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Experimental Investigation of Minimum Quantity Lubrication in Meso-scale Milling with Varying Tool Diameter

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Abstract. Minimum quantity lubrication (MQL) is a method that uses a very small amount of liquid to reduce friction between cutting tool and work piece during machining. The implementation of MQL machining has become a viable alternative to flood cooling machining and dry machining. The overall performance has been evaluated during meso-scale milling of mild steel using different diameter milling cutters. Experiments have been conducted under two different lubrication condition: dry and MQL with variable cutting parameters. The tool wear and its surface roughness, machined surfaces microstructure and surface roughness were observed for both conditions. It was found from the results that MQL produced better results compared to dry machining. The 0.5 mm tool has been selected as the most optimum tool diameter to be used with the lowest surface roughness as well as the least flank wear generation. For the workpiece, it was observed that the cutting temperature possesses crucial effect on the microstructure and the surface roughness of the machined surface and bigger diameter tool actually resulted in higher surface roughness. The poor conductivity of the cutting tool may be one of reasons behind.

1. Introduction

Minimum quantity lubrication (MQL) has progressively emerged into the area of metal machining and, has already been established as a viable alternative to dry and flood cooling machining. The amount that should be applied in MQL is subjective and depends on the material, process and tools. As a general rule of thumb, MQL uses 5 to 80 ml/hour (0.2 to 2.5 oz./hour) on the tools which has less than 40 mm diameter[1]. Some major advantages of MQL include improved environment, better surface finish, increased tool life, reduced wear and damage at tool tips; reduce health hazards, and overall low costs in various micromachining processes. Machining processes using MQL have been studied for all conventional meso or micro machining processes like micro and meso scale drilling[2],[3] micro milling[4], [5], turning[6],[7] and grinding[8]. Implementing MQL in machining process helps to increase the tool life and produce better surface finish. It is also the best remedy for promoting eco-friendly industry due to reduction in waste. In this paper, the performance of meso-milling under MQL has been studied and compared with the same machining experience under dry condition. There have been numerous studies on micro or meso milling using MQL and dry machining. For example, [9] studied the micro-milling using MQL with varying the cutting parameters and analyzed the tool performance and machined surface condition. The tool performance was analyzed by [5] and it showed that MQL increased the tool life by 100 times compared to dry machining. MQL Assisted Meso-scale milling has been studied by [10] and it was shown how that the use of compressed chilly air and nanofluid MQL is effective for improving surface finish and reducing machining force. However, very limited research article are available where the machining performance has been studied for using different diameters of milling tool. In our work, the diameter of the tool bit has been varied to observe its effect on the overall heat transfer by measuring the machining temperature. The surface condition of the work piece and tool has been investigated after machining with two lubrication methods.

2. Experiments

The experiments were conducted using the MIKROTOOLS Integrated Multi-purpose modelled DT-110. This machine has three travel axes (X, Y, and Z axes) to move the tools with ultra-precision milling capabilities with submicron accuracies. Bluebe MQL system was used with lubricant Accu-Lube LB 2000 (LB-1) which is manufactured from biodegradable ingredients, extracted and blended on the basis of vegetable oils. With its high lubricity and heat transfer properties, it is capable to increase heat dissipation and prolongs tool life. Figure 1(a) and 1(b) shows the milling machine and the lubrication system respectively.

a) b)

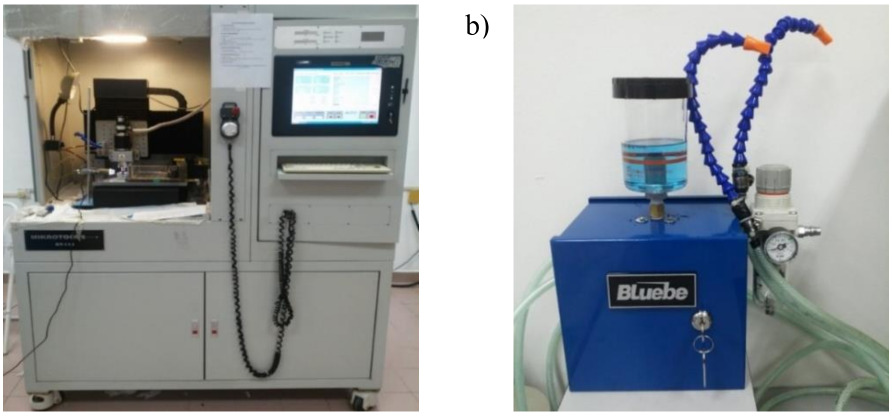


Figure 1. MICROTOOLS Integrated Machine DT-110(a) Bluebe MQL system(b).

The milling tools selected were made of carbide but two different diameters were chosen to observe the effect of cutting tool's increased diameter on the heat transfer during machining. The work piece metal chosen was mild steel for its stable mechanical and chemical properties as well as specific energy for cutting and compatibility with carbide tools. Fluke Ti20 thermal imaging system was employed to measure the machining temperatures at different condition. The other machining parameters are listed in **Table 1**.

Table 1. Machining Condition and parameters.

Parameters	Description
Work piece Material	Mild steel (35mm x 10mm x 10mm)
Cutting tools	Two flute carbide end mill tools (diameter 0.5 mm and 0.8 mm)
Depth of cut	0.15 mm
Machining length	12 mm
Spindle speed	2300 rpm
Feed rate	2 mm/s
Lubrication conditions	Dry and MQL

3. Results and Discussion

The heat generated during micro milling can be divided in two portions; one portion is absorbed by the work metal while the other part is absorbed by the MQL coolant system. Hence, the energy balance equation can be written as Equation 1.0

$$H_{total}=H_{metal}+H_{MQL} \quad (1.0)$$

Where H is the heat energy. H_{total} is the amount of heat dissipated during the machining process.
H_{metal} is the energy absorbed by the metal which can be expressed as =kA[dT/dx]
Here, k=thermal conductivity (w/m°C), A=area,
dT/dx=temperature gradient over the metal thickness
While H_{MQL}=the portion of the heat energy absorbed by the MQL mist=$h_{MQL}A(T_m-T_a)$
Here h_{MQL}=Heat transfer coefficient for the mist created during MQL,
T_m=Metal temperature on the machined surface(°C)
T_a=ambient temperature (°C)
Therefore, (1.0) can be re-written as Equation 2.0

$$H_{total}= kA[dT/dx]+ h_{MQL}A(T_m-T_a) \quad (2.0)$$

As can be seen form the equation, if the heat carried by the metal itself is higher, the MQL cooling becomes less dominant. However, it was observed that the machining temperature was lower when MQL was used in the micro milling on the mild steel since it carried away some of the heat generated during the machining compared with the machining temperature during dry machining. The cutting temperature measured in the present work refers mainly to average chip tool interface temperature, as seen in **Table 2**. It is also seen that the machining temperature was increasing with increase in diameter of the cutting tool. The trend may be attributed to the [dT/dx] term in Equation 2.0, as the diameter was increasing, the heat conduction rate by the cutting tool was dropping.

Table 2. Machining temperature for two different diameter tool with MQL and dry condition.

Cutting Tool Diameter	**MQL condition**		**Dry condition**	
	0.5mm	0.8mm	0.5mm	0.8mm
Cutting Temperature (°C)	26.9	27.9	27.6	29.0

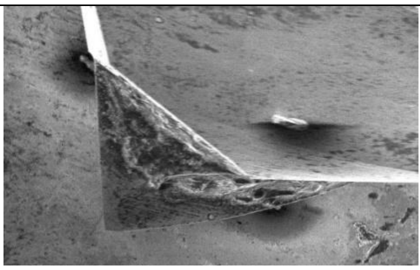
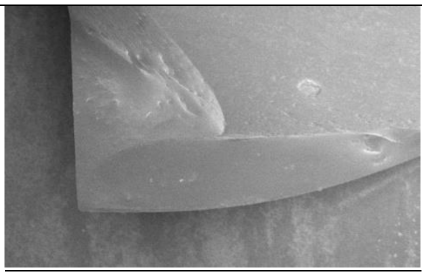
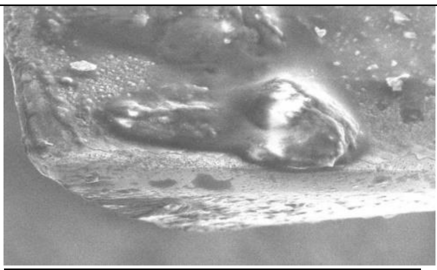
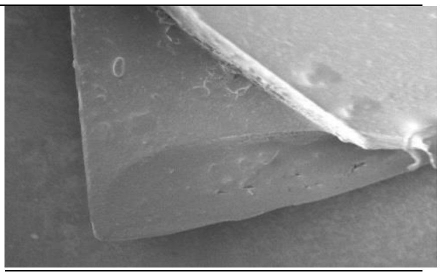
The surface conditions including the microstructure and surface roughness were examined for the cutting tool and work piece.

The tools' surfaces were observed using Field Emission Scanning Electron Microscope (FESEM) and surface roughness tester while Olympus DP26 Microscope and surface roughness tester were used to observed the microstructure of the mild steel

Table 3 shows the condition of the tool after machining. The figures in Table 3 were developed using field emission scanning electron microscope (FESEM) under magnification of 200 and 5kV. The views are generated after micro milling operations on mild steel using the different diameter tools. Under all environment, abrasive scratch marks appeared on the flanks but the most obvious one was observed for the tools that underwent dry machining. Besides, chipping wear was also be identified especially on 0.8mm tool diameter under dry machining. This can be atrributed to the sharp ragged edges and multiple irregular wear pattern along the edge of the tool. This condition may lead to catastrophic failure in the early life of the tool which concealed the failure mode.

The flank wear formed were uniform over localized area and it was accelerated with higher temperature. This condition appear as rough surface mainly on the flank of the tool and to a lesser extent towards the face of the tool. According to the results obtained, the highest temperature generated (29.0 °C) and the most apparent flank wear occur on tool with 0.8mm diameter under dry machining condition.

Table 3. Observation of tool wear for different lubrication condition and tool diameter.

Dry machining	**MQL**
 Tool Diameter: 0.5 mm	 Tool Diameter: 0.5 mm
 Tool Diameter: 0.8 mm	 Tool Diameter: 0.8 mm

The Surface roughness test was done using Veeco WYKO NT1100 optical profiler. The result for both dimeter cutting tools are shown in Figure 2.

It is observed that surface roughness of the cutting tools was higher for dry machining. The highest Ra value obtained was 1.86 for tool diameter 0.8mm at dry machining condition. The trend also shows that with increased diameter, the surface roughness deteriorated regardless of the lubrication method used. The reason may be attributed to the larger torque experienced by the bigger diameter tool. Higher machining temperature may also be one of the reason.

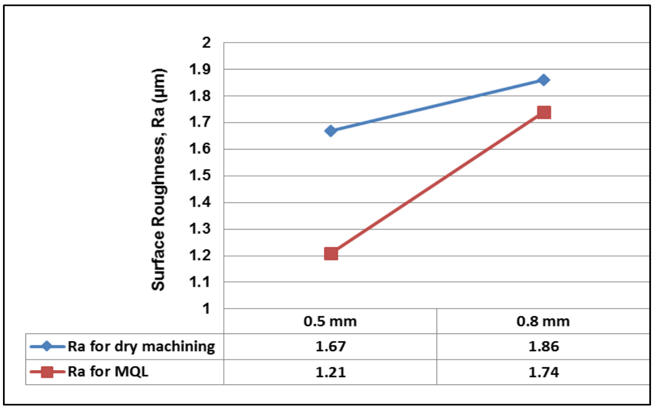


Figure 2. Surface Roughness vs Tool Diameter graph.

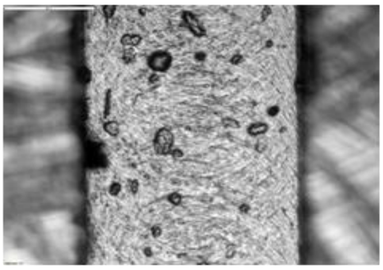
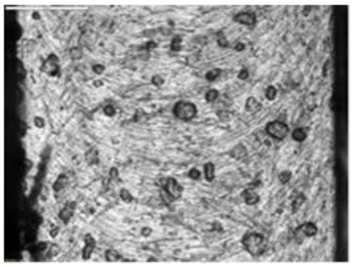
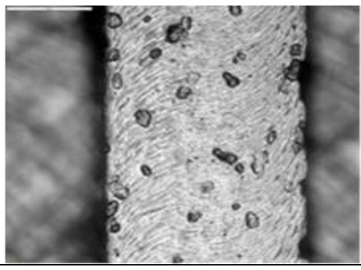
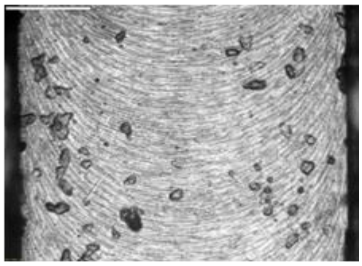
For investigation of the machined work-piece, the surface roughness (R_a) and microstructure of machined surface were examined. It is found that the surface roughness increased linearly with increase in tool diameter. The value of Ra for 0.8mm diameter of cutting tool is the highest for both lubrication conditions while the surface roughness under MQL condition is found to be better than dry machining condition, which are 560.92μm under MQL and 792.79μm under dry machining condition respectively. This proved that the presence of MQL will give better surface roughness due to lower cutting temperature provided by the lubrication that reduce the heat generated while machining process. The results are summarized in Table 4.

Table 4. Surface roughness of machined surface under different lubrication and tool diameter.

Tool Diameter	**MQL condition**		**Dry condition**	
	0.5mm	0.8mm	0.5mm	0.8mm
Surface Roughness of machined surface	461.73	560.96	611.46	792.79

Microstructure captured by the Olympus DP26 Microscope, both for the condition under MQL and Dry machining for using two different diameter tool is displayed in **Table 5**.

Table 5. Microstructure of the machined surface under different lubrication and tool diameter.

Tool Diameter → / **Lubricant condition ↓**	**0.5 mm↓**	**0.8 mm↓**
Dry condition		
MQL condition		

Based on mild steel surface properties, the microstructure of the machined surface is seen to contain ferrite and pearlite structure. As both of ferrite and pearlite, they have very poor hardness. This in turn lead to different physical characteristics (such as variable friction coefficients) causing vibrations to increase and highly fragmented chips to occur. Presence of MQL cannot reduce this chip–tool interface temperature totally because the fluid can hardly penetrate into that the interface where the chip–tool contact is mostly plastic in nature. That is why there are still surface defects like dimples on the machined surface of mild steel, surface dimples do occur as a result of the dual phase structure of the work piece material and always occur at a hard to-soft grain transition. They do not occur when cutting moves across a soft-to-hard grain boundary. The presence of MQL provided at least better dissipation of the heat compared to dry machining and help to move the chips away better that dry machining. The effect of diameter of the tool bit was not a dominating factor for this case.

4. Conclusion

In this study, experimental investigation was carried out to observe the effect of MQL and tool diameter on the machined surface and tool wear. It has been found that the presence of MQL benefits in reducing the cutting temperature, which improves the chip tool interaction and maintain sharpness of the cutting edges. The cutting temperature had a significant effect on the microstructure and the surface roughness on mid steel that is why presence of MQL provided better microstructure and better surface roughness.In terms of tool wear and surface roughness, 0.5mm tool performed better compared to 0.8mm tool with lesser wear under MQL contion.

Acknowledgement

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References

[1] T Walker 2013 *The HANDBOOK A guide to machining with Minimum Quantity Lubrication*. Unist, Inc
[2] A E D Durval, U Bragaa, N L C Gilberto and W A Miranda 2002 *J. Mater. Process. Technol.*, **vol. 122** pp. 127–138
[3] M N Bahar 2016 *Int. J. Eng. Mater. Manuf.* **vol. 1** no. 2 pp 65–70
[4] A Syahmi, A Bin, R Bahar, and T F Ariff 2016 in *Proceedings of 6th International Conference on Industrial Engineering and Operations Management*, pp. 1782–1787
[5] S Kajaria, S Chittipolu, S Adera and W N Hung 2012 *Mach. Sci. Technol.* **vol. 16** no. 4 pp 524–546
[6] V N Gaitonde, S R Karnik, and J P Davim 2012 *Mach. Sci. Technol.* **vol. 16** no. 2 pp. 304–320
[7] M Hadad and B. Sadeghi 2013 *J. Clean. Prod.* **vol. 54** pp. 332–343
[8] M Hadad and B Sadeghi 2012 *Int. J. Mach. Tools Manuf.* **vol. 63** pp. 1–15
[9] V Shaikh, N Boubekri and T W Scharf 2014 *Int. J. Manuf. Eng.* **vol. 2014** pp 1–13
[10]P H Lee, T S Nam, C Li and S W Lee 2010 *Proc. 2010 Int. Conf. Mech. Ind. Manuf. Technol. (MIMT 2010)*, pp. 457–462,