Experimental Study on Minimum Quantity Lubrication in Mechanical Micromachining (AIM-HI)

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Abstract - Mechanical micromachining is a promising technique for making complex microstructures. It is challenging to apply mechanical micromachining in the industry due to the low strength of the micro tools. Therefore, it is not easy to accurately control the product dimension error and to raise the production rate. In this paper, the applications of minimum quantity lubrication (MQL) in micro-milling and micro-grinding are presented. MQL is considered as a green manufacturing technology in metal cutting due to its low impact on the environment and human health. This study compares the tool wear and surface roughness in MQL micromachining to completely dry condition based on experimental investigations. The supply of MQL in vibration-assisted grinding is also studied. It is found that the use of MQL results in longer tool life and better surface roughness in mechanical micromachining.

Keywords - Minimum quantity lubrication; Mechanical micromachining; Tool wear; Surface roughness.

I. INTRODUCTION

Research related to environmentally benign or sustainable manufacturing attracts more and more attention in recent years due to the new environmental regulations and the international treaties about global warming. As a result, the environmental regulations encourage companies to pursue the development of new green products and green manufacturing technologies. Cutting oils are considered to be harmful to human health and the environment due to the hazardous substances contained in them. Therefore, dry cutting is thought as a green technology in machining because of elimination of cutting fluids and the feasibility of dry cutting has been studied for years [1, 2]. However, dry cutting has some unavoidable disadvantages, such as high cutting temperature, short tool life and poor dimension accuracy. Minimum quantity lubrication (MQL) is believed to be a solution to dry cutting for environmentally friendly machining. Minimum quantity lubrication refers to the use of cutting fluids in a very small amount. It is expected that the workpiece surface is near-dry with very little or no cutting oil left on it after machining processes so MQL is also known as near-dry machining (NDM).

Lopez *et. al.* [3] investigated the effects of MQL on tool wear in milling aluminum alloys. In order to study the penetration of the cutting fluid to the cutting zone, the computational fluid dynamics (CFD) simulation was also performed. The results showed that the high-velocity oil mist could be effectively delivered to the cutting zone and offer sufficient cooling and lubricating. Tawakoli *et. al.* [4] applied MQL in grinding hardened 100Cr6 steels and 42CrMo4 soft steels. Lower cutting forces and better surface integrity were obtained by MQL grinding in the experiments. However, in MQL grinding of 42CrMo4 steels, the surface roughness was not as good as that in flood cooling. Silva *et. al.* [5] applied 40 ml/hr of lubricant in cylindrical plunge grinding of ABNT 4340 steels. Experimental results showed that better surface finish was attained with the application of MQL. In addition, the grinding wheel can remain sharp for longer periods before dressing.

Vibration assisted machining is an innovative machining technique in which a small vibration is applied to the cutting tool or the workpiece to achieve better cutting performance [6]. When a frequency vibration more than 16 KHz is superimposed to the cutting tool or the workpiece, it is known as the ultrasonically assisted machining [6]. The imposed of ultrasonic vibrations in grinding was proved to be able to reduce the grinding force and to improve the surface finish [7]. Isobe et. al. [8] accomplished mirror surface grinding for mold steels by superimposing ultrasonic vibrations on the tool. The vibration frequency was up to 60 KHz. The high quality of workpiece roughness Rz of 0.14 μm was obtained by this method.

Jun *et. al.* [9] investigated the effect of cutting fluids on micro-milling. In addition to dry and MQL milling tests, they also studied the wet cutting in micro-end milling by means of applying large drops of the cutting fluid. Lower cutting forces and longer tool life were observed in MQL milling when compared to dry and flood cooling methods.

It is challenging to apply mechanical micromachining to making complex microstructures due to the low strength of the micro tools. As a result, fast tool wear or tool breakage is often encountered. Therefore, it is not easy to enhance the product dimension accuracy and to increase the production rate. The minimum quantity lubrication is an appropriate technique to provide both cooling and lubricating in mechanical micromachining where the oil mist can easily reach the cutting zone [3]. The objective of this research is to study the tool wear and surface quality in the micro-milling, micro-grinding and vibration-assisted grinding.

II. EXPERIMENTAL SETUP

The cutting tests are performed on a desk-top milling machine as shown in Figure 1. The miniature milling machine is composed of 3-axis machining table (consisting of 3 linear stages), a frame, and a spindle (5000-50000 rpm). Different micro-tools are used in micro-milling and micro-grinding experiments. In micro-milling, 2-flute flat end mills with 600 μm in diameter are used. The slotting experiments are performed at 300-μm axial depth of cut while the spindle speeds and feed rates are changed. In micro-grinding, the diamond mounted points are used. The micro-tool also has 600 μm in diameter and the grain size is #200. The abrasive type is diamond. Flat surface grinding experiments are done for further investigation. In vibration-assisted grinding, the diameter of grinding tool is 1.5 mm for better results under the selected vibration conditions. The workpiece material is SKD61 steel in all the cutting tests. Its hardness is HRC38. In vibration-assisted grinding, workpiece holders for providing small amplitude vibrations are designed and fabricated. The operating frequency of the workpiece holder is 11.4 KHz and its corresponding amplitude is 0.9 μm.

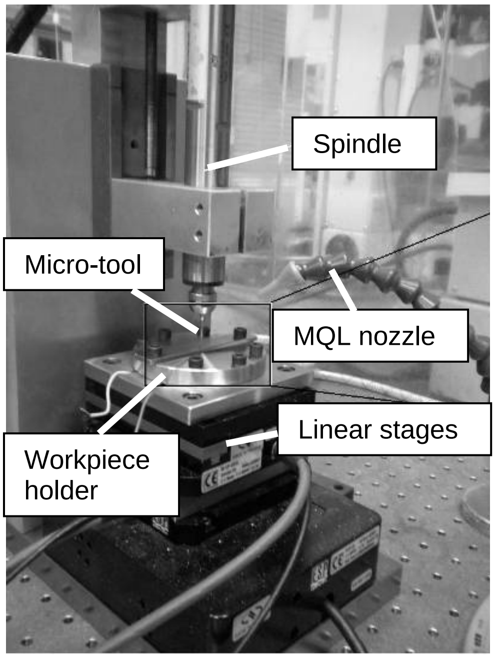

Fig. 1 Experimental setup for cutting tests

The minimum quantity lubrication is provided by a cutting fluid applicator (Bluebe FK type). The Blube system provides the oil mist to the cutting zone with different oil flow rates at a pressure of 0.5 MPa. Bluebe lubricant LB-1 is selected as the cutting fluid.

The same cutting conditions are applied for both dry cutting and MQL machining for comparison. During the experiments, the workpiece surface roughness is measured with a surface roughness tester. A microscope is used to observe the machined workpiece surface and the tool end face.

III. R ESULTS AND DISCUSSIONS

Micro-milling and micro-grinding experiments are carried out to explore the effect of minimum quantity lubrication on surface roughness and tool life. Both dry cutting and MQL cutting are performed for comparison.

A. Micro-milling

In this section, the minimum quantity lubrication is supplied with oil flow rate of 7.5 mL/hr and air flow rate of 40 L/min. The first set of cutting tests is done for both dry and MQL milling with different feeds. The relationship between the surface roughness and tool flank wear is shown in Figure 2. In the experiments, it is observed that the tool life reduces with regard to the decreased feed. This phenomenon is significant in dry cutting. The cutting lengths for the cases of 1.0 μm/rev, 1.5 μm/rev and 2.0 μm/rev feed before the tool breaks are 96, 120 and more than 168 mm respectively. At the end of the cutting tests, tool breakages are observed for the first two cases while the tool flank wear is about 90 μm for the case of 2.0 μm/rev feed. At the same time, the tool wear is insignificant at the end of cutting test with MQL as shown in the figure. Thus it is conclude that the application of MQL in the micro-milling can effectively extend the tool life. For example, the reductions of tool flank wear lengths in MQL cutting compared to dry cutting range from 54.59% to 67.65% under the different feeds after cutting 96mm long work material. It is worth mentioning that in conventional milling processes, the tool life increases with regard to the decreased feeds. The different trend seems to be observed in this study. It should be noticed that the experimental results in this study are based on the amount of cutting lengths, in which the tools at lower feeds are experienced longer cutting time. The other reason for the observed tool wear trend in micro-milling is the extreme low feed in micro-milling process. Under this condition, the nose radius of the cutting tool and the feed are comparable. In micro-milling, tremendous small feed will cause the occurrence of negative effective rake angle which will hinder the chip flow and thus faster tool wear [10].

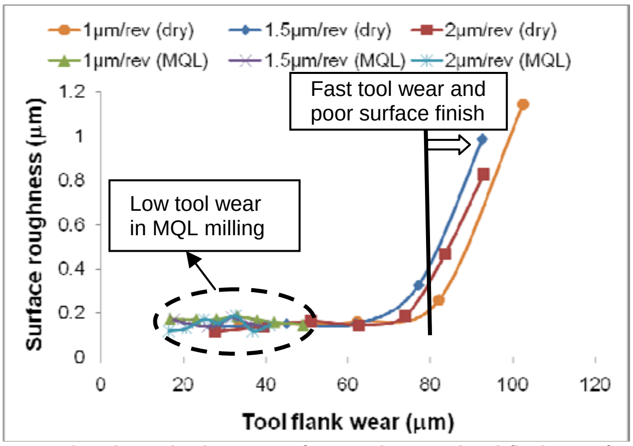

Fig. 2 The relationship beween surface roughness and tool flank wear for different feeds under dry and MQL condisions (spindle speed = 30000 rpm, depth of cut = 300 μm)

The surface roughness is recorded during the milling tests. It is found that in this study the values of surface roughness (R_a) under MQL for different feeds all range between 0.1 and 0.2 μm. On the other hand, in dry cutting, the values of surface roughness are below 0.2 μm before the cutting length reach 48 mm. The surface roughness will suddenly increase to more than 0.8 μm when the cutting length increases. Before the tool breakage, the values of machined surface roughness reaches 1.1 μm, 1.0 μm and 0.8 μm for the feed of 1.0 μm/rev, 1.5 μm/rev and 2.0 μm/rev respectively. It is not easy to track the point of deteriorated surface finish directly from the relationship between the cutting length and cutting conditions in the micro-milling. However, the relationship between the surface roughness and tool flank wear is obvious. From Figure 2, it is known that the values of surface roughness increase quickly when the tool flank wears reach 80 μm. The tools break soon after the tool flank wears are more than 100 μm.

Figure 3 shows the relationship between the surface roughness and the progressive tool flank wear under different spindle speeds for both dry and MQL conditions. The trends are similar to those in Figure 2. In the cutting tests, it is observed that the cutting lengths for MQL milling are more than 168 mm since the tool wears remain low in these slotting tests. For dry micro-milling, the cutting lengths are 96 mm, 96 mm and 72 mm for spindle speed of 20000 rpm, 30000 rpm and 40000 rpm respectively. The experimental results show that the application of MQL can extend the tool life under all cutting speeds. After cutting 96mm long work material, the reductions of tool flank wear lengths in MQL cutting compared to dry cutting are about 68% under all cutting speeds in this paper. It is observed that the data for MQL micro-milling are located on the lower-left part of the figure which means both low tool wear and good surface finish in all cutting tests. Based on the results in Figures 2 and 3, it is recognized that the use of MQL in micro-milling can significantly extend tool life and as a result improve the surface roughness. It is also noted that the control of tool wear is important in micro-milling to prevent tool breakage.

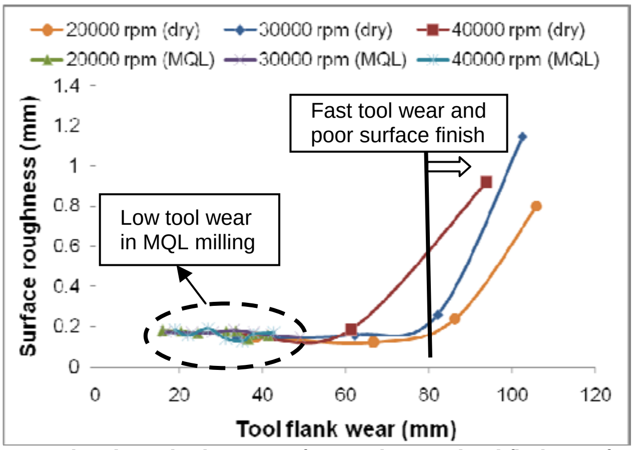

Fig. 3 The relationship beween surface roughness and tool flank wear for different spindle speeds under dry and MQL condisions (feed = 1.0 μm/rev, depth of cut = 300 μm)

B. Micro-grinding

In this section, the minimum quantity lubrication is supplied with oil flow rate of 1.88 mL/hr and air flow rate of 30 L/min. The effect of spindle speeds on the machined surface roughness in dry and MQL grinding is shown in Figure 4. The values of surface roughness are measured along the feed direction. Other cutting conditions are feed of 0.5 μm/rev, depth of cut of 50 μm and cross feed of 20 μm. According to Figure 4, the surface finish is improved when the spindle speed increases from 30000 rpm to 39000 rpm for both dry and MQL grinding. This is similar to the trend in conventional cutting. However, when the cutting speed further increases to 48000 rpm, the surface finish becomes worse. This is due to the fast tool wear caused by high cutting temperature. Since MQL could alleviate the effect of the cutting heat generation, the observed surface roughness is better than that in dry grinding for the spindle speed of 48000 rpm. Moreover, scratches are observed on the ground surface in the selected cutting conditions. Fewer scratches detected in MQL grinding results in a better surface finish in MQL cutting, especially for the spindle speed of 30000 rpm. The results also demonstrate the effective lubrication in MQL micro-grinding. At spindle speed of 30000 rpm, the application of MQL in micro-grinding leads to an improvement of surface roughness from 0.477 μm to 0.148 μm. In the range of 30000 to 48000 rpm spindle speed, the surface roughness for MQL micro-grinding ranges from 0.119 to 0.148 μm, which shows a consistent values of surface roughness in the cutting tests. Similar results are observed for different feeds while other cutting conditions remain the same. The best surface finish is found when the feed is 0.5 μm/rev.

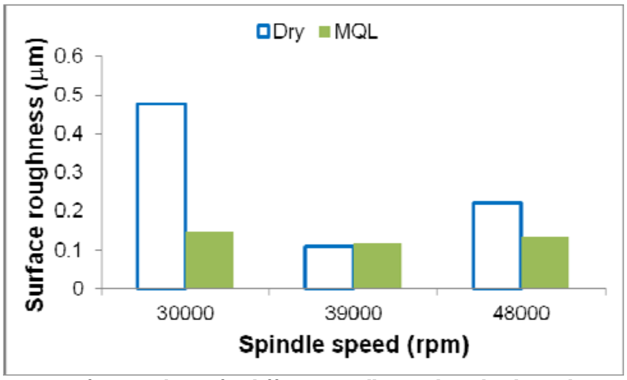

Fig. 4 Surface roughness for different spindle speeds under dry and MQL conditions (feed = 0.5 μm/rev) (fig. 7 in the paper)

The tool wear in micro-grinding is not easy to be studied quantitatively as in micro-milling. The tool lives of micro-tools are compared by the areas of material removed before tool breaks. The surface roughness values are also recorded as reference in the tests. In addition to dry and MQL grinding, micro-grinding with pure air as coolant is also performed for comparison. The results are shown in Figure 5. The MQL micro-grinding shows the longest tool life among the three lubrication conditions. It is noted that the experiments stops when the areas of machined surface reaches 343 mm^2 even though the tool is not broken for saving the time on the experiments. This means that a new micro-tool in MQL grinding can remove more than 343 mm^2-materials before the tool breaks. It is also found in the figure that the surface roughness for MQL are always less than 0.15 μm and better than those for dry and cutting with pure air. For the first three cuts in MQL grinding, the values of surface roughness show a decreasing trend. This could be the result of the slight wear of the micro-tool at the beginning of cutting tests. For dry grinding, a new tool can only remove 98-mm^2 materials before the tool breaks. It is found that the surface finish gets worse as the machined surface area increases. This is caused by the fast tool wear in dry cutting. Burned marks are noticed on the machined surface just before the tool breaks. This is an evidence of high cutting temperature due to the serious tool wear. Some residual chips are found on the tool while not observed in MQL cutting. This is also a cause of worse surface finish in dry grinding. For grinding with the aid of pure air, the maximum area removed by a new tool is 147 mm^2. The cooling effect can extend tool life, although not significant, than that in dry cutting. However, the surface roughness is worse than that in dry cutting. By examining the micro-tool end face, many chips are found. It is indicated that the bad surface finish for grinding with pure air is attributed to the inefficient chip removal. In short, the application of MQL in micro-grinding is a solution to extend the tool life because of the positive effects of lubricating, cooling and chip removal in the micro-scale machining.

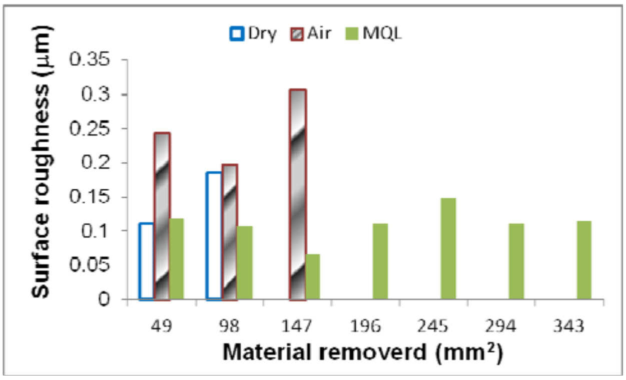

Fig. 5 Surface roughness for dry, air-aided and MQL micro-grinding (spindle speed = 39000 rpm, feed = 0.5 μm/rev and air flow rate = 30 L/min)

C. Vibration-assisted Grinding

For studying the effect of MQL on vibration-assisted grinding, the grinding tool is changed. Its diameter is 1.5 mm while the grain size remains the same, #200. The MQL conditions are the same as those in the previous section, oil flow rate of 1.88 mL/hr and air flow rate of 30 L/min. The depth of cut is reduced to 10 μm. The spindle speed is 35000 rpm and the feed is 1.92 μm/rev. Similar to the previous section, the face grinding tests are carried out on the vibration-assisted grinding system. The workpiece is fixed on the workpiece holder and the small amplitudes of vibrations of 0.9 μm are provided by the piezoelectric actuator in the vertical direction.

Some experiments are done for the comparison between conventional grinding and vibration-assisted grinding. It is shown that the vibration-assisted grinding can achieve high quality surface finish in most cases. For the selected grinding tests, the cutting conditions with the spindle speed of 25000 rpm and the feed of 1.92 μm/rev result in the best surface finish in this study. The surface roughness (R_a) under this process conditions is 0.05 μm and near mirror surface is observed.

However, in order to study the effect the MQL on the tool life in vibration-assisted grinding, the spindle speed is raised to 35000 rpm because the tool wear is not significant for vibration-assisted grinding for lower spindle speeds in this study. The experiments stop when the area of material removed 98 mm^2. The experimental results are shown in Figure 6. The evolvement of the surface roughness for dry grinding and vibration-assisted grinding are similar. The area of material removed for both dry grinding and vibration-assisted grinding are 65.3 mm^2. It is observed from the figure that the application of minimum quantity lubrication in vibration-assisted grinding can effectively extend the tool life. There is not any abrasive particle missing at the end of cutting tests. However, it is also noted in the figure that some of the surface roughness values are higher than that in dry vibration-assisted grinding. By inspecting the end face of the tool, some oil remains on the tool at the end of cutting test with MQL. The excess oil can be an obstacle to the removal of very small chips in grinding. From the experimental results, it is known that the use of minimum quantity lubrication in vibration-assisted grinding can significantly extend the tool life for high spindle speed but inferior surface finish may be observed.

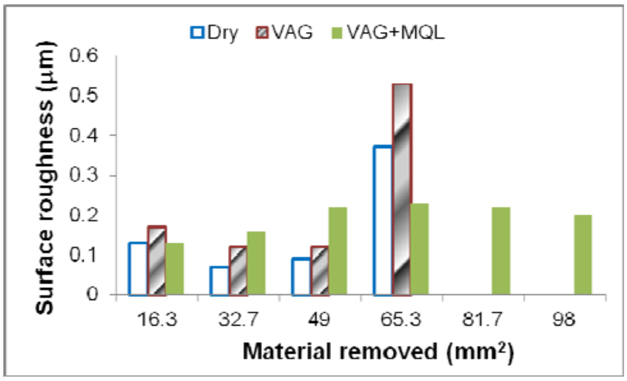

Fig. 6 Surface roughness for dry grinding, vibration-assisted grinding and vibration-assisted grinding with MQL

IV. CONCLUSION

The effects of minimum quantity lubrication on surface finish and tool life in micro-milling, micro-grinding and vibration-assisted grinding are studied. The following conclusions can be drawn based on the experimental results.

For micro-milling, surface roughness deteriorates quickly when the tool flank wears increase to 80 μm and the tools break soon in the following cutting tests for micro-tools of 600 μm-diameter. It is found that the surface roughness is close related to the tool flank wear in micro-milling, regardless of cutting conditions. The employment of MQL in micro-milling can significantly reduce tool wear and as a result improve the surface roughness.

For micro-grinding, the application of MQL in micro-grinding can effectively extend the tool life because of successful lubricating, cooling and chip removal in the micro-scale machining. However, the improvement of surface finish with the aided of MQL is noticed for the spindle speeds of 30000 and 48000 rpm, but not for the spindle speed of 39000 rpm.

For vibration-assisted grinding, it is observed that the utilization of minimum quantity lubrication can significantly prolong the tool life. However, worse surface finish, although not significant, is detected compared to that in dry vibration-assisted grinding.

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