Int J Adv Manuf Technol (2012) 62:99–105
DOI 10.1007/s00170-011-3789-1

ORIGINAL ARTICLE

Study on minimum quantity lubrication in micro-grinding

Kuan-Ming Li · Cheng-Peng Lin

Received: 12 July 2011 / Accepted: 16 November 2011 / Published online: 2 December 2011

Abstract This paper discusses the performance of the minimum quantity lubrication (MQL) in micro-grinding based on ground surface roughness and tool life. The effects of grinding and lubricating parameters on machining performance are studied. Experiments for dry grinding and grinding with pure air are also conducted for comparison. It is observed that surface roughness and tool life are improved with the application of MQL in micro-grinding. Experimental results show that efficient chip removal from the cutting zone in micro-grinding is important for achieving good surface finish and adequate tool life. The application of a small amount of cutting oil in MQL can significantly extend the tool life. In this study, the tool life in MQL is seven times longer than that in dry grinding and five times longer than that in grinding with air cooling. If the oil flow is surplus to requirements or the air flow is inadequate, excess oil will stay on the grinding tool after the grinding test. As a result, poor surface roughness is observed. The optimal lubrication conditions in this experimental exploration are the combination of an oil flow of 1.88 ml/h and an air flow of 25 L/min.

Keywords Minimum quantity lubrication · Surface roughness · Tool life · Micro-grinding

K.-M. Li (✉)
Department of Mechanical Engineering,
National Taiwan University,
Taipei 10617, Taiwan
e-mail: kmli@ntu.edu.tw

C.-P. Lin
Department of Mechanical and Electro-Mechanical Engineering,
National Sun Yat-Sen University,
Kaohsiung 80424, Taiwan

1 Introduction

Grinding is different from other conventional machining processes because of the high negative rake angle of the abrasive grits and the high specific cutting energy. Specific cutting energy in grinding is usually one order higher than that in other machining processes, such as turning and milling [1]. This high specific energy leads to high heat generation and cutting temperatures in the cutting zone. As a result, problems related to high cutting temperatures, such as poor dimension accuracy, damage on the surface integrity, and high wear rate of grinding wheel often occur. Therefore, it is important to introduce sufficient cooling and lubrication in grinding to ensure the workpiece dimensional accuracy and the surface quality.

The functions of cutting fluids in machining processes include cooling, lubrication, and easy chip transportation. As a result, the application of cutting fluids in machining processes can improve the tool life, the product surface finish, and the dimension accuracy. However, chemicals in the cutting fluids have negative impacts on the environment and human health regarding to their use or disposal. The costs related to cutting fluids are also high in machining processes [2]. In order to alleviate the environmental and economical impacts, investigations on minimum quantity lubrication (MQL) was addressed as an alternative method to the conventional flood cooling in mid-1990s [3]. In MQL machining, an air–oil mixture is delivered to the cutting zone instead of a flow of cutting fluid. Aerosols, or small oil droplets, are supplied to the cutting zone providing the required cooling and lubrication as well as chip removal [4]. The influence of cutting speed, feed, and depth of cut on machining performance in terms of cutting force, tool wear, and surface roughness was studied in [5–8]. It was indicated that the machining performance of MQL machining is comparable to that of machining under flood cooling lubrication and better than that of dry machining [5, 7]. In interrupted cutting, MQL was more effective than flood cooling and dry machining [5, 9]. In milling, it was observed that fewer burrs were formed in MQL compared to that in flood cooling and dry machining [6].

Hafenbraedl and Malkin [10] conducted experiments on internal grinding tests of hardened AISI 52100 bearing steels with 12 ml/h ester oil in a flow of air at a pressure of 69 kPa. The experimental results showed that specific cutting energy, surface finish, and G ratio were all improved compared to those under completely dry or flood cooling. However, the thermal distortions of the workpiece for both dry and near-dry grinding were observed. This indicated that the cooling from the MQL was not sufficient in conventional internal grinding. Silva et al. [11] applied 40 ml/h of lubricant in a flowing air stream of 30 m/s when cylindrical plunge grinding of ABNT 4340 steel. Better surface finish and residual distributions were observed with the application of MQL. In addition, no significant clogging of the grinding wheel pores was detected so the grinding wheel can remain sharp for longer periods before dressing. Shen et al. [12] investigated the effects of nanofluids in MQL grinding cast irons. They applied water-based Al_2O_3 and diamond nanofluids in MQL grinding. A higher G ratio, smaller grinding forces, better surface finish, and reduced grinding temperatures were found compared to those in dry grinding. Alves et al. [13] studied the effects of MQL on the roughness and roundness in plunge cylindrical grinding of AISI 52100 steels. Different oil flow rates, 48, 60, and 80 ml/h, were selected as the lubrication parameters. It was found that the surface roughness and roundness were not improved by MQL compared to those in grinding with the conventional cooling method. Moreover, a mixture of oil and chips were observed in the grinding zone. This might be the reason for the increased surface roughness in MQL grinding. Tawakoli et al. [14] applied 66 ml/h of lubricant in a flow of air at a pressure of four bars when grinding hardened 100Cr6 steels and 42CrMo4 soft steels. The experimental results showed that lower grinding forces, reduced friction coefficient, higher material removal rate, and better surface integrity were obtained by MQL grinding. However, better surface finish was observed only in MQL grinding 100Cr6 steels. In MQL grinding of 42CrMo4 steels, the surface roughness was worse than that in flood cooling. Sadaghi et al. [15] investigated the grinding performance with the MQL technique. Different oil flow rates, air pressures, and oil types were applied to surface grinding Ti-6Al-4V as comparison. The results indicated that the MQL grinding could achieve similar or better grinding performance compared to conventional cooling. It was found that MQL grinding with synthetic oil achieved better surface quality and lower grinding forces than vegetable oil.

However, the effectiveness of applying cutting fluids, especially with conventional cooling, in micro-cutting is not clear [16]. Moreover, the plowing effect in micromachining causes significant friction force at the tool–workpiece interface, which leads to fast tool wear and short tool life [17]. An effective cooling and lubricating method is required for high-performance production in micromachining. The MQL technique is a suitable method to provide both cooling and lubricating effects in micro-grinding. With the help of compressed air, the oil mist with high velocity could be effectively delivered to the grinding zones and provide sufficient cooling and lubricating [18]. In addition, the MQL technique is appropriate for micro-scale machine tools with less impact on high-precision electronic components, such as high-speed spindles, linear stages, and high-resolution controllers. The objective of this study is to study the surface roughness and tool life in the micro-grinding process on a meso-scale machine tool. The comparison between MQL and completely dry grinding process is presented. Experiments on the subject of the lubrication parameters, oil flow rate, and air flow rate are also conducted in this study.

2 Experimental setup

In this work, the grinding experiments are carried out on a desktop milling machine. The desktop milling machine is equipped with a high-speed spindle (up to 50,000 rpm) and a three-axis machining table (linear AC motor with 0.6-nm resolution). The grinding system is shown in Fig. 1. The grinding tool is 600 μm in diameter and the grain size is

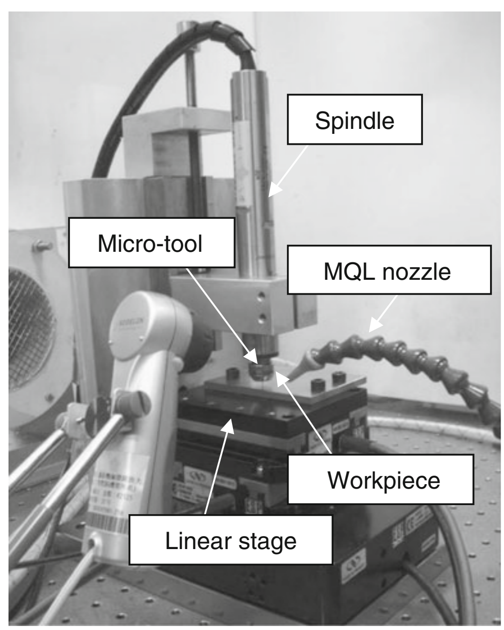


Fig. 1 The experimental setup for micro-grinding

#200. The abrasive type is diamond. The oil mist is supplied by a cutting fluid applicator (Bluebe FK type). The Blube system provides the air–fluid mixture to the grinding zone as the minimum quantity of cutting fluid with an oil flow rate of 1.88 ml/h at a pressure of 0.5 MPa. The nozzle is located at a distance of 30 mm from the tool tip. Its orientation is set at 45° from the horizontal plane and 45° from the direction of feed in the vertical plane. This orientation is found to be most effective in reducing the cutting temperature on the rake face according to the work of Ueda et al. [9]. Bluebe lubricant LB-1, a vegetable oil, is selected as the cutting fluid.

The workpiece material is SK3 with HRC18. The grinding experiments are done on the grinding system at a 50-μm axial depth of cut while three different spindle speeds and four different feed rates are adopted as shown in Table 1. The tool path used to grind a flat workpiece surface is shown in Fig. 2. The same cutting conditions are also applied to dry grinding for comparison.

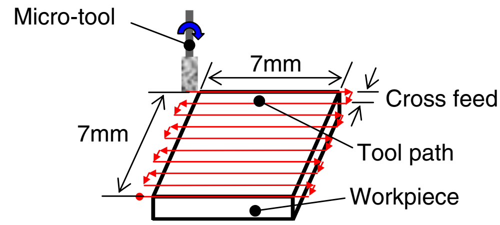


Fig. 2 Schematic of grinding tool path

3 Results and discussions

The effect of MQL on the surface roughness and the tool wear are presented in the following sections. The oil flow rate is 1.88 ml/h and the air flow rate is 30 L/min. The dry grinding tests are also carried out for comparison. The lubricating conditions, different oil flow rate, and air flow rate are also discussed. The best lubricating conditions in this study are presented based on the experimental results and discussions.

3.1 Surface roughness

The tool performance at different feeds is first investigated based on the surface roughness. Figure 3 shows the effect of the feeds on the surface roughness of the machined surface along the feed direction under both dry and MQL conditions. It is observed that the surface roughness obtained for a feed of 0.5 μm/rev is the best for both dry and MQL grinding. In conventional machining, it is known from the cutting theory that the surface roughness will decrease with respect to the reduction of the feed. However, the tool surface roughness in Fig. 3 gets worse even though the feed decreases when the feed is less than 0.5 μm/rev. The results come from the unwanted rubbing of the grinding grits on the workpiece. The evidence is shown in Fig. 4. In the figure, it is seen that there are many scratches on the workpiece surface in addition to the grinding marks. The lubrication effect of MQL under this cutting condition is limited so the values of the surface roughness under a feed of 0.4 μm/rev for dry and MQL grinding are close. On the contrary, the surface roughness is better under a feed of 0.5 μm/rev due to the elimination of scratch marks, as shown in Fig. 5. Nevertheless, scratch marks are observed in dry grinding, but not in MQL grinding, for a feed of 0.6 μm/rev. Consequently, a deteriorated surface roughness is found in dry grinding. It is seen in the figure that the surface roughness increases as the feed increases from 0.5 to 0.6 μm/rev for both dry and MQL grinding.

For grinding conditions of feeds greater than 0.5 μm/rev, the surface roughness gets worse with respect to the increase of the feed. In addition, the surface roughness of the machined surface in MQL is much better than that in dry grinding. The lubricating effect of MQL is one of the reasons to the improved surface finish. The other benefit of MQL is its effectiveness of chip removal from the cutting zone. The chips pile up around the grinding tool in dry grinding while the chips are flushed away in MQL grinding. Figure 6 shows the chips sticking to the tool in dry grinding under the grinding condition of a 0.6-μm feed. This phenomenon is not observed in MQL grinding under all cutting

Table 1 Cutting conditions

Work material	SK3 steels (hardness: HRC18)
Spindle rotational speed	30,000, 39,000, and 48,000 rpm
Cross feed	20 μm
Feed	0.3, 0.4, 0.5, and 0.6 μm/rev,
Depth of cut	50 μm
Cutting fluid	LB-1 (Bluebe lubricant)
Air supply	20, 25, and 30 L/min at 0.5 Mpa
Lubricant supply	1.88 and 0.63 ml/h

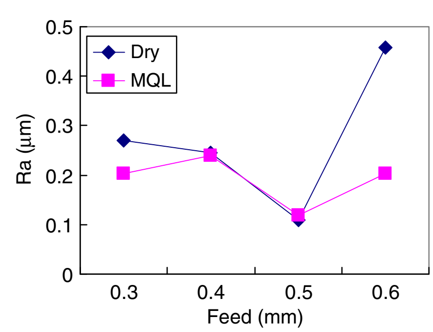


Fig. 3 Surface roughness for different feeds under dry and MQL conditions

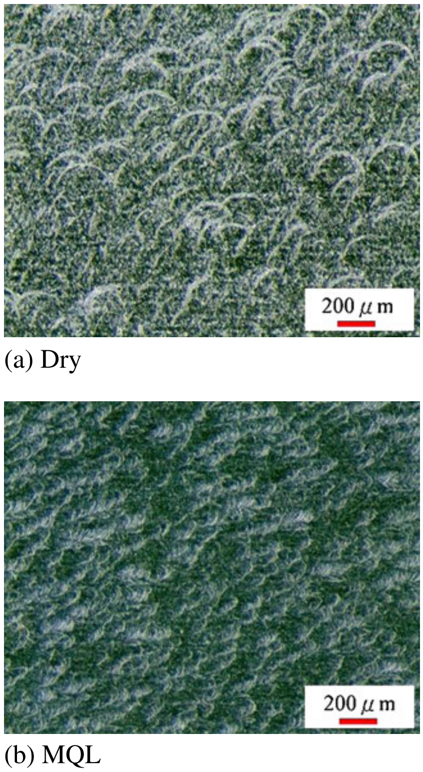


Fig. 4 Photograph of the ground surface (spindle rotational speed= 39,000 rpm and feed=0.4 μm/rev). **a** Dry, **b** MQL

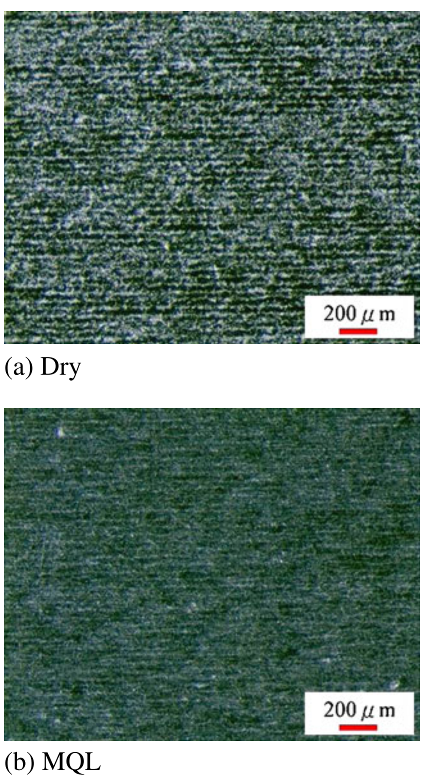


Fig. 5 Photograph of the ground surface (spindle rotational speed= 39,000 rpm and feed=0.5 μm/rev). **a** Dry, **b** MQL

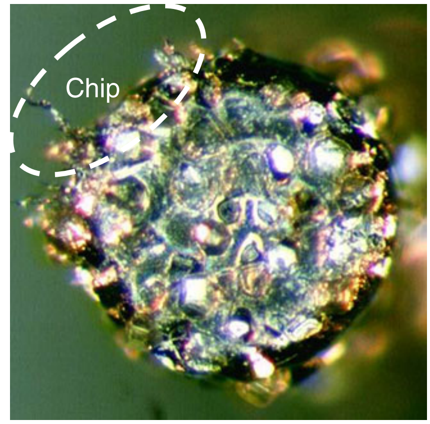


Fig. 6 Photograph of the worn tool (spindle rotational speed= 39,000 rpm and feed=0.6 μm/rev)

conditions. As a result, the surface roughness under dry grinding is much worse than that in MQL grinding. For a feed of 0.6 μm, the surface roughness (R_a) for dry grinding is 0.46 μm while it is 0.20 μm for MQL grinding. In addition, the surface roughness of the machined surface under MQL is not only better than that in dry grinding, but also has stable values in the range of 0.12–0.24 μm under the selected cutting conditions.

Figure 7 shows the effect of the spindle speeds on the surface roughness of the machined surface along the feed direction under both dry and MQL conditions. The surface roughness has the best result in both dry and MQL grinding when the spindle speed is 39,000 rpm. The trend is similar to that in conventional grinding. The surface roughness becomes better when the cutting speed increases. However, if the cutting speed is too high, the tool wears fast due to high cutting temperature and leads to worse surface finish. The scratches are observed in dry and MQL conditions when the spindle speed is 30,000 rpm. However, in MQL grinding, fewer scratches are observed and resulted in a better surface finish. From Figs. 3 and 7, it is observed that the surface roughness in this study is 0.11–0.48 μm for dry grinding and 0.12–0.24 μm for MQL. The application of MQL brings not only a better surface finish, but also a more consistent surface finish under different cutting conditions.

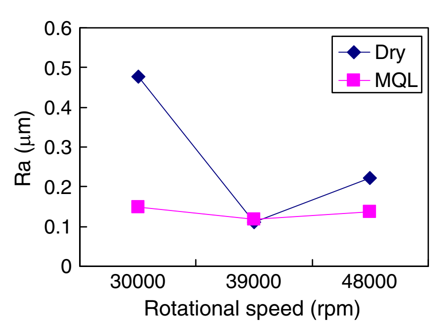


Fig. 7 Surface roughness for different spindle rotational speeds under dry and MQL conditions (feed is 0.5 μm/rev)

3.2 Tool life

It is not easy to quantitatively observe the tool wear in micro-grinding. The tool life tests are conducted in terms of the areas of the material removed before the tool breaks. An example of a broken tool is shown in Fig. 8. To reduce the time of the experiments, the areas of material removed are limited to 343 mm^2, although in some cases, more material can be removed before the tool fails. The tool life tests are performed under the feeds of 0.5 and 0.6 μm/rev while the spindle speed remains at 39,000 rpm and the depth of cut is 50 μm.

For dry grinding, a new tool can finish grinding of 98 and 49 mm^2 for the feeds of 0.5 and 0.6 μm/rev, respectively. At the same time, a new tool can remove more than 343-mm^2 materials without tool break in MQL. This indicates that the use of MQL in micro-grinding can significantly improve the tool life. The machined surface in dry grinding with the feed of 0.5 μm before the tool breaks shows burned marks, which is shown in Fig. 9. The burned marks on the machined surface as a result of high cutting temperature are due to serious tool wear and residual chips on the tool. On the other hand, the machined surfaces in MQL grinding do not show any burned marks under all cutting conditions. The chip stacking on the tool is neither observed in MQL tool life tests. This indicates that the application of MQL presents sufficient lubricating effect, cutting temperature reduction, and efficient chip removal so as to extend the tool life.

3.3 Different oil flow rates

The effect of the oil flow rates on machined surface and tool life are presented in this section. Two different oil flow rates, 0.63 and 1.88 ml/h, are used in the grinding tests with the aid of an air flow of 30 L/min. Dry grinding and grinding with pure air (i.e., without any oil supplied) are also conducted for comparison. Figure 10 shows the relationship among the surface roughness, the oil flow rates, and the amount of area removed. The experimental data of surface roughness for MQL are better than that for dry grinding and grinding with air only. For dry grinding, the surface finish deteriorates relating to the amount of area removed. This is

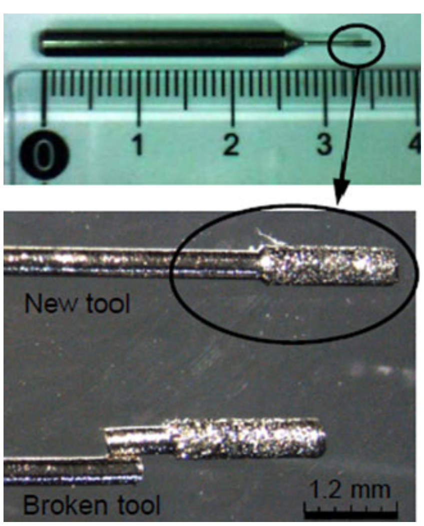
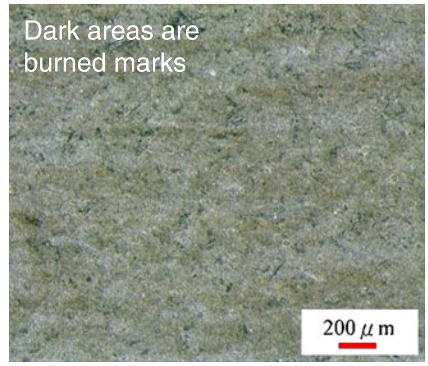
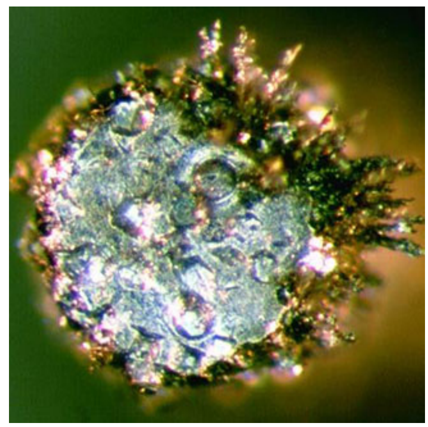


Fig. 8 Photograph of a broken tool



(a) Workpiece



(b) Micro-tool

Fig. 9 Photograph of the machined surface and the micro-tool after grinding 98 mm^2 materials (spindle rotational speed=39,000 rpm and feed=0.6 μm/rev). **a** Workpiece, **b** micro-tool

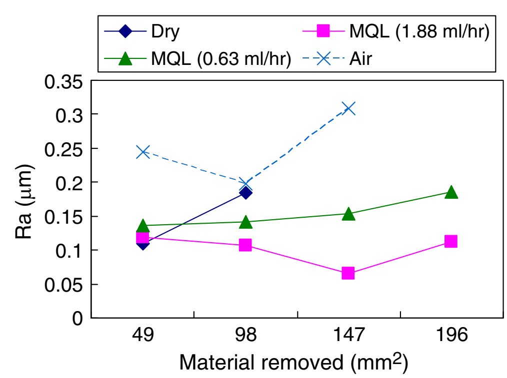


Fig. 10 Surface roughness for different oil flow rates (spindle speed=39,000 rpm, feed=0.5 μm/rev and air flow rate=30 L/min)

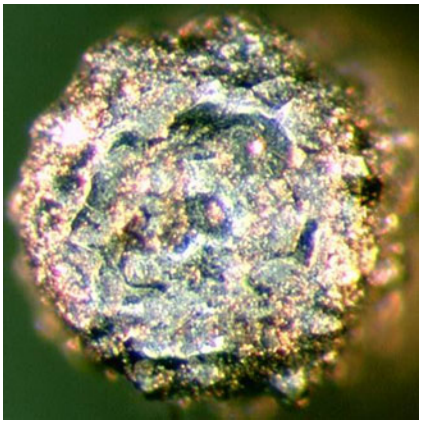


Fig. 11 Photograph of the tool in grinding with pure air after grinding 49-mm^2 materials

due to fast tool wear in dry grinding. In MQL grinding, the surface roughness does not show any trend for an oil flow rate of 1.88 ml/h. The value is between 0.07 and 0.12 μm. For the first three cuts, the surface roughness improvement could be the result of the slight, but not significant, wear of the micro-tool. At the same time, under an oil flow rate of 0.63 ml/h, the surface finish gets worse with respect to the total amount of material removed. The similar behaviors between dry grinding and MQL with 0.63 ml/h indicate that this small amount of oil flow rate is not sufficient for lubrication. For the grinding test with pure air as a lubricating medium, it is observed in Fig. 10 that the surface finish is even worse than that of dry grinding. The poor surface finish under grinding with pure air is attributed to the ineffective chip removal, as shown in Fig. 11. However, the cooling from the air extends the tool life compared with that of dry grinding.

The tool life is affected by the cutting conditions and the lubrication conditions. As shown in Fig. 12, the tool life is reduced when the feed increases from 0.5 to 0.6 μm/rev for grinding without any oil. The tool life tests stop when the machined area reaches 343 mm^2. Therefore, the amount of area removed in MQL grinding for both feeds are more than 343 mm^2. It is also known from the figure that the tool life under MQL grinding is at least three times longer than that in dry grinding. In brief, the recommended minimum oil flow rate for micro-grinding in this study is 1.88 ml/h.

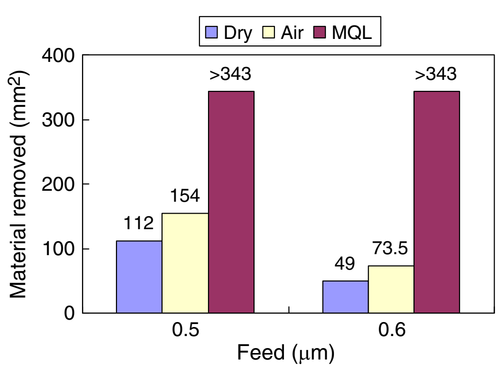


Fig. 12 Tool life for different oil flow rates (spindle speed=39,000 rpm oil flow rate=1.88 ml/h, and air flow rate=30 L/min)

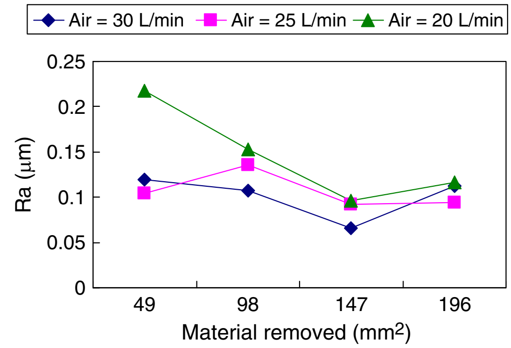


Fig. 13 Surface roughness for different air flow rates (spindle speed=39,000 rpm, feed=0.5 μm/rev and oil flow rate=1.88 ml/h)

3.4 Different air flow rates

The effect of air flow rate on the tool life in MQL grinding is shown in Fig. 13, while the oil flow rate remains at 1.88 ml/h. Among the lubrication conditions, the worst surface roughness is 0.218 μm after removing 49-mm^2 area with an air flow rate of 20 L/min. It is indicated that an air flow rate of 20 L/min is insufficient for MQL. Some oil remains on the grinding tool after the grinding test as shown in Fig. 14. This is contradictory to the concept of the MQL in which no or very little cutting fluid is left on the workpiece or the tool after the grinding test. In addition, the extra oil on the tool is a driving force for the chips to attach to the tool. Therefore, worse surface roughness is observed in the experiments. Moreover, for the same oil flow rate, higher air flow rate generates smaller oil drops in a faster air stream. The faster air stream can penetrate the cutting zone easily

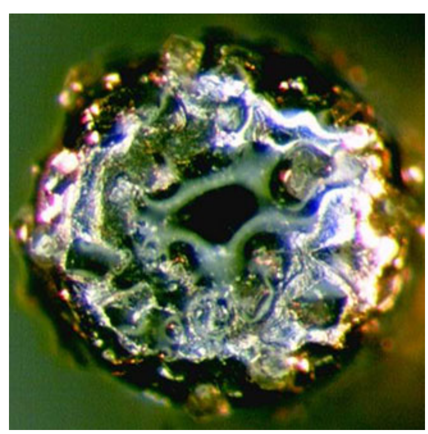


Fig. 14 Photograph of the worn tool with slurry on it (air flow rate=20 L/min)

and take away more heat. The surface roughness under 25 and 30 L/min are comparable and better than that under 20 L/min so the air flow is sufficient for both cases. Nevertheless, in all three cases, the trends of the surface roughness do not show any increasing trends, which means the lubrication is enough compared to dry grinding.

4 Conclusions

The effect of cutting conditions and lubricating parameters on ground surface finish and tool life in MQL micro-grinding SK3 steels are studied. Micro diamond tools with a 600-μm diameter and a grain size of #200 are used to grind flat surfaces on steels.

Experimental results show that the surface roughness is improved with the help of MQL. The values of surface roughness under MQL do not alter much with respect to the feeds or cutting speeds. Very few scratches are observed on the ground surface in grinding under MQL when the feed is higher than or equal to 0.5 μm/rev. On the other hand, scratches on the ground surface are seen under all cutting conditions in dry grinding in this study. Thus, the application of MQL can lead to better surface finish. In addition, when the feed is low (less than or equal to 4 μm/rev), the lubricating effect of MQL is limited. Moreover, chip removal from the cutting zone by MQL also helps to improve the ground surface finish. When pure air is supplied to the cutting zone, chip accumulates on the grinding tool. As a result, a worse surface finish compared to that in dry grinding is observed.

Compared with the grinding tests in dry grinding and grinding with pure air cooling, the use of MQL in micro-grinding can successfully extend the tool life. In this investigation, the tool life in MQL can be seven times longer than that in dry grinding and five times longer than that in grinding with air cooling. Comparing the tool conditions in dry grinding and grinding with pure air, the tool lives are close. This indicates that air cooling is ineffective in micro-grinding. Therefore, the small amount of cutting fluid in micro-grinding is necessary for long tool life. No burned marks are detected on the ground surface in MQL. This also verifies the effectiveness of MQL for tool wear reduction and surface integrity improvement.

However, inadequate combination of oil flow and air flow for MQL will have negative impact on the surface roughness and the tool life. If the air flow is insufficient or the oil flow is too much, excess oil remains on the grinding tool. Consequently, poor surface roughness is noticed due to unsatisfactory chip transportation. Based on this study, the recommended MQL parameters in micro-grinding are the combination of an oil flow of 1.88 ml/h and an air flow of 25 L/min.

Acknowledgments The authors would like to express their appreciation to National Science Council in Taiwan for their financial support of this research.

References

1. Boothroyd G, Knight WA (1989) Fundamentals of machining and machine tools, 2nd edn. M. Dekker, New York
2. Weinert K, Inasaki I, Sutherland JW, Wakabayashi T (2004) Dry machining and minimum quantity lubrication. Ann CIRP 53 (2):511–537
3. Klocke F, Eisenblaetter G (1997) Dry cutting. Ann CIRP 46 (2):519–526
4. Brockhoff T, Walter A (1998) Fluid minimization in cutting and grinding. Abrasives 38–42
5. Wang ZG, Rahman M, Wong YS, Neo KS, Sun J, Tan CH, Onozuka H (2009) Study on orthogonal turning of titanium alloys with different coolant supply strategies. Int J Adv Manuf Technol 42(7–8):621–632
6. Rahman M, Kumar AS, Salam MU (2001) Evaluation of minimal quantities of lubricant in end milling. Int J Adv Manuf Technol 18 (4):235–241
7. Li K-M, Liang SY (2007) Performance profiling of minimum quantity lubrication in machining. Int J Adv Manuf Technol 35 (3–4):226–233
8. Thakur DG, Ramamoorthy B, Vijayaraghavan L (2010) Investigation and optimization of lubrication parameters in high speed turning of superalloy Inconel 718. Int J Adv Manuf Technol 50 (5–8):471–478
9. Ueda T, Hosokawa A, Yamada K (2006) Effect of oil mist on tool temperature in cutting. J Manuf Sci Eng, Trans ASME 128 (1):130–135
10. Hafenbraedl D, Malkin S (2000) Environmentally conscious minimum quantity lubrication (MQL) for internal cylindrical grinding. NAMRC XXVIII, Lexington, Kuntucky
11. Silva LR, Bianchi EC, Fusse RY, Catai RE, Franca TV, Aguiar PR (2007) Analysis of surface integrity for minimum quantity lubricant-MQL in grinding. Int J Mach Tool Manuf 47(2):412–418
12. Shen B, Shih AJ, Tung SC (2008) Application of nanofluids in minimum quantity lubrication grinding. Tribol Trans 51(6):730–737
13. Alves JAC, Fernandes UB, Silva Junior CE, Bianchi EC, Aguiar PR, Silva EJ (2009) Application of the minimum quantity lubrication (MQL) technique in the plunge cylindrical grinding operation. J Braz Soc Mech Sci Eng 31(1):1–4
14. Tawakoli T, Hadad MJ, Sadeghi MH, Daneshi A, Stockert S, Rasifard A (2009) An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication-MQL grinding. Int J Mach Tool Manuf 49(12–13):924–932
15. Sadeghi MH, Haddad MJ, Tawakoli T, Emami M (2009) Minimal quantity lubrication-MQL in grinding of Ti-6Al-4V titanium alloy. Int J Adv Manuf Technol 44(5–6):487–500
16. Friedrich CR (2000) Near-cryogenic machining of polymethyl methacrylate for micromilling tool development. Mater Manuf Process 15(5):667–678
17. Jun MBG, Joshi SS, DeVor RE, Kapoor SG (2008) An experimental evaluation of an atomization-based cutting fluid application system for micromachining. J Manuf Sci Eng, Trans ASME 130 (3):0311181–0311188
18. Lopez de Lacalle LN, Angulo C, Lamikiz A, Sanchez JA (2006) Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. J Mater Process Technol 172 (1):11–15