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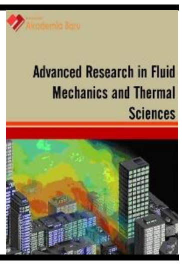

Advanced Research in Fluid Mechanics and Thermal Sciences

Measurement of Liquid Film Thickness Accumulated on Surface Machined by Minimum Quantity Lubrication (MQL)

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ABSTRACT

This paper investigated the liquid film thickness of cutting oil accumulated on test surface machined by minimum quantity lubrication (MQL) milling process. The objective of investigation is to give the overview of cutting oil behavior on the machined surface. The measurement was carried out by using laser-induced fluorescence (LIF) method. The experiments were carried out by varying the cutting speed to investigate its effects on the cutting oil film thickness. This investigation found that the cutting oil film thickness remains stable at certain area for cutting speed below than 40 m/min. However, the decreasing thickness started to occur around one-third point of the milled route. At cutting speed 40 m/min, the cutting oil film thickness presents unstable fluctuations along the entire milled route. However, the thickness almost stays the same along the entire milled route. The average liquid film thickness is not significantly affected with increasing cutting speed. The maximum average thickness is approximately 2.6 mm.

1. Introduction

Liquid spray is a phenomenon of multiple tiny liquid droplets formed through an atomization process generated by nozzle. Over the last few decades, liquid spray has given great benefits to leading industrial sectors such as manufacturing, automotive, healthcare and agriculture. In automotive sector for example, a great spray combustion to enhance engine performance is highly depending on the spray characteristic of fuel injector [1]. In manufacturing sector, a good spray characteristic of cutting oil is necessary for cooling and lubricating purpose during machining process [2]. Until now, various innovations of the cutting oil delivery method [3–5] have been done to replace conventional flood cooling. Among the famous ones that are widely applied nowadays is minimum quantity lubrication (MQL).

MQL utilizes nozzle injection of cutting oil to reduce friction effects occurred in the tool-workpiece interfaces. Despite the extremely little amount of oil used compared to flood cooling

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method, the oil spray from MQL is proven to be effective in lengthening tool life, minimizing triggered high temperature during machining process, decreasing the needed cutting force and reducing chips in the cutting zone [6]. To date, various studies [7–9] have been carried out to improve the performance of machining process using MQL. However, most of the investigation related to MQL were merely focused on studying the effects of machining parameter to quality of machining performance.

Although several literatures [10, 11] have well-described the fundamental characteristic of oil spray in MQL such as the droplets amount and size, report on the effects of machining parameter to the oil spray behavior upon the on-going process of machining is still scarce. This kind of knowledge is highly important for MQL machining process in a way to find the know-how of cutting oil to efficiently penetrate the cutting zone. However, limitation in the investigation can be caused by the difficulty to conduct measurement procedure since the flow field of oil spray in MQL i.e. tool-workpiece interfaces is extremely narrow [12].

Here, this paper is presented with aim to investigate the liquid film thickness of cutting oil accumulated on test surface machined by MQL milling process. Although the measurement was not conducted during the machining process is on-going, this study is expected to give the overview of cutting oil behavior on the machined surface. Specifically, the capability of cutting oil to penetrate the cutting zone can be slightly explained through this study. The measurement was carried out using a fluorescence imaging method i.e. laser-induced fluorescence (LIF). The experiments were carried out by varying the cutting speed to investigate its effects on the cutting oil film thickness.

2. Experimental Setup and Procedure

2.1 Machining Process

The machining process was conducted by using a CNC milling machine with an oil spraying system provided by an MQL generator. The most common aluminium block used in manufacturing industry, Al6061 was chosen as the workpiece material. It was in 100 mm^2-top surface area and 45 mm-thickness. A piece of 8 mm-diameter coated carbide end mill cutter was used as the cutting tool. The test liquid was a fully natural cutting oil with 18.5 cSt-viscosity. It was deposited from the nozzle of MQL generator whose orifice is in 0.8 mm-inner diameter.

Figure 1 shows the image of machining setup and illustration of nozzle position. The workpiece was milled starting from one corner to the other end in the feed direction. The milling process was continued line by line on the entire surface of workpiece. Upon milling, the nozzle tube was bend 45° from cutting tool edge and faced the cutting zone and placed in parallel with the feed direction. The nozzle orifice was distanced in 5 mm from the edge of cutting tool, as illustrated in the figure. Experiments were carried out by varying the cutting speed to investigate its effects on the cutting oil film thickness. The description of machining parameter is tabulated in Table 1.

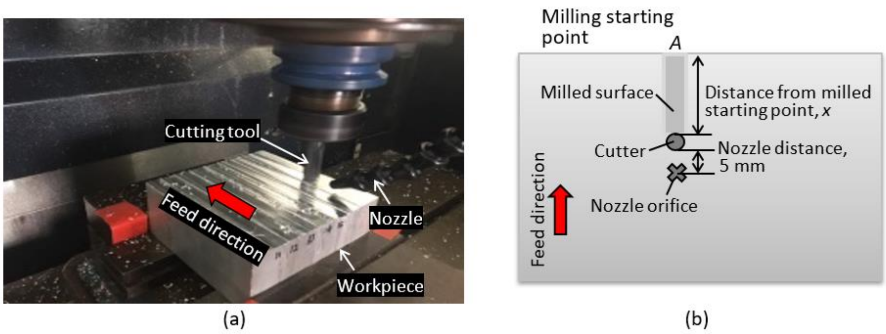

Fig. 1. (a) Image of machining setup and (b) illustration of nozzle position from top view

Table 1
Machining parameter

Machining Parameter	Value
Workpiece material	Al6061
Cutting tool material	Coated carbide end mill
Cutting tool diameter	8 mm
Depth of cut	0.3 mm
Feed rate, V_f	230 mm/min
Cutting speed, V_c	30, 35, 40 m/min
Air pressure	0.035 MPa
Oil flow rate	0.15 ml/min
Oil viscosity	18.5 cSt
Size of nozzle orifice	0.8 mm (inner diameter)
Nozzle position	Orifice 5 mm from cutting tool edge, parallel with feed direction

2.2 Measurement of Liquid Film Thickness

The next stage of experiments after milling process is to measure the liquid film thickness of cutting oil accumulated on the test surface using LIF method. This method has been applied by many researchers [13–15] to investigate local film thickness presents unsteady effects in the flow behavior due to its high temporal and spatial resolution. The liquid film thickness is theoretically calculated based on Eq. (1) as follows

$$I_e = \phi I_0 \cdot \exp(-c_{dye} \cdot \delta \cdot \epsilon_\lambda) \quad (1)$$

where I_e as emitted light intensity, I_0 as incident light intensity, δ as liquid film thickness, c_{dye} as dye concentration in liquid solution and ϵ_λ as molar absorption of the fluorescent dye. To measure a liquid film thickness flows over a solid surface from the top view as in this study, this equation is applicable where the emitted light intensity is expressed as a function of liquid film thickness [16]. The light emission of liquid film is enabled upon excitation of coumarin153 which can be achieved by irradiating a continuous laser light whose wavelength must match with the absorption spectrum of fluorescence dye. The brightness of emitted light intensity will show a proportional relationship to the liquid film thickness. A dedicated calibration procedure is required to obtain the relationship equation.

In this study, the test liquid solution was prepared by dissolving coumarin153 dye into the cutting oil with 0.06 wt%-concentration. The fluorescence excitation was executed by a diode laser in line-beam shape with 405 nm-wavelength and 200 mW-power. At this wavelength, coumarin153 will maximally absorb the energy from the laser and then excite to the highest fluorescence spectrum of 532 nm-wavelength [17]. The light intensity of this wavelength will be captured for the liquid film thickness measurement.

The validity of Eq. (1) was verified by conducting a calibration method. Figure 2 shows the schematic view of tools setup for liquid film thickness measurement upon calibration and actual experiment. The calibration probe was fabricated by inserting a known-thickness board between an optical flat and sample of unmilled workpiece. The board was inserted at the top corner, providing a varying thickness-slot in between the optical flat and workpiece. The slot was then filled up with the test liquid. The diode laser was irradiated to the calibration probe to correlate the emitted light intensity with the known-thickness of test liquid. Local brightness of the emitted light was captured at 30 frames per second in 1080 × 1920 pixels using a video camera. A green filter was placed on the emitted light path to filter the light other than 532 nm-wavelength. The captured image was processed, and the light intensity was quantified using image processing program.

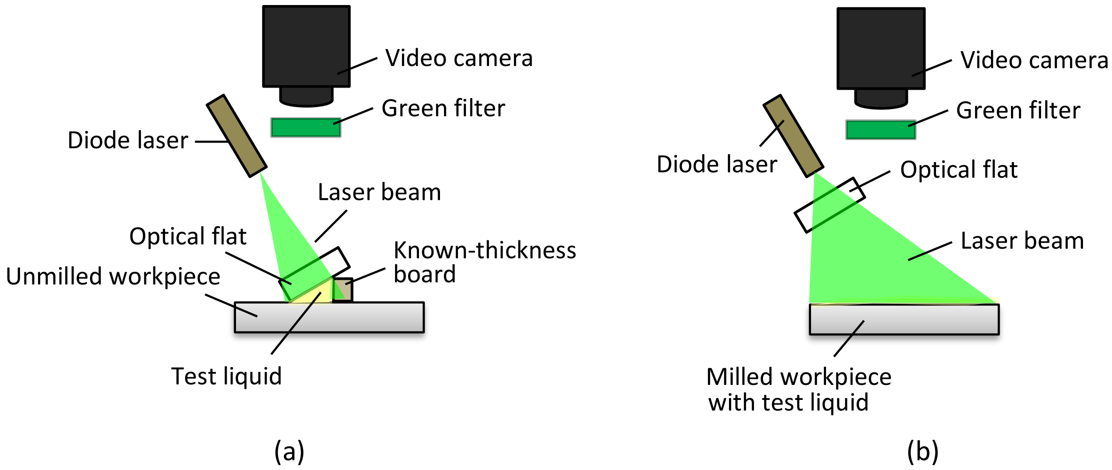

Fig. 2. Schematic view of tools setup for liquid film thickness measurement upon (a) calibration and (b) actual experiment

To conduct the actual experiment, the tools arrays and experimental procedure were adapted from that of used in the calibration method, but the calibration probe was replaced by the milled workpiece as shown in Figure 2. The sample of raw and processed image of emitted light are shown in Figure 3. Point *A* in the images refers to the milling starting point. The bright line appeared in the middle indicates the emitted light referring to the liquid film formed on the milled route.

The proportional relationship between the emitted light intensity and liquid film thickness of obtained from the calibration is shown in Figure 4. It presents a linear model of Eq. (2) as follows

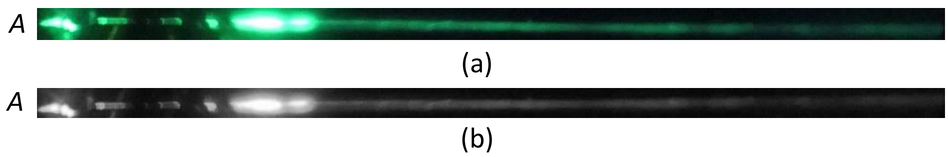

Fig. 3. Sample of (a) raw and (b) processed image (V_f= 230 mm/min; V_c= 30 m/min)

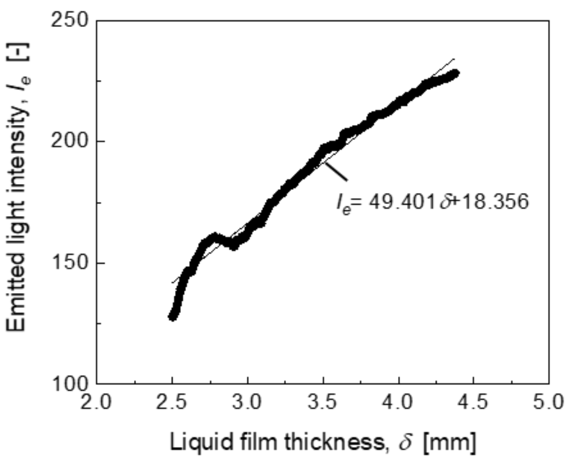

Fig. 4. Results of calibration - relationship between emitted light intensity and oil film thickness

$$I_e = 49.401\delta + 18.356 \quad (2)$$

This equation was used to calculate the thickness of liquid film accumulated on the test surface by substituting the value of emitted light intensity.

3. Results and Discussion

3.1 Liquid Film Thickness Fluctuation

Figure 5 shows the liquid film thickness in the cases of cutting speed 30 m/min, 35 m/min and 40 m/min for (a), (b) and (c), respectively. The corresponding feed rate was 230 mm/min. The plotted data refers to the height of cutting oil accumulated along the test surface from starting till finishing point of the milling process. From the figure, it is evident that the liquid film thickness for cases (a) and (b) show a similar trend. The thickness is seen to present very little ups and downs compared to that of case (c). Furthermore, there are significantly large area on the test surface for cases (a) and (b) where liquid film remains constant after going up and down in the thickness change. This indicates that there are some locations along the milled route, where the cutting oil can uniformly develop on the test surface. This implies that after penetrating the cutting edge, the cutting oil does not fly off far from the cutting zone but spread at certain area on the milled route.

Furthermore, the similar decreasing trend of liquid film thickness in both cases (a) and (b) is also revealed. The slump of thickness for both cases is found to occur starting from one-third point of the milled route. The thickness can be seen to decrease up to 30 % and 60 % from its highest value, respectively for case (a) and (b). A careful observation to figure for case (a) shows that the liquid film thickness presents a little rise at distance 10 mm, 40 mm and 80 mm from the starting point. A dramatic reduction is significantly seen approximately at distance 30 mm and 50 mm from the starting point. Surprisingly, these two locations also present huge falling of liquid film thickness for case (b). However, there is no significant growth of thickness found, except on the distance 90 mm where the liquid film rapidly climbs to a peak before staying the same till finishing point.

The decreasing trend of thickness with a steep slope can be attributed to the adhering of built-up edge and chips on the milled route starting from that point. This suggests that the spraying strength has enabled the cutting oil to penetrate the cutting edge by removing away the built-up edge and chips in that area. However, the removal process may have not been done properly when the milling process reached to one-third point of the milled route. Hence the built-up edge and chips were dispersed not far from the test surface but near to that area. Therefore, revisit milling process may be run smoothly in the beginning part but eventually become harder upon approaching one-third point of the milled route due to the decreasing layer of cutting oil.

On the other hand, liquid film thickness in case (c) is found to exhibit numerous fluctuations compared to that of cases (a) and (b). As seen in the figure, almost every point of the milled route presents significant wavelike characteristics of liquid film. There are various ups and downs of liquid film thickness in extremely short wavelength. Close to the same location for cases (a) and (b) i.e. distance 50 mm from the starting point, the liquid film thickness is found to act oppositely. The liquid film is seen to climb into the highest peak and remain in very little ups and downs before suddenly hit the lowest point of thickness. It then steeply increases and remains as wavy layer till the finishing point of milled route.

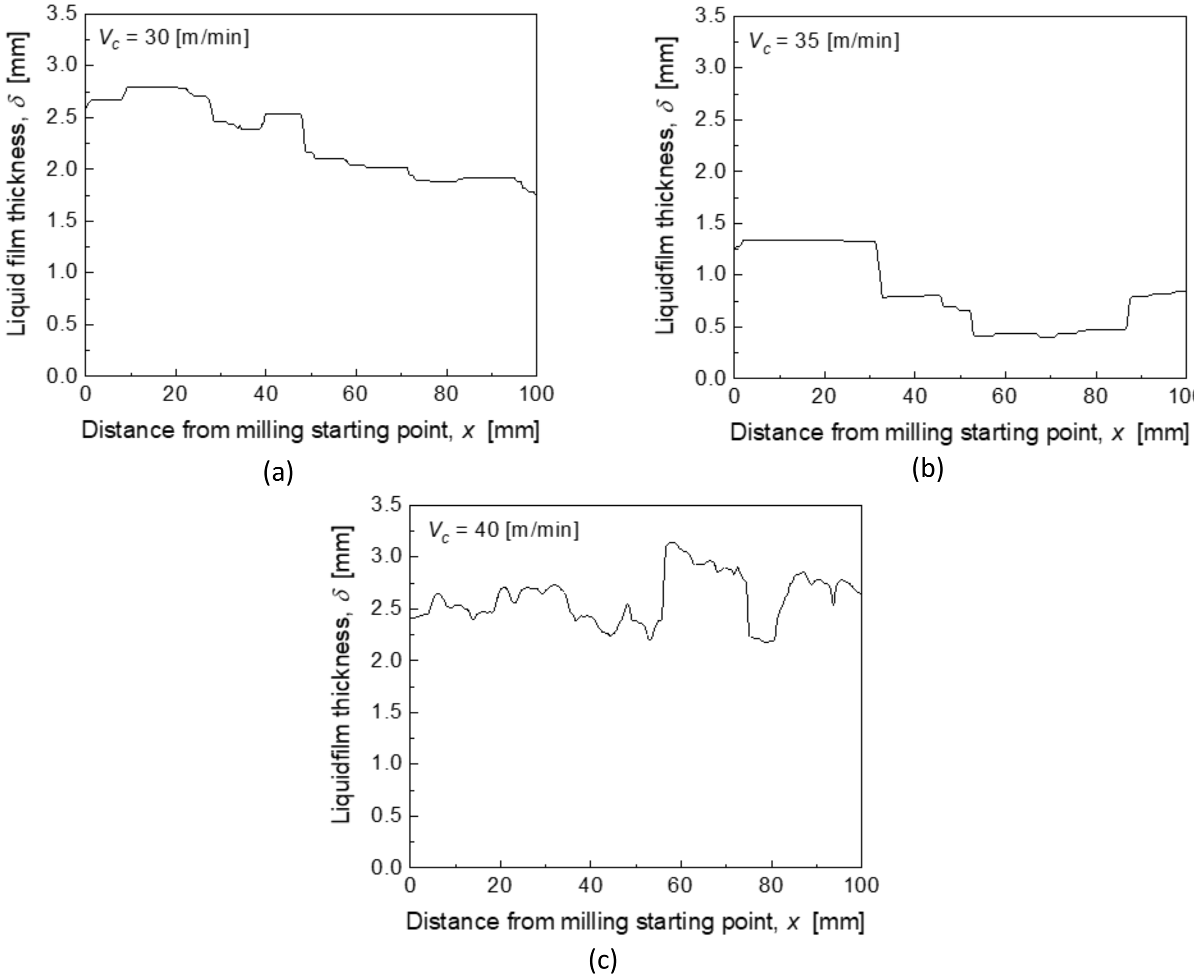

Fig. 5. Liquid film thickness under feed rate 230 mm/min and cutting speed (a) 30 m/min, (b) 35 m/min and (c) 40 m/min

However, the thickness fluctuation is seen to remain on almost the same level. This gives a totally different results from cases (a) and (b) that clearly shows a continuous decreasing trend at certain area. This suggests that under cutting speed 40 m/min, the cutting oil spray has more strength to penetrate the cutting edge. The strength has even caused the built edge or chips to fly off far from the milled route. This can be confirmed from the report of Hiromi *et al.,* [18] which explained that adhered built-up edge can be reduced with increasing cutting speed. Therefore, a smoother revisit milling process is expected to be achieved not only at certain point but along the entire milled route, compared to that of gained under lower cutting speed. Here, the nozzle position and direction which is parallel to the feed direction play the main role to facilitate oil accessing the cutting zone and remove the chips and built-up edge. Although it is contradicted with the statement of Lopez *et al.,* [19], this study suggests that placing the nozzle orifice parallel to the feed rate direction can assist to remove the accumulated chips and built-up edge. Only then the cutting oil can successfully penetrate the cutting edge.

3.2 Average Liquid Film Thickness

To observe the effects of cutting speed, Figure 6 shows the average value of liquid film thickness for cutting speed 30 m/min, 35 m/min and 40 m/min. The average value was calculated by summing all the thickness measured for each point on the test surface and then divided by the number of those points. From the figure, average oil film thickness is seen to not significantly affected by increasing cutting speed. Specifically, the average thickness falls into 60 % lower when increased to 35 m/min but rebounds 10 % larger than the initial value when further increased to 40 m/min. Furthermore, it is also evident that cutting oil tends to accumulate on the test surface with thickness not higher than 2.6 mm. However, extended investigation must be carried out to measure the surface roughness of test surface under these operated cutting speed. Only then this average liquid film thickness of cutting oil can be said to relevantly indicate the performance of machining process.

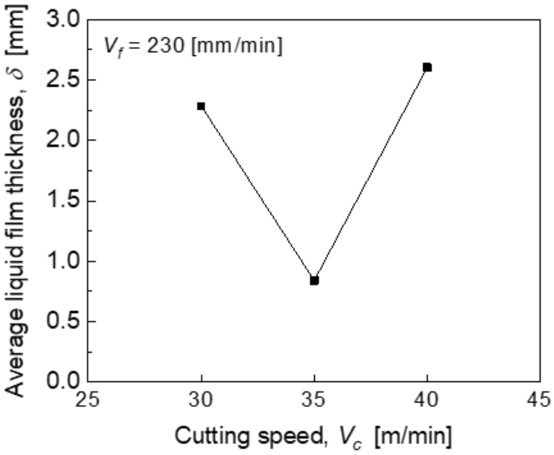

Fig. 6. Average liquid film thickness with increasing cutting speed

4. Conclusions

This paper investigated the liquid film thickness of cutting oil accumulated on test surface machined by MQL milling process. Several findings can be concluded as follows

I. Under cutting speed below than 40 m/min, the cutting oil film thickness remains stable at certain area. However, the decreasing thickness started to occur around one-third point of the milled route.
II. Under cutting speed 40 m/min, the cutting oil film thickness presents unstable fluctuations along the entire milled route. However, the thickness almost stays the same along the entire milled route.
III. The average liquid film thickness is not significantly affected with increasing cutting speed. The maximum average thickness is approximately 2.6 mm.

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