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Article

Investigation of Lubricant Oil Film Thickness on Workpiece under Minimum Quantity Lubrication Milling Process

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Abstract

Minimum Quantity Lubrication (MQL) technology has drawn attention as an effective lubrication technique despite its small usage of lubricants during the machining process. The technology has undeniably minimized the manufacturing cost as well as the adverse impacts towards the environment and health of operators. However, the ability of the small droplets of lubricant oil to penetrate the cutting zone must be investigated to enhance the machining performance. The penetration ability can be predicted if the amount of lubricant oil adhered to the workpiece is known. Nonetheless, observing the lubricant behavior is commonly challenged by the existing tools during the machining process. Therefore, a non-intrusive technique must be applied to conscientiously observe the lubricant behavior. In this paper, the thickness of lubricant oil resulted by the droplets accumulation on the workpiece during MQL milling process was measured using a Laser-Induced Fluorescence technique to predict the lubricating effects of the lubricant. The surface roughness of workpiece was also measured to investigate how the thickness of lubricant oil affects the machining performance. Experiments were conducted for MQL milling process of aluminium alloy 6061 under constant value of cutting speed and increasing value of lubricant flow rates. The MQL nozzle was tilted 45°, directed perpendicular to the milling direction and fixed together with the cutting tool to let them move together throughout the milling path. Results analysis was performed on the sample whose cutting tool was halfway to the milling path. As a result, the average lubricant oil film thickness was found to increase and obviously fluctuate with increasing flow rates, ranging from 0.2 mm to 0.7 mm. A careful observation of the lubricant oil thickness near the location of cutting tool also suggested that the droplets of lubricant oil probably struggle to penetrate the cutting zone due to the sudden falls at those locations. Furthermore, the correlation between the thickness of lubricant oil film to the performance of milling process under the MQL spraying condition was successfully made since the results trending of the surface roughness of workpiece shows a well agreement with the trending of lubricant oil film thickness.

Keywords

minimum quantity lubrication, oil film thickness, milling process

1 Introduction

Cutting fluids play an important role in various industries involving machining processes. Lubricant oils mainly aid in the shear heat dissipation to lubricate and cool the tool-workpiece interfaces, keeping the cutting zone from overheating [1]. It also repels the flying chips away from damaging and thus degrading the surface finish of the machined surface [2]. Since the machinery application has grown rapidly to date, various type of oil with great properties has been widely introduced to satisfy the demands of this industry. However, its excessive use in conventional flood cooling can lead to adverse impacts on the environment, operators, and maintenance costs, thereby jeopardizing the energy sustainability [3].

Therefore, a near dry machining method, i.e. Minimum Quantity Lubrication (MQL) technology has been introduced to improve machinability even with controlled amount of oil consumption [4]. It was reported that MQL used only 200 ml/hr, which is substantially less than the amount needed by flood cooling [5]. Combination of high-pressurezied air and oils in MQL generates an aerosol form of lubricant spray. The tiny droplets of oil from the aerosol must be succesfully penetrate the tool-workpiece interfaces to increase the lubricating effects in the cutting zone. Therefore, the performance of MQL technology highly depends on the behavior of lubricant oils to infiltrate the cutting zone during the machining process.

A large number of research has been conducted to prove the performance of MQL technology in various machining process such as turning, [6] milling [7], drilling [8] and grinding [9]. In order to clarify the lubricating effects in MQL, the mechanism of lubricant oil to penetrate the cutting zone must be investigated [10]. To date, the observation of lubricant oil behavior is still scarce. This might be attributed to the challenge in developing the visualization tools while the machining is ongoing, in addition to the natural flow of lubricant oil that cannot be disrupted. In this paper, a non-intrusive method called as Laser Induced Fluorescence (LIF) is applied to measure the lubricant oil thickness while MQL milling process is ongoing. This technique has been extensively used to explain the behaviour of fluid flow in numerous fields of study [11- 13].

Since the amount of oil must be adequately supplied to assure outstanding performance of MQL, the flow rate of lubricant oil must be efficiently controlled [14]. This paper targets to investigate the effects of lubricant oil flow rate to the lubricant oil film thickness formed on the milled workpiece. The surface roughness of workpiece will be measured as well to correlate the findings of oil film thickness with the performance of MQL milling process.

2 Methods

The working oil was firstly prepared by dissolving fluorescent dye, i.e., coumarin 153 in mixed esters lubricant oil i.e., Unist Coolube® 2210 cutting fluid with a concentration of 0.03 mass%. In the Laser Induced Fluorescence (LIF) method, the calibration procedure is essential to establish the relationship between fluorescence light intensity of working oil and the oil film thickness. Figure 1 shows the schematic view of the experimental probe for the calibration method. A transparent optical flat was used as highly flat reference surfaces in the calibration probe. By using the optical flat as the cover of the probe, a known-thickness plate was inserted at the top edge of the workpiece made of aluminum alloy Al606 in order to create a column that varied from the thinnest point A to the thickest point B. The thickness of the plate is 4.8 mm while the length from A to B is 38 mm. The working oil was then injected into the column. A 405 nm-wavelength diode laser was irradiated normal to the optical flat surface to excite the coumarin 153 contained in the working oil and cause the emission fluorescence light from the oil. A lined shape of laser beam was used to easily measure the emitted light intensity throughout test section, i.e., the thinnest point A to the thickest point B. Simultaneously in a complete dark condition without any light source, a green colored emitted fluorescence light will appear and a Canon EOS 80D DSLR model camera was used to record the fluorescence light intensity. A green filter was used to filter the deep-violet blue color of diode laser from appeared on the recorded frame while a NDX filter was used to reduce the emitted fluorescence light intensity to a measurable range. The recorded video was then converted into still image as shown in Fig. 2. The fluorescent light can be seen increasingly intensified from point A to point B, indicating that the working oil became thicker from the thinnest to the thickest column. An image processing was then carried out to quantify the emitted light intensity and thus establish the linear relationship between the emitted light intensity, I (-) and the oil film thickness, δ (mm) as resulted in the previous work [15]. The liner relationship is expressed as Eq. (1) below:

$$I = 5.702\delta + 1.6725 \quad (1)$$

By manipulating the Eq. (1), the thickness of lubricant oil film during the actual experiment, i.e., the ongoing machining process can be obtained if the intensity of light emitted from the lubricant oil is quantified. Table 1 tabulates the experimental condition. Figure 3 illustrates the experimental setup for the actual experiment. An MQL generator (KURODA Eco Saver KEP-WR) was used to produce the MQL lubricant oil spray while the milling process is run by Makino KE55 CNC Vertical milling machine. The optical flat was also placed on the path of diode laser irradiation in order to eliminate its surface during the calibration procedure. Figure 4 illustrates the top view of workpiece during milling operation. Measurement of lubricant oil film thickness was started from the milling starting point,

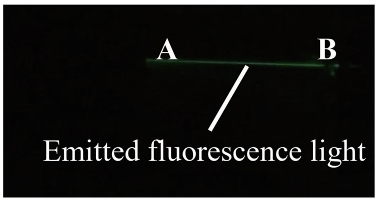

Fig. 2 Sample of still image captured to calibrate fluorescence light intensity and oil film thickness

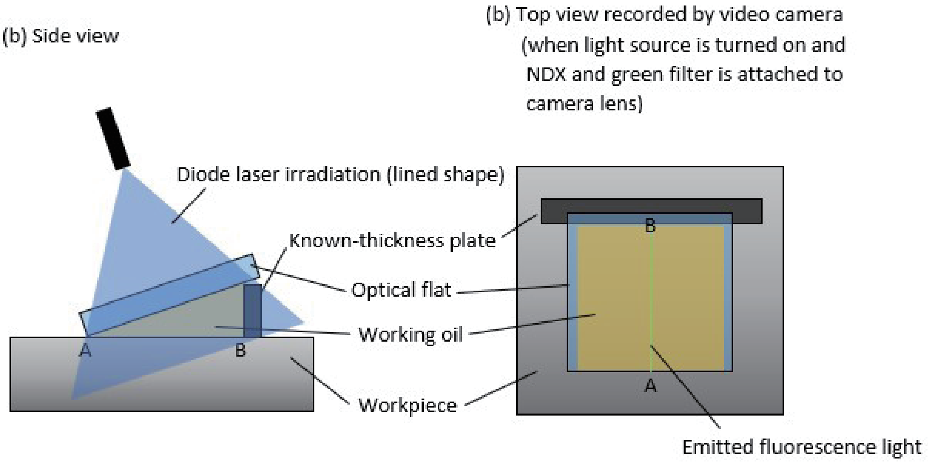

Fig. 1 Schematic view of the experimental probe for the calibration method from (a) side view and (b) top view

x throughout the workpiece. As the experiment room turned dark, similar steps as in calibration procedure, including the laser irradiation, video recording and image processing. The Eq. (1) was used to determine the lubricant oil film thickness along the milled area, i.e., from the milling starting point, x up to the milling end point of the workpiece based on the intensity of emitted light appeared in the recorded image. Again, intensified emitted light appeared in the image indicating thicker lubricant oil film. As the recording was performed normal to the milled surface, lubricant oil film thickness was visualized through the vertical thickness, i.e., one-dimensional flow, in z direction from the top view, as indicated in Fig. 5. The surface roughness of workpiece was measured by using Elcometer 7061 MarSurf PS1 surface roughness tester to correlate the thickness of lubricant oil to the performance of milling process under the MQL spraying condition. The measurement as conducted to read arithmetic mean roughness value, *Ra* and mean roughness depth value, *Rz*.

Table 1 Experimental condition

Parameter	Condition
Feed per tooth	0.0893 mm/tooth
Axial depth of cut	0.5 mm
Cutting speed	14.514 m/min
Table feed	165 mm/min
Revolution speed	462 rpm
Air pressure	35 kPa
Oil flow rate	120, 150, 198, 250 ml/hr
Specific gravity of oil	0.93
Concentration of working oil	0.03 mass%
Viscosity of working oil	11.075 mPa.s
Cutting tool diameter	10 mm
Nozzle diameter (internal)	2 mm
Nozzle position	90 deg. from milling path
Nozzle angle	45 deg. from horizontal axis
Camera image resolution	6000 × 4000 pixels (3.7 μm pixel size)

3 Results and discussion

3.1 Average lubricant oil film thickness

Since the video recording was performed entirely when the cutter is moving from the milling starting point towards the stopping point, any frame of the still image data converted from the recorded video data along the milling process can be selected for result analysis according to the desired location of cutting tool. In this paper, the frame of still image when the cutting tool is located at 62 mm to 72 mm during the milling process is ongoing was selected for analysis, as represented by the dashed line in Fig. 6. Figure 6 shows the results of average lubricant oil film thickness versus the distance from milling

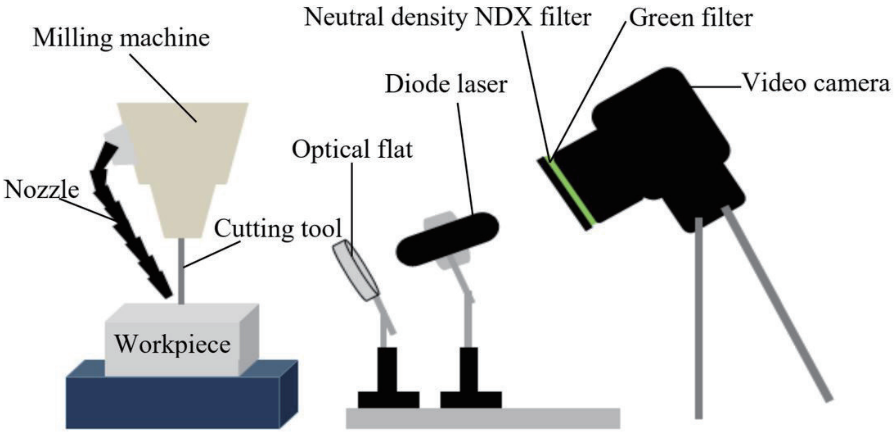

Fig. 3 Schematic view of experimental setup for the actual experiment

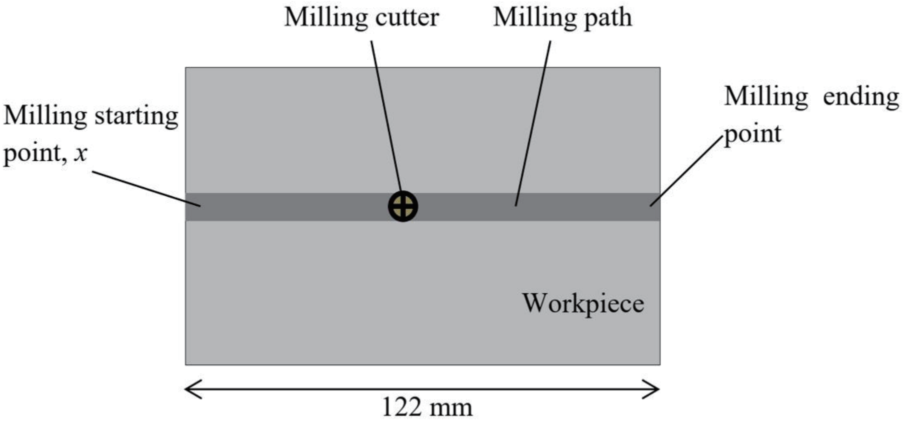

Fig. 4 Illustration of top view of workpiece during milling operation

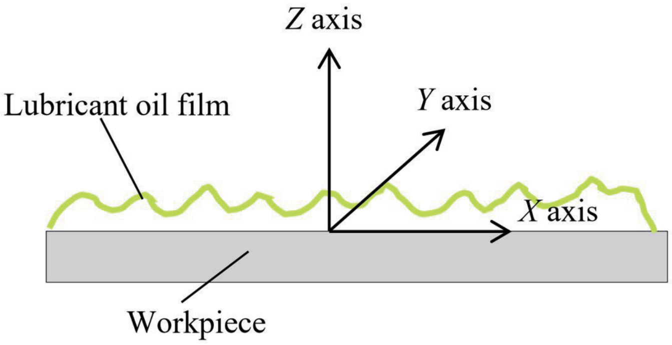

Fig. 5 Illustration *z* axis for lubricant oil film thickness measurement

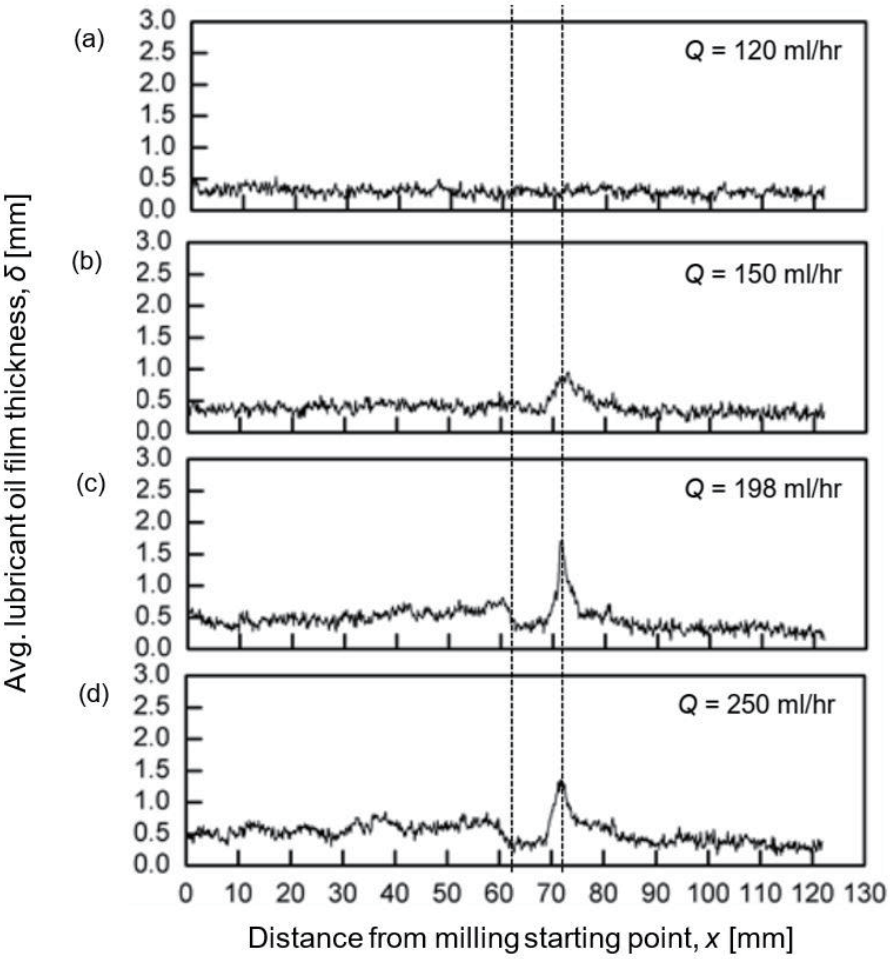

Fig. 6 Average lubricant oil film thickness versus the distance from milling starting point at lubricant oil flow rates of (a) 120 ml/hr, (b) 150 ml/hr, (c) 198 ml/hr and (d) 250 ml/hr

starting point at lubricant oil flow rates of 120 ml/hr, 150 ml/hr, 198 ml/hr and 250 ml/hr. The term “average” lubricant film thickness used here means the data was from the average of multiple samples of experimental data under the same condition. For lubricant oil flow rate of 120 ml/hr, the thickness of lubricant was mostly in the range of 0.2 mm until 0.4 mm and above. These outcomes are relevant as the previous study had mentioned that the lubricant oil film thickness was seen to decrease at the cutting edge but fell in the range of 40 μm to 200 μm away from the cutting edge [16]. Moreover, the lubricant oil film thickness was mostly in the range of 0.3 mm and 0.5 mm and above for the lubricant oil flow rate of 150 ml/hr. The highest lubricant oil film thickness of 0.952 mm was obtained at 72 mm from milling starting point just after the cutter is located. The lubricant oil film thickness was more stable, having a slight increase starting at 22 mm from milling starting point. However, the decreasing trend of lubricant oil film thickness just after the cutter is located was evidently seen.

For lubricant oil flow rates of 198 ml/hr and 250 ml/hr, the lubricant oil film thickness was found to be higher. For lubricant oil flow rate of 198 ml/hr, the lubricant oil film thickness was detected mostly in the range of 0.4 mm until 0.6 mm and above. Highest lubricant oil film thickness of 1.715 mm was obtained at 71 mm from milling starting point. However, the lubricant oil film thickness traced along the milling path until the position of cutter was more irregular with several occurrences of distinct increase and decrease. Nevertheless, the decreasing trend after the position of moving cutter still resumed for this flow rate.

For lubricant oil flow rate of 250 ml/hr, lubricant oil film thickness was found higher with the highest thickness observed in the range of 0.4 mm until 0.7 mm and above. The highest lubricant oil film thickness of 1.346 mm was obtained at 72 mm from milling starting point. In addition, the irregularities of lubricant oil film thickness until the position of cutter was seen more intense. Besides, the trend of decreasing lubricant oil film thickness just after the cutter is located was also seen for this flow rate. This suggests that lubricant oil spray tends to accumulate at certain location along the milling distance instead of spreading evenly during the milling process.

3.2 Frequency of average lubricant oil film thickness on 40 to 62 mm from milling starting point

Figure 7 shows the histogram of average lubricant oil film thickness for 40 mm to 62 mm distance from milling starting point versus frequency at lubricant oil flow rates of 120 ml/hr, 150 ml/hr, 198 ml/hr, and 250 ml/hr. For lubricant oil flow rate of 120 ml/hr, its mean value was at 0.301, median at 0.300, and mode at 0.300. The red lines referred to the bell curve showing the normal distribution of the lubricant oil film thickness. Figures 7 (b), (c), and (d) show that as lubricant oil flow rate increased from 150 ml/hr to 250 ml/hr, the average lubricant oil film thickness range also rose. For lubricant oil flow rate of 150 ml/hr, small negative skewness distribution was exhibited at a value of -0.12. At this flow rate, more oil concentrated at higher average lubricant oil film thickness. Its mean fell at 0.419, median at 0.426, and two mode values at 0.410 and 0.480.

For lubricant oil flow rate of 198 ml/hr, marginal positive skewness distribution as seen at 0.11. As can be seen from Fig. 7 (c), more lubricant oil adhered at lower range of average lubricant oil film thickness. However, this range was supplementary high than that of 150 ml/hr. Moreover, its mean value was at 0.612, median at 0.606, and mode values at 0.437, 0.505, 0.516, and 0.521. For lubricant oil flow rate of 250 ml/hr, it possessed negative skewness distribution at -0.62. Most

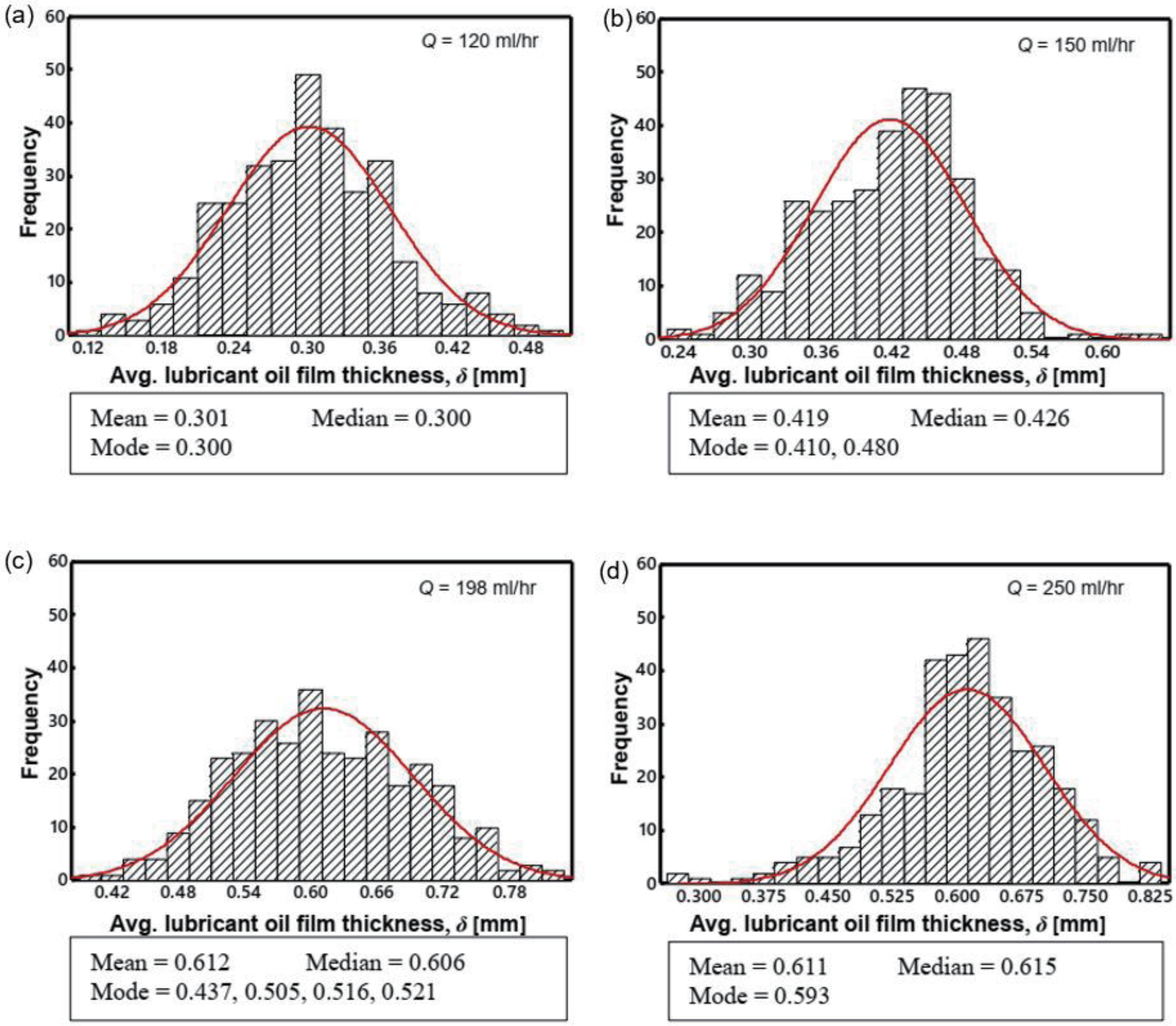

Fig. 7 Histogram of average lubricant oil film thickness for 40 mm - 62 mm distance from milling starting point versus frequency at lubricant oil flow rates of (a) 120 ml/hr, (b) 150 ml/hr, (c) 198 ml/hr and (d) 250 ml/hr

lubricant oil concentrated at a high range of average lubricant oil film thickness. Its mean value was at 0.611, median at 0.615, and mode at 0.593. Nevertheless, higher lubricant oil film thickness could create a barrier to lower heat transferred to the cutting tool that contributes to positive effect to MQL performance [17]. The nozzle angle set in this study might have led to uneven spraying of lubricant oil as the lubricant mists flew away from the cutting of milling process area [18]. Therefore, the histogram data for average lubricant oil film thickness during must be investigated at different distances from milling starting point.

3.3 Frequency of average lubricant oil film thickness on 72 mm to 90 mm from milling starting point

Figure 8 shows the histogram of average lubricant oil film thickness for 72 mm to 90 mm distance from milling starting point versus its frequency at lubricant oil flow rates of 120 ml/hr, 150 ml/hr, 198 ml/hr, and 250 ml/hr. The red lines represents the bell curve showing the normal distribution of the lubricant oil film thickness. For lubricant oil flow rates of 120 ml/hr, the average lubricant oil film thickness fell almost in the same range. However, the range of average lubricant oil film thickness increased for lubricant oil flow rates of 150 ml/hr, 198 ml/hr, and 250 ml/hr. This trend can be confirmed from the results shown in Fig. 6, where a significant fluctuation of lubricant oil film thickness is seen under the lubricant oil flow rates of 150 ml/hr, 198 ml/hr, and 250 ml/hr.

Nonetheless, the frequency of lubricant oil still tends to concentrate at lower average lubricant oil film thickness. For lubricant oil flow rates of 198 ml/hr and 250 ml/hr, only a little lubricant oil gathered at 1.00 mm and above average lubricant oil film thickness. The average lubricant oil film thickness could reach this range because there was more adherence of lubricant oil beside the MQL milling process as it could not slide into the cutting zone. Other than that, all lubricant oil flow rates of 150 ml/hr, 198 ml/hr, and 250 ml/hr show positive skewness distribution.

3.4 Average surface roughness of workpiece

Figure 9 shows the results of average surface roughness

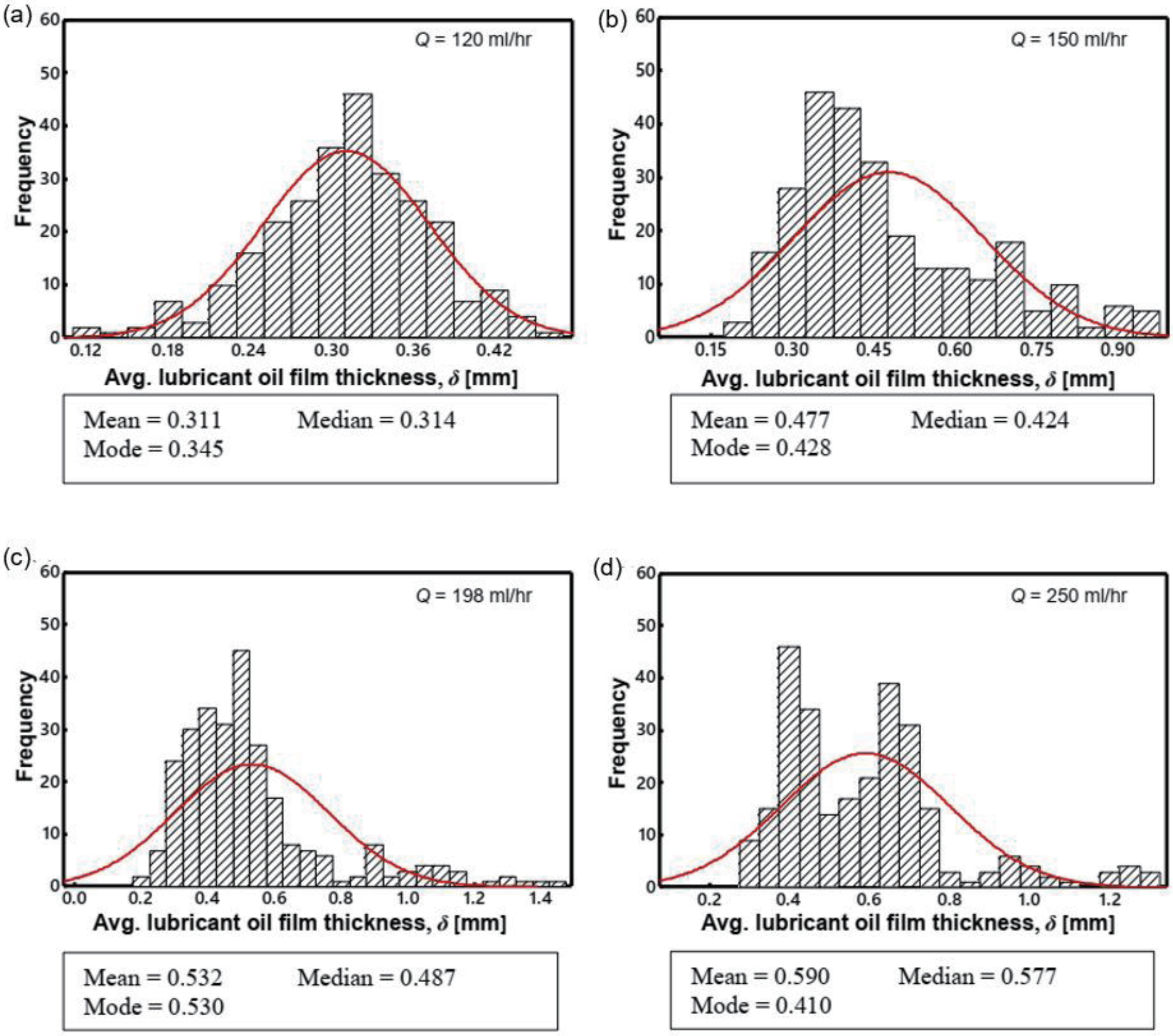

Fig. 8 Histogram of average lubricant oil film thickness for 72 mm - 90 mm distance from milling starting point versus frequency at lubricant oil flow rates of (a) 120 ml/hr, (b) 150 ml/hr, (c) 198 ml/hr and (d) 250 ml/hr

versus distance from milling starting point for lubricant oil flow rates of 120 ml/hr, 150 ml/hr, 198 ml/hr, and 250 ml/hr. At 60 mm and 90 mm from the milling starting point, it is evident that both arithmetic mean roughness value, *Ra* and mean roughness depth value, *Rz* decreased with increasing lubricant oil flow rates. This proves the surface finish of workpiece becomes greater if more lubricant oil was sprayed onto the workpiece, which was also mentioned in the past literature [19]. The effects of thicker lubricant oil film as found in the results explained in Figs. 6, 7 and 8 also successfully confirmed by the trending found in Fig. 9. However, there was a slight increase of arithmetic mean roughness value, *Ra* and mean roughness depth value, *Rz* for results at 30 mm from the milling starting point when the lubricant oil flow rate change from 150 ml/hr to 198 ml/hr. This indicates that at the beginning phase of cutting process, the milling tool probably is still in adjusting mode with the workpiece surface to perform a smooth cutting process. Therefore, the lubricant oil droplets bounced away from the cutting area as the moving cutter generated an aerodynamics barrier reaction. Consequently, this reaction suppressed the infiltration of lubricant oil into the cutting zone [20].

4 Conclusion

To conclude, the average lubricant oil film thickness was found to increase and obviously fluctuate with increasing flow rates, ranging from 0.2 mm to 0.7 mm. A careful observation of the lubricant oil thickness near the location of cutting tool also suggested that the droplets of lubricant oil probably struggle to penetrate the cutting zone due to the sudden falls at that locations. Furthermore, the correlation between the thickness of lubricant oil film to the performance of milling process under

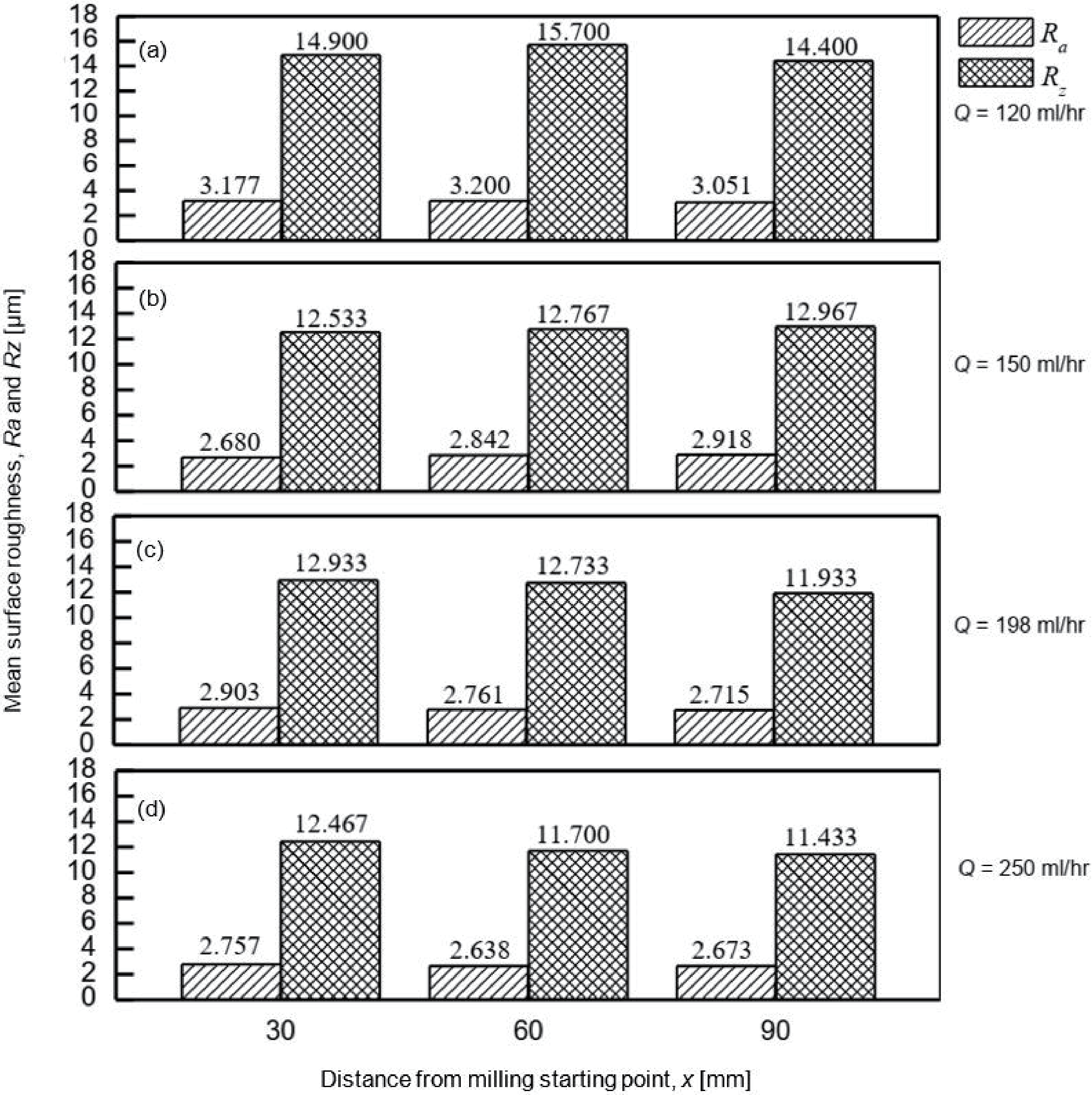

Fig. 9 Average surface roughness versus distance from milling starting point for lubricant oil flow rates of (a) 120 ml/hr, (b) 150 ml/hr, (c) 198 ml/hr and (d) 250 ml/hr

the MQL spraying condition was successfully made since the results trending of the surface roughness of workpiece shows a well agreement with the trending of lubricant oil film thickness.

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