delta + 2.166$
Olive oil	$I = 3.419\delta + 1.3071$
Calophyllum inophyllum oil	$I = 0.1922\delta + 0.7667$

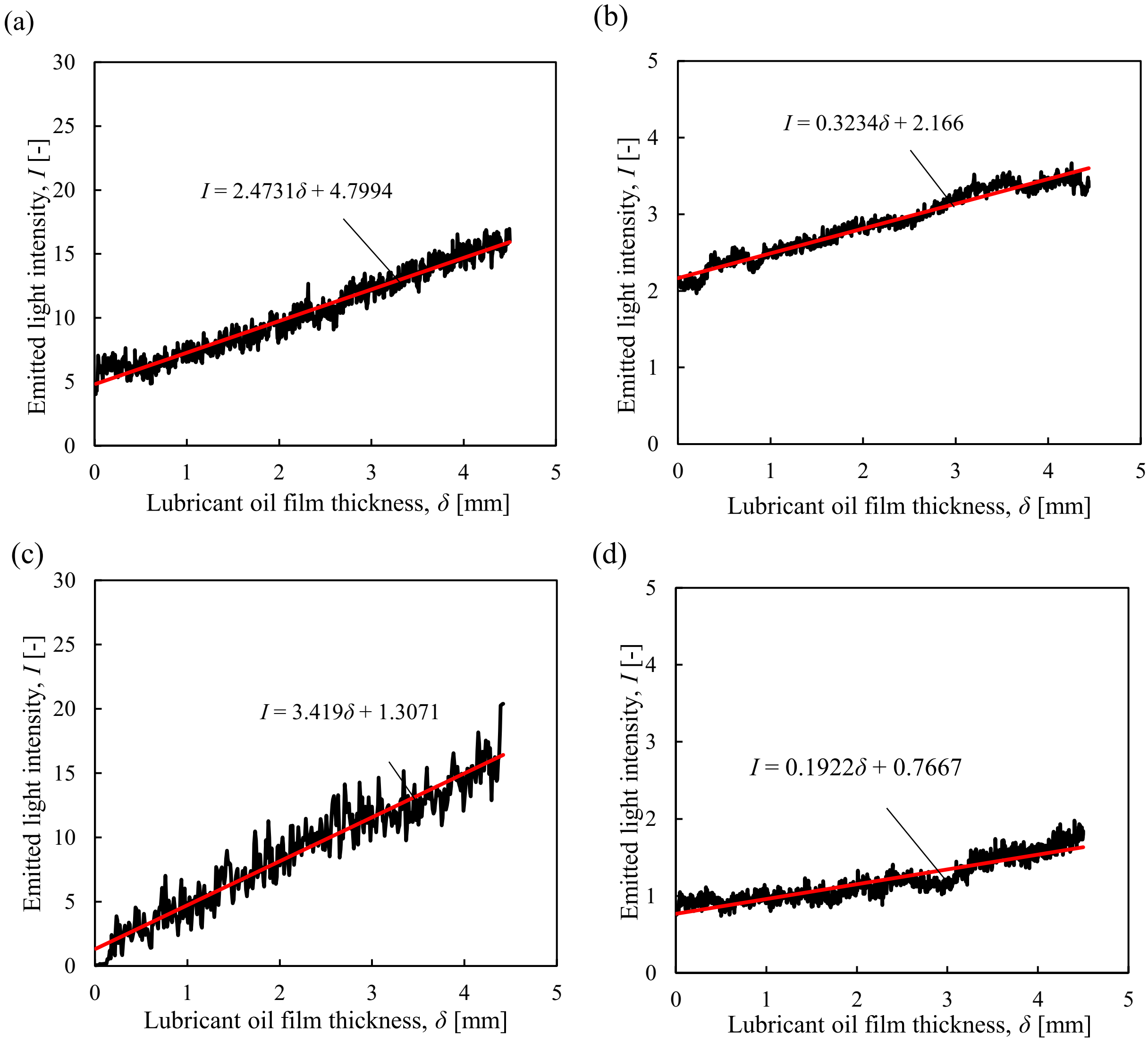

Figure 3. Relationship between emitted light intensity and lubricant oil film thickness of (a) mixed esters oil (b) sunflower oil (c) olive oil and (d) calophyllum inophyllum oil.

3. Results and Discussions

Figure 4 indicates the average lubricant oil film thickness obtained under different oil viscosity represented by different oil type, i.e. (a) mixed esters oil (b) sunflower oil (c) olive oil and (d) calophyllum inophyllum oil, respectively. The cutting speed was fixed at 29.514 m/min. It was indicated that as the oil viscosity increases, the height of lubricant oil acquired along the distance of machining milling point decreases. This was supported contrarily by the past work which proved that lower viscosity of oil delivered a better spreadability of lubricant onto the contact region of workpiece (Junior, Falco, Batista & Silva, 2017). Nonetheless, the thickness of lubricant oil is seen to be higher in olive oil contrasted to mixed esters at viscosity of 30.224 cSt and 11.075 cSt, respectively. The range of lubricant oil film thickness in olive oil was found between 0.45 mm to 1.5 mm while in mixed esters was found between 0.45 mm to 1.0 mm. This implied that greater capability and deeper penetration effect through the cutting zone was obtained with olive oil.

From the starting distance of machining milling point, the similar downturn trend of average lubricant oil film thickness at all conditions of oil viscosities were achieved. This could be affected by the role play of MQL nozzle position that is placed parallel to the direction of the feed. Hence, the dispersion effect of cutting oil penetrated to the milled route from the nozzle orifice largely exposed at the beginning of the milling point and the average lubricant oil film thickness was recorded higher than 0.5 mm for all cases. Ultimately, the thickness of lubricant oil becomes slightly reduce along the entire milling point due to less amount of lubricant oil developed onto the surface area. Consequence of scaling and probability of built-up-edge formation were raised and chips was possibly accumulated on the milled surface. Therefore, only little amount of cutting oils were successfully penetrated and reached the milled surface (López De Lacalle, Angulo, Lamikiz, & Sánchez, 2006).

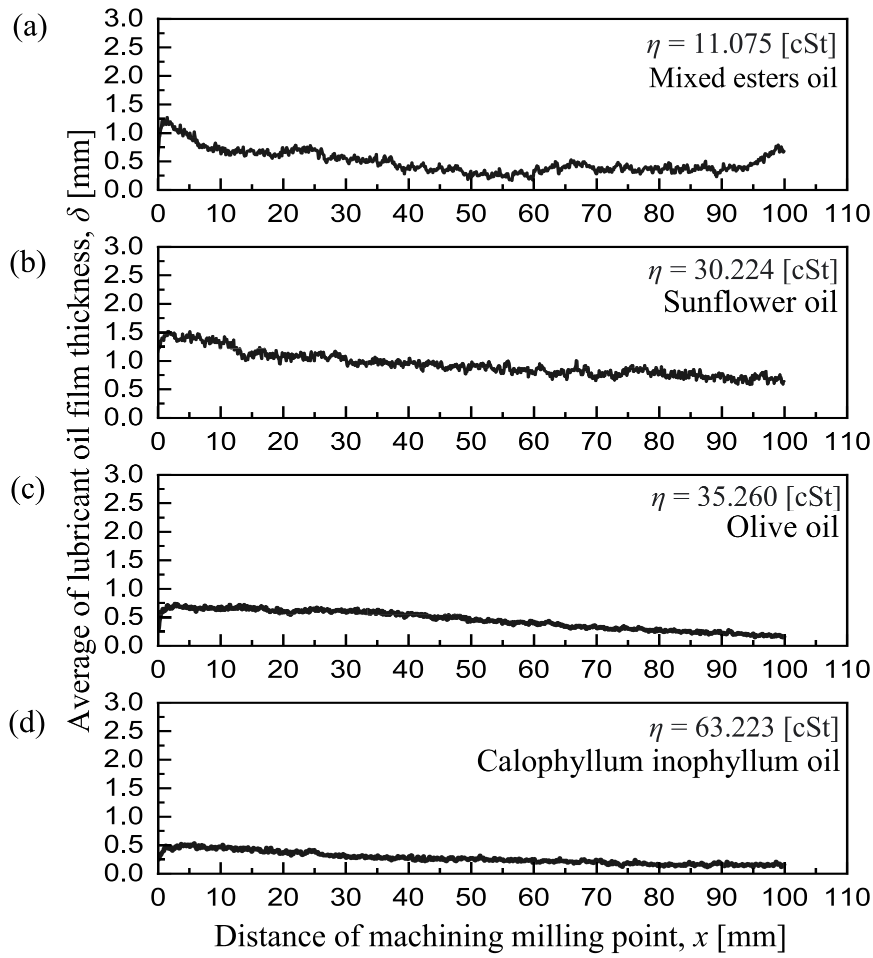

Figure 4. Average lubricant oil film thickness, δ against distance of machining milling point, x for (a) mixed esters oil (b) sunflower oil (c) olive oil and (d) calophyllum inophyllum oil**.**

4. Conclusion

The behaviour of MQL lubricant oil during the milling process was investigated in this study. Here, a non-intrusive method was applied to observe the behaviour of MQL lubricant oil. The effects of lubricant oil viscosity to the oil film thickness aggregated on the milled surface by MQL application was analysed. Several conclusions have been made as below:

a) Overall, the average of lubricant oil film thickness was significantly affected by the oil viscosity. As the oil viscosity increases, the average of lubricant oil film thickness along the distance of machining milling point decreases. This occurrence happened due to the spreadability of lubricant oil onto the milled region. In addition, low viscosity lubricant oil tends to be easier to penetrate from the MQL nozzle while lubricant oil with high viscosity bit difficult to penetrate as the formation of lubricant oil is thicker.
b) The nozzle of MQL generator which was positioned at 45° laterally in the direction of the feed could be the factor that dispersion effect of cutting oil penetrated to the milled route were largely exposed at the beginning of milling point. However, the average lubricant oil film thickness becomes fewer along the entire milling point due to the built-up edge formation and chips accumulation that caused little amount of cutting oil penetrated onto the surface.

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