INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 15, No. 11, pp. 2443-2451 NOVEMBER 2014 / 2443
DOI: 10.1007/s12541-014-0612-6

The Effects of Minimum Quantity Lubrication (MQL) on Machining Force, Temperature, and Residual Stress

Xia Ji[1,#], Beizhi Li[1], Xueping Zhang[2], and Steven Y. Liang[3]

1 School of Mechanical Engineering, Donghua University, Shanghai, 201620, China
2 School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
3 George W. Woodruff School of Mechanical Engineering, George Institute of Technology, Atlanta, GA 30332-0405, USA
Corresponding Author / E-mail: jixia0206@163.com, TEL: +86-021-6779-2564, FAX: +86-021-6779-2439

KEYWORDS: Cutting force, Cutting temperature, Residual stress, Minimum Quantity Lubrication (MQL)

Minimum quantity lubrication (MQL) machining has achieved noticeable attention in both academic and industry research areas due to its minimum costs and maximum environmental protection. This paper focuses on the analysis of the effects of MQL parameters such as the flow rate of lubricant and the air-oil mixture ratio on cutting performances in terms of cutting force, cutting temperature, and residual stress. Additionally, the cutting performances in MQL machining are also compared with the dry and flood cooling machining. The results show that the cutting fluid can considerably reduce the cutting force and cutting temperature in machining. For MQL machining, there is a maximum effective flow rate of lubricant and it is influenced by the cutting speed. When the flow rate of lubricant is beyond the maximum effective value, the air-oil mixture ratio will no longer affect the cutting performances in machining. This research can support the process planning in achieving the desired residual stress profile by strategically adjusting the MQL parameters.

Manuscript received: May 4, 2014 / Revised: July 14, 2014 / Accepted: July 15, 2014

NOMENCLATURE

f = feed rate
F_c = cutting force
F_t = thrust force

1. Introduction

Reducing the production costs and improving the product quality are the effective ways to strengthen the competitiveness of enterprises. This need gave birth to a new technology called minimum quantity lubrication (MQL). MQL machining refers to the use of a small amount of cutting fluid, and has achieved noticeable attention in academic and industry research areas. This is because the usage of minimal quantities of fluid in MQL machining can definitely reduce the cost of using cutting fluids and the auxiliary equipment.[1,2] In addition, the available researches indicate that under certain experimental conditions, the MQL machining has better performances than dry machining, and is comparable to the conventional flood cooling machining.[2-5] Therefore, the implementation of MQL machining as a viable alternative to traditional flood cooling machining is an important research area.

A large number of studies have appeared in the literature to investigate the effects of MQL on cutting performances in terms of the cutting force,[6-8] cutting temperature,[9-12] tool wear,[6,13] dimensional accuracy,[9,14] and surface finish of machined components[1,14,15] in various machining processes, such as turning,[2,7,9] milling,[3,16] drilling,[17] and grinding.[4,18-20] As for the cutting force, experimental results show that there is a considerable reduction in cutting force components for the MQL technique as compared to dry cutting and flood cooling machining.[21] But for MQL machining, the cutting forces decrease with the increase of lubricant within a certain range, and beyond this range the reduction is no longer significant.[22] Compared with dry machining, MQL enables substantial reduction in cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges.[9] But comparing with flood cooling machining, the cooling effect of MQL in grinding is not as good as lubrication effect.[18] In addition, the experimental results show that MQL can significantly extend the tool life compared to dry condition.[4] The results of turning AISI 1040 steel show that the application of MQL improves the dimensional accuracy due to the reduction of wear and damage at the tool tip.[9] Surface roughness obtained in MQL is comparable to that of flood cooling, while it is better than that of dry cutting.[21] The superficial residual stresses of the machined components under different lubrication conditions are analyzed by experimental results in turning of AISI 52100. Results show that the tool nose radius and feed rate are the most influencing parameters on both maximum and minimum principal stresses, while the lubrication is the least important factor.[23] A predictive model of residual stress in MQL machining is developed by the analytical method, and the effects of MQL on cutting force, cutting temperature, and residual stress are analyzed based on the analytical predictive model.[24,25]

It is worth noting that while a large number of articles have appeared regarding the effects of lubrication condition on machinability characteristics such as cutting force, cutting temperature, tool wear, and the surface finish of the machined components, only a few articles have been published on the analysis of residual stress in MQL machining, even though the surface residual stresses on the final part is critical to the function behavior of the workpiece. What is more, the existing researches of residual stress in MQL machining mainly focus on the effects of cutting parameter and tool geometry on the cutting performances, few of them investigate the effects of MQL parameters. Therefore, more investigations on how machining-induced residual stresses vary with MQL could supply an effective way to control the quality of machined components through MQL.

This paper presents an experimental investigation of cutting force, cutting temperature, and residual stresses in MQL machining. Unlike the previous research, this paper focuses on the analysis of the MQL parameters such as flow rate of lubricant and air-oil mixture ratio, but not the cutting parameters and tool geometry. Additionally, the cutting performances in MQL machining are also compared with dry machining and the flood cooling machining.

2. Experimental Procedure

2.1 Cutting condition

Experiments were carried out by orthogonal turning a tube of AISI 4130 alloy steel with 63.5 mm outside diameter and 4.775 mm thickness in a Hardinge T42SP CNC turning center. Before starting the tests all the workpieces, coming from the same batch, were stress relieved in order to eliminate all the residual stresses induced in the material by previous production processes. During the experiment, the workpiece was held by a three-jaw chuck as shown in Fig. 1. The carbide tool insert (N123K2-0600-0004-CR 1125, SANDVIK) with PVD coating was mounted on a standard SANDVIK LC123K08-2525CM tool holder, which resulted in the 5^0 rake angle and 11^0 clearance angle. The tool edge radius is about 40 mm which is supplied by the tool supplier.

To evaluate the cutting performances under different cutting conditions, representative levels of cutting parameters are selected based on the results of sensitivity analysis of the cutting performance. The selected cutting parameters were as follows: the cutting speed with 1.049 m/s, 2.098 m/s, and 3.147 m/s; the feed rate with 0.0508 mm/rev, 0.1016 mm/rev, and 0.1524 mm/rev; the width of cut is a constant with 4.775 mm.

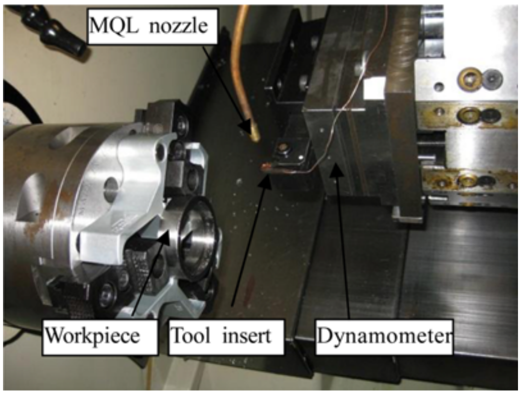


Fig. 1 Experimental setup

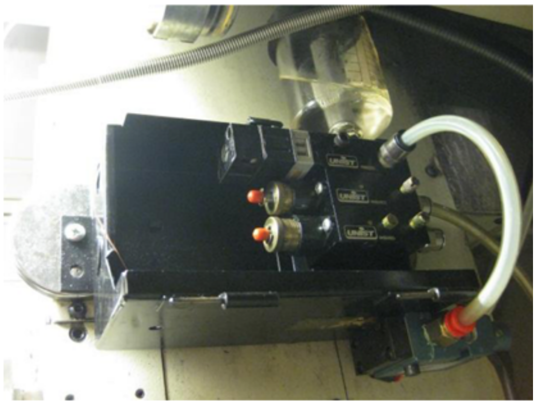


Fig. 2 MQL supply system

For MQL machining, the air-oil mixture was supplied by a UNIST system at a pressure of 40 psi. Coolube 2210, a vegetable oil, was chosen as the cutting fluid. The position and the angle of the MQL nozzle were adjusted by experimental observation to avoid being blocked by chips, as shown in Fig. 2. Different flow rates of lubricant and three different air-oil mixture ratios were selected to investigate the effects of MQL parameters on the cutting performances. The fluid utilized for flood cooling machining was an emulsion of water and oil (Coolube 2210) ejected on the wokrpiece with a flow rate of 2.5 l/min.

2.2 Measurement system

The cutting performances in terms of the cutting force, cutting temperature, and residual stress under different cutting conditions were measured. The cutting forces were measured by a tool-post dynamometer (Kistler 9257B), as shown in Fig. 1. The cutting temperatures in machining process were measured by thermocouple and thermal camera. The thermocouple is located underneath the tool insert with a distance of 4.3mm from the tool tip. It was covered by thermal conductive composite as indicated in Fig. 3. The thermal camera (Flir SC6000) was fixed in front of the lathe, as shown in Fig. 4. For safety considerations, the glass door of the lathe must be kept closed during the flood cooling machining, while the infrared light cannot go through the glass door of the lathe. Therefore, during the actual experiment process, the thermal camera only recorded the

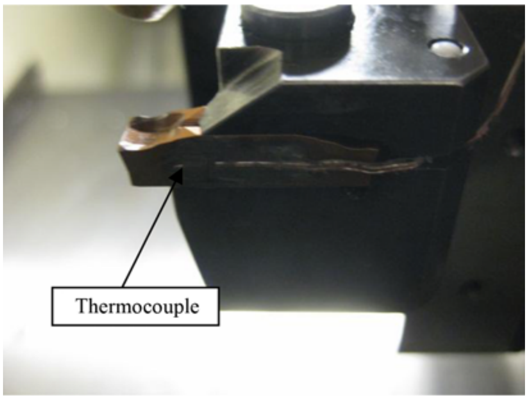


Fig. 3 Position of thermocouple

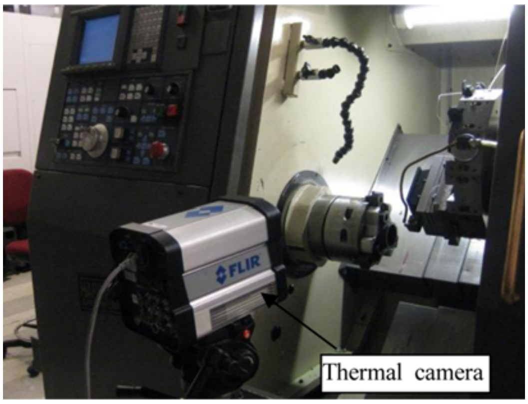


Fig. 4 Location of thermal camera

temperature history under dry and MQL machining.

The residual stresses are measured by the X-ray diffractometer (ProtoLXR type). In order to obtain the residual stress distribution along the depth into the workpiece, several points are subjected to different degrees of corrosion by different etching times. The corrosive depth of each point is measured by optical profilometer. The schematic of residual stress measurement for the workpiece is shown in Fig. 5.

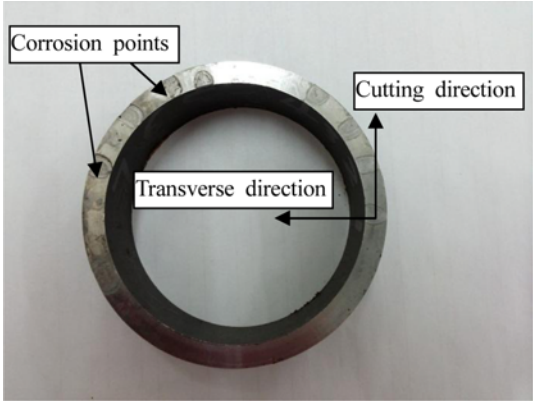


Fig. 5 The schematic of residual stress measurement

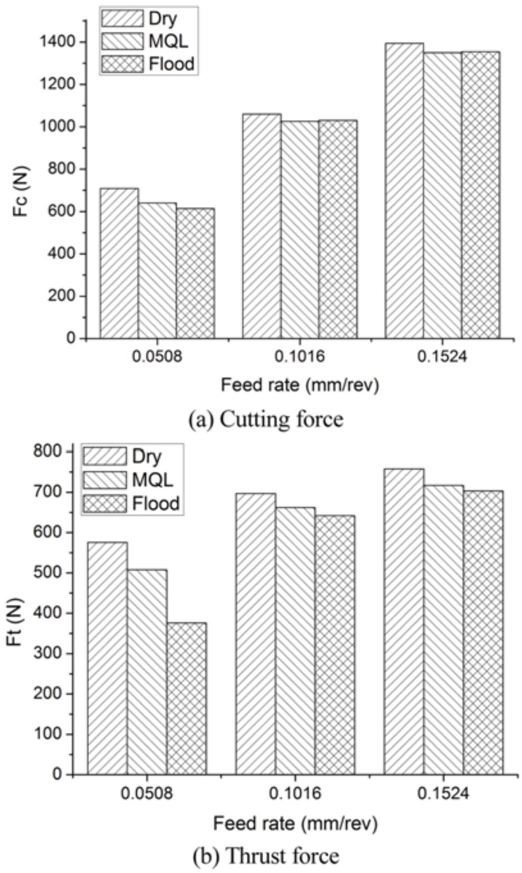


Fig. 6 Comparisons of cutting force in dry, MQL, and flood cooling machining

3. Experimental Results and Discussion

3.1 Cutting force

In order to explore the effects of lubrication conditions in the machining process, keep the cutting parameters invariant, the measured cutting forces under dry, MQL, and flood conditions are compared as shown in Fig. 6. In this analysis, the cutting speed is 3.147 m/s, the flow rate of lubricant is 48 ml/h, the width of cut is 4.775 mm, and the air-oil mixture ratio is medium quantity. From the comparison results, it is found that the cutting force in dry machining is the largest among three different lubrication conditions. The cutting force in MQL machining is slightly larger than the flood cooling machining under lower feed rate condition. But in general, there is no significant difference in the cutting force between MQL and flood cooling machining. The results in Fig. 6 also show that, no matter which lubrication condition is applied, the cutting forces increase in magnitude with the increase of feed rate. This is because when the feed rate increases, the cut area increases, so the cutting forces will increase in magnitude as well.

In actual experiments, the MQL parameters include the flow rate of lubricant, the air pressure, the air-oil mixture ratio, the diameter and the position of the MQL nozzle, etc. In this analysis, the flow rate of lubricant and the air-oil mixture ratio are changed to investigate the effects of MQL parameters on cutting forces. First, the measured cutting forces under different flow rates of lubricant are shown in Fig. 7 and Fig. 8. In this analysis, the width of cut is 4.775 mm, and the air-

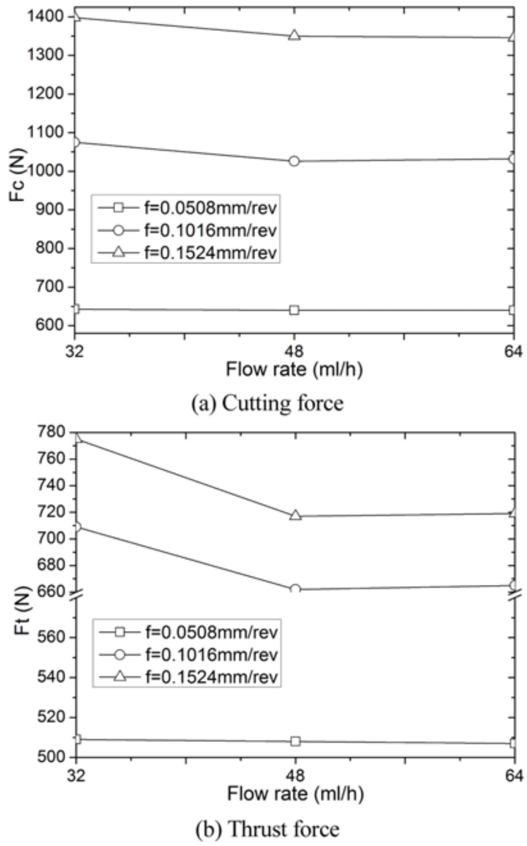


Fig. 7 Relationship between cutting force and flow rate of lubricant (Cutting speed = 3.147 m/s)

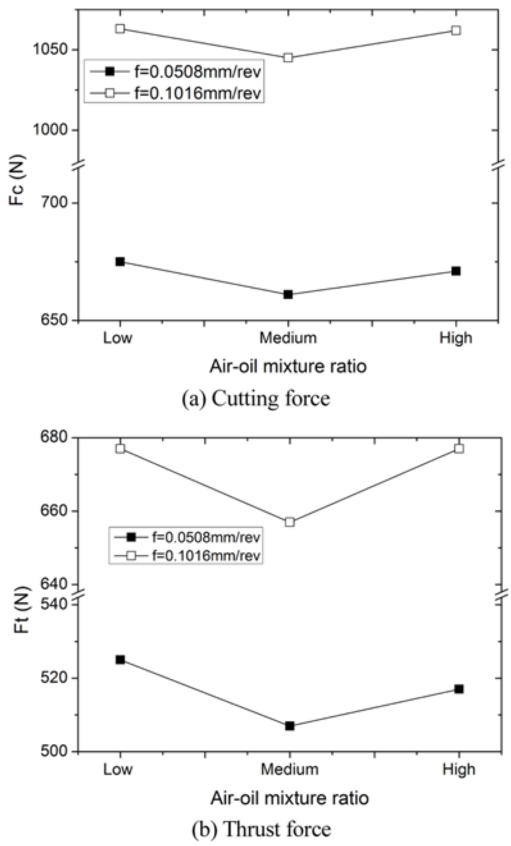


Fig. 9 Relationship between cutting force and air-oil mixture ratio (Cutting speed = 2.098 m/s, flow rate of lubricant = 16 ml/h)

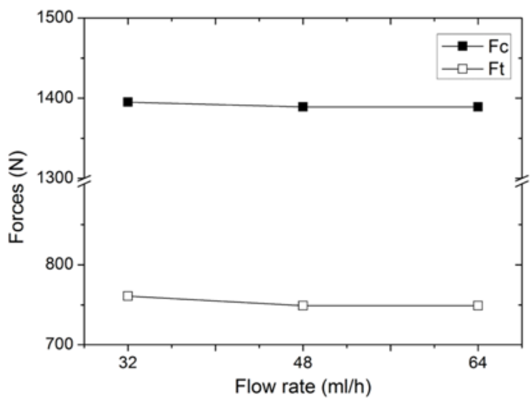


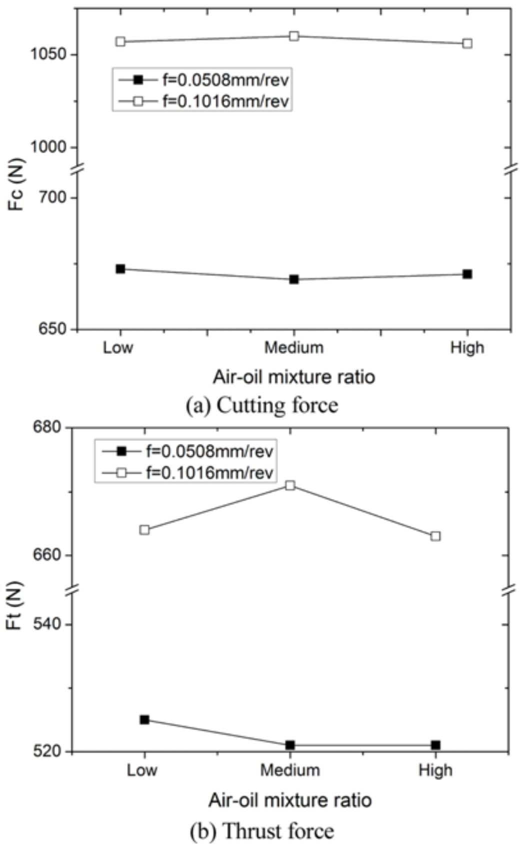
Fig. 8 Relationship between cutting force and flow rate of lubricant (Cutting speed = 1.049 m/s, feed rate = 0.1524 mm/rev)

oil mixture ratio is medium quantity. Three feed rates and two cutting speeds are chosen. From the experimental results shown in Fig. 7 and Fig. 8, it is found that the cutting force decreases in magnitude with the increase of flow rate at first. When the flow rate attains a certain magnitude, the cutting force no longer changes. This is because the boundary lubrication model exists in MQL machining. Under boundary lubrication condition, the lubrication effect is not only depended on amount of lubricant, but also determined by the property of lubricant, the material property of the workpiece and the tool, the surface finish of the workpiece, etc. The maximum effective amount of lubricant is to fill the peak and valley of tool-workpiece contact area. The experimental results are consist with the conclusion of Zhang.[26]

From the comparisons between Fig. 7 and Fig. 8, it is found that when the cutting speed is 3.147 m/s, the maximum effective flow rate of lubricant is 48 ml/h. While the cutting speed is 1.049 m/s, the maximum effective flow rate of lubricant is about 32 ml/h. From the comparisons between Fig. 7 and Fig. 8, it is found that for the experimental value explored, the maximum effective flow rate of lubricant is slightly influenced by the cutting speed, but not by the feed rate.

In order to investigate the relationship between the air-oil mixture ratio and the cutting force, three different air-oil mixture ratios and two feed rates are selected. The measured cutting forces under different air-oil mixture ratios are shown in Fig. 9 and Fig. 10. Results in Fig. 9 show that under low flow rate condition, a low quantity or high quantity air-oil mixture ratio is not beneficial to reduce the cutting force in MQL machining. From the results in Fig. 10, it is found that when the flow rate of lubricant is 48 ml/h, the relationship between the cutting force and air-oil mixture ratio is not clear.

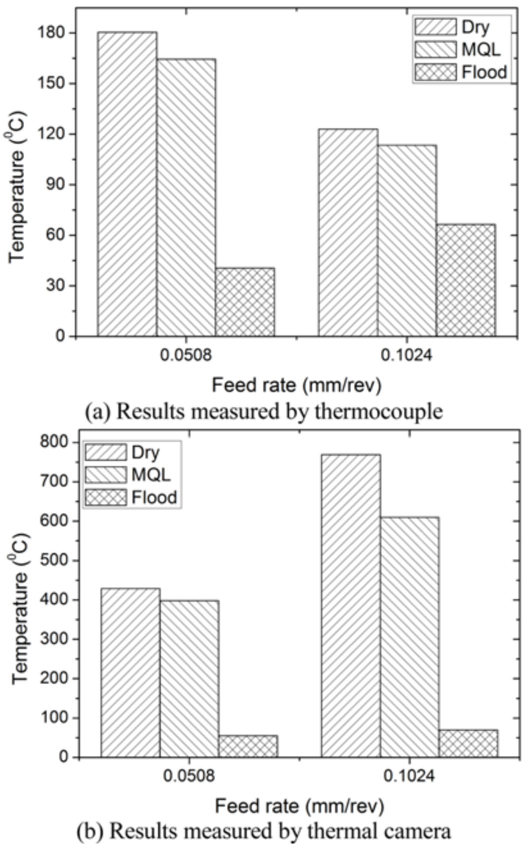
From the comparisons between Fig. 9 and Fig. 10, it is found that the when the flow rate of lubricant is 48 ml/h, the air-oil mixture ratio has minimal effect on the cutting force. This is because when the flow rate of lubricant is beyond the maximum effective magnitude, no matter how the air-oil mixture ratio changes, the effective amount of lubricant permeated into the cutting zone will not change. Therefore, for the values explored, when the flow rate of lubricant is beyond 48



(a) Cutting force

(b) Thrust force

Fig. 10 Relationship between cutting force and air-oil mixture ratio (Cutting speed = 2.098 m/s, flow rate of lubricant = 48 ml/h)



(a) Results measured by thermocouple

(b) Results measured by thermal camera

Fig. 11 Comparisons of cutting temperature under dry, MQL, and flood condition

ml/h, the cutting force will not be significantly affected by the air-oil mixture ratio.

According to the analysis, the flow rate in Fig. 9 is not beyond the maximum effective value. Therefore, the cutting force will be influenced by the air-oil mixture ratio. When the air-oil mixture ratio is too low, the amount of lubricant passed through the cutting zone in the unit time is larger than the air, and the lubrication effect is more effective than the cooling effect. When the air-oil mixture ratio is too high, the volume of air in the unit time is larger than the lubricant, and the cooling effect is more effective than the lubrication effect. While the air-oil mixture ratio is medium, the lubrication effect and the cooling effect can reach a balance. Therefore, the cutting force is lowest under medium air-oil mixture ratio.

3.2 Cutting temperature

The cutting temperatures measured by thermocouple and thermal camera under dry, MQL, and flood cooling machining are shown in Fig. 11. In this analysis, the cutting speed is 2.098 m/s, the flow rate of lubricant in MQL is 16 ml/h, and the air-oil mixture ratio is medium quantity. Results indicate whether by thermocouple or by thermal camera, the flood cooling machining gets the lowest cutting temperature among the three lubrication conditions. Compared to the results measured by thermocouple and by thermal camera, it is found that the cutting temperature measured by thermocouple is significantly lower than the results measured by thermal camera. The discrepancy may be attributed to the fact that the cutting time for temperature

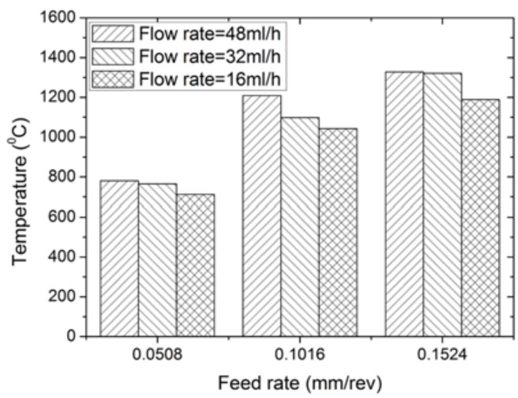


Fig. 12 Relationship between cutting temperature and flow rate of lubricant

measurement is not long enough to reach the steady state. The thermal camera records the instantaneous cutting temperature where the infrared light radiates, while the temperature measured by thermocouple is non-instantaneous due to the conductivity of the workpiece. Therefore, the cutting temperatures measured by thermocouple will not be discussed in the following.

In order to investigate the effects of MQL parameters on the cutting temperature, the temperatures measured by thermal camera under different flow rates of lubricant are shown in Fig. 12. In this analysis, the cutting speed is 3.147 m/s, and the air-oil mixture ratio is medium

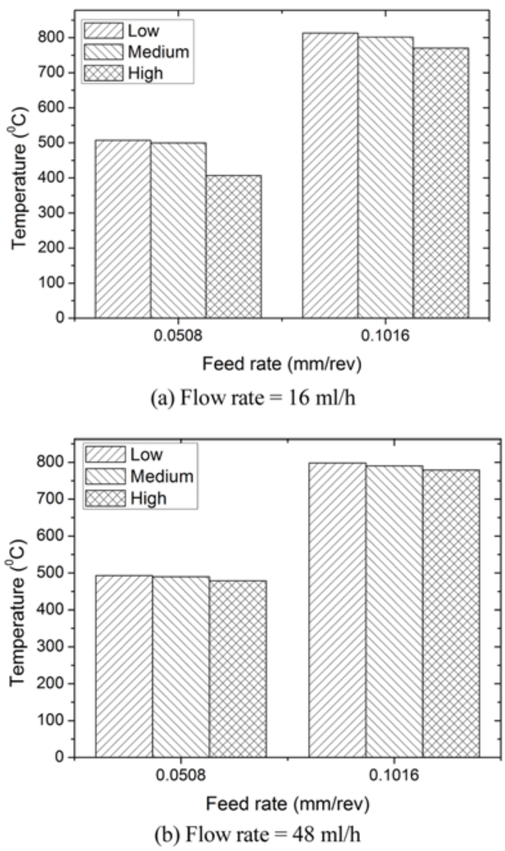


Fig. 13 Relationship between cutting temperature and air-oil mixture ratio

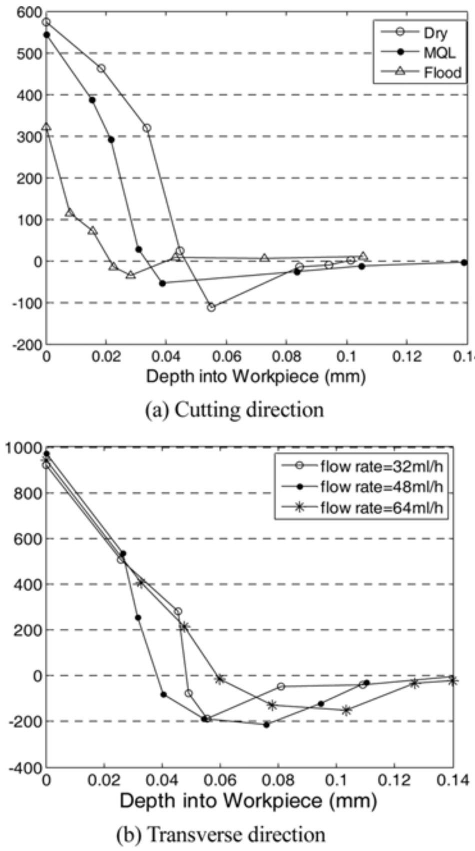


Fig. 14 Comparisons of residual stress distribution under dry, MQL, and flood machining

quantity. Results indicate that for the experimental value explored, the cutting temperature decreases with the increase of flow rate of lubricant, but the trend is not significant. This is because the continuous chip produced during the machining process may block the sprayed air-oil mixture, and it will affect the cooling effect of MQL in the machining process.

The cutting temperatures measured by the thermal camera under different air-oil mixture ratios are shown in Fig. 13. In this analysis, the cutting speed is 2.098 m/s. Results indicate that the lower cutting temperature is obtained under the high quantitatively of air-oil mixture ratio. It is also found that when the flow rate of lubricant is 48 ml/h, the air-oil mixture ratio has little effect on the cutting temperature. The result is consistent with the cutting force analysis. This may be because under this cutting condition, the flow rate of lubricant is beyond the maximum effective value. Therefore, the cutting temperature and cutting force will no longer be influenced by the air-oil mixture ratio.

3.3 Residual stress

First, the measured in-depth residual stresses under dry, MQL, and flood machining are compared as shown in Fig. 14. In this analysis, the cutting speed is 1.049 m/s, the feed rate is 0.0508 mm/rev, the flow rate of MQL is 16 ml/h, and the air-oil mixture ratio is medium quantity. Results indicate that the flood cooling machining obtains the minimum tensile residual stress at the surface of the machined workpiece among three lubrication conditions, while there is no significant difference of the superficial tensile residual stresses between the dry machining and MQL machining. The results are consistent with the analysis of cutting temperature. So it is concluded that the superficial residual stress of the machined workpiece is mainly determined by the thermal stress produced by cutting temperature in the machining process.

From the comparison results in Fig. 14(a), it is also found that the application of cutting fluid can significantly reduce the depth of maximum compressive residual stress. In the cutting direction, the maximum compressive residual stress in dry machining is the largest in magnitude among three lubrication conditions, and this trend is not clear in the transverse direction. It is concluded that the depth and magnitude of the maximum compressive residual stress in the machined workpiece mainly depend on the mechanical stress produced by the cutting force during the machining process. In addition, the results in Fig. 14 show that the penetration depth of residual stress decreases with the increase of cutting fluid in cutting direction, but is not very clear in the transverse direction. This is because the penetration depth of residual stress depends not only on the cutting force, but also on the tool geometry. In this analysis, the tool geometry is the same under three lubrication conditions.

The measured in-depth residual stresses under different flow rates of lubricant are shown in Fig. 15. In this analysis, the cutting speed is 3.147 m/s, the feed rate is 0.1016 mm/rev, and the air-oil mixture ratio is medium quantity. Results show that the depth of maximum compressive residual stress decreases in magnitude with the increase of the flow rate of lubricant. This trend is consistent with the analysis of cutting force, and it can be inferred that the depth of maximum

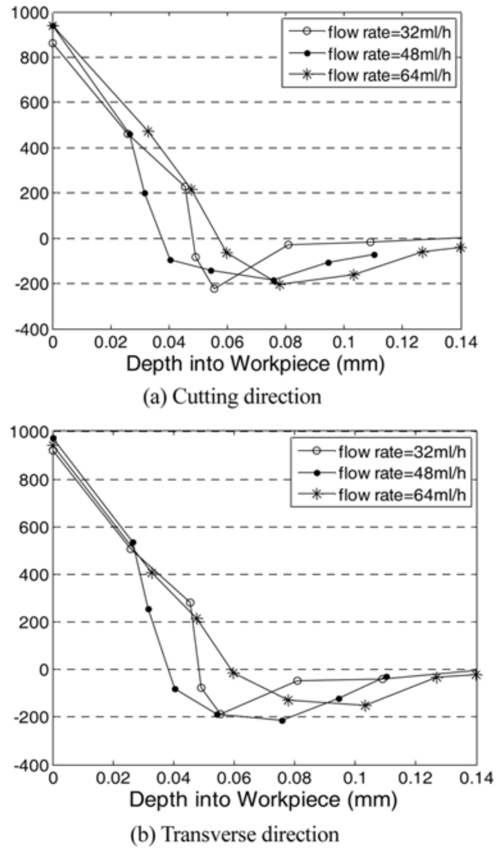


Fig. 15 Residual stress distributions under different flow rates of lubricant

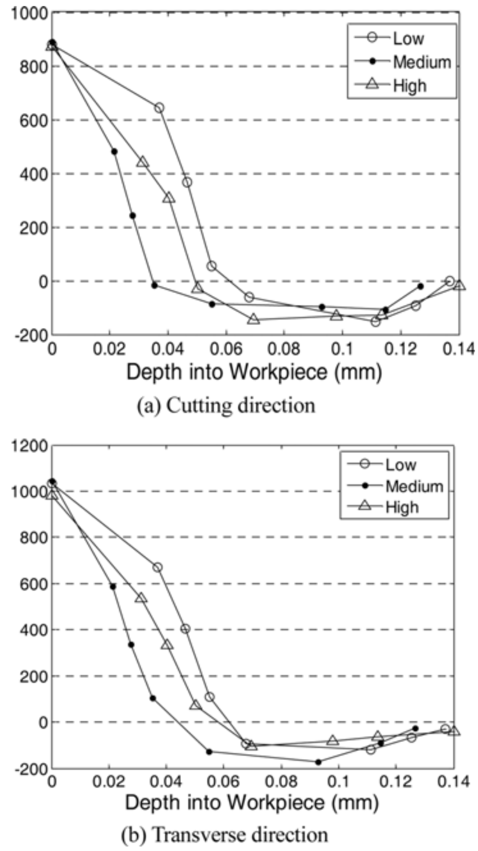


Fig. 16 Residual stress distributions under different air-oil mixture ratios

compressive residual stress mainly depends on the mechanical stress produced by cutting force during the machining process. Results also show that, for the experimental value explored, the flow rate of lubricant has little effect on the residual stress at the surface of the machined wokpiece and the maximum compressive residual stress in MQL machining.

The measured in-depth residual stresses under different air-oil mixture ratios are shown in Fig. 16. In this analysis, the cutting speed is 2.098 m/s, the feed rate is 0.1016 mm/rev, and the flow rate is 48 ml/h. Results show that the air-oil mixture ratio has little effect on the residual stress distribution. According to the analysis of cutting force and cutting temperature in Section 3.1 and 3.2, when the flow rate of lubricant is beyond the maximum effective value, the air-oil mixture ratio will no longer affect the cutting force and cutting temperature, while these two attributes are the main sources of residual stress in machining.

4. Conclusion

This research presented an experimental investigation of cutting force, cutting temperature, and residual stress in MQL machining. A specific analysis of the effects of MQL parameters such as flow rate of lubricant and air-oil mixture ratio on cutting force, cutting temperature, and residual stress are discussed based on the measured results. Additionally, the cutting performances in MQL machining are compared with the dry and flood cooling machining.

The comparisons of experimental results show that the application of cutting fluid considerably reduces the cutting force and cutting temperature in machining. However, there is no significant difference in cutting force between MQL and flood cooling machining. For MQL machining, there exists a maximum effective flow rate of lubricant in machining, and it is slightly influenced by the cutting speed, but not by feed rate. When the flow rate of lubricant is beyond the maximum effective value, the air-oil mixture ratio will no longer affect the cutting force, cutting temperature, and residual stress.

Experimental results show that the residual stress at the surface of the machined workpiece mainly depends on the thermal stress produced by the cutting temperature in machining process, and decreases with the application of cutting fluid. The depth and magnitude of maximum compressive residual stress are more influenced by the mechanical stress produced by cutting force in machining. The penetration depth of residual stress depends not only on the cutting force but also on the tool geometry.

The results of this study can be used to support parameter optimization and process planning in achieving desired residual stress profile in industry.

ACKNOWLEDGEMENT

The authors would like to thank the National Natural Science

Foundation of China (No. 51175331) for supporting the research.

REFERENCES

1. Leppert, T., "Effect of Cooling and Lubrication Conditions on Surface Topography and Turning Process of C45 Steel," International Journal of Machine Tools and Manufacture, Vol. 51, No. 2, pp. 120-126, 2011.
2. Dhar, N., Ahmed, M., and Islam, S., "An Experimental Investigation on Effect of Minimum Quantity Lubrication in Machining AISI 1040 Steel," International Journal of Machine Tools and Manufacture, Vol. 47, No. 5, pp. 748-753, 2007.
3. Yuan, S. M., Yan, L. T., Liu, W. D., and Liu, Q., "Investigation of Machinability in Minimum Quantity Lubrication Milling of GH4169 Aerospace Superalloy," Applied Mechanics and Materials, Vol. 34, No. pp. 666-670, 2010.
4. Li, K. M. and Lin, C. P., "Study on Minimum Quantity Lubrication in Micro-Grinding," The International Journal of Advanced Manufacturing Technology, Vol. 62, No. 1-4, pp. 99-105, 2012.
5. Nguyen, T. K., Do, I., and Kwon, P., "A Tribological Study of Vegetable Oil Enhanced by Nano-Platelets and Implication in MQL Machining," Int. J. Precis. Eng. Manuf., Vol. 13, No. 7, pp. 1077-1083, 2012.
6. Yuan, S. M., Yan, L. T., Liu, W. D., and Liu, Q., "Effects of Cooling Air Temperature on Cryogenic Machining of Ti-6Al-4V Alloy," Journal of Materials Processing Technology, Vol. 211, No. 3, pp. 356-362, 2011.
7. Varadarajan, A., Philip, P., and Ramamoorthy, B., "Investigations on Hard Turning with Minimal Cutting Fluid Application (HTMF) and Its Comparison with Dry and Wet Turning," International Journal of Machine Tools and Manufacture, Vol. 42, No. 2, pp. 193-200, 2002.
8. Liu, Z. Q., Xu, J., Han, S., and Chen, M., "A Coupling Method of Response Surfaces (CRSM) for Cutting Parameters Optimization in Machining Titanium Alloy under Minimum Quantity Lubrication (MQL) Condition," Int. J. Precis. Eng. Manuf., Vol. 14, No. 5, pp. 693-702, 2013.
9. Dhar, N., Islam, M., Islam, S., and Mithu, M., "The Influence of Minimum Quantity of Lubrication (MQL) on Cutting Temperature, Chip and Dimensional Accuracy in Turning AISI-1040 Steel," Journal of Materials Processing Technology, Vol. 171, No. 1, pp. 93-99, 2006.
10. Li, K. M. and Liang, S. Y., "Modeling of Cutting Temperature in Near Dry Machining," Journal of Manufacturing Science and Engineering, Vol. 128, No. 2, pp. 416-424, 2006.
11. Ueda, T., Hosokawa, A., and Yamada, K., "Effect of Oil Mist on Tool Temperature in Cutting," Journal of Manufacturing Science and Engineering, Vol. 128, No. 1, pp. 130-135, 2006.
12. Vasu, V. and Reddy, G. P. K., "Effect of Minimum Quantity Lubrication with Al_2O_3 Nanoparticles on Surface Roughness, Tool Wear and Temperature Dissipation in Machining Inconel 600 Alloy," Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanoengineering and Nanosystems, Vol. 228, No. 1, pp. 3-16, 2011.
13. Marksberry, P. and Jawahir, I., "A Comprehensive Tool-Wear/Tool-Life Performance Model in the Evaluation of NDM (Near Dry Machining) for Sustainable Manufacturing," International Journal of Machine Tools and Manufacture, Vol. 48, No. 7, pp. 878-886, 2008.
14. Islam, M. N., "Effect of Additional Factors on Dimensional Accuracy and Surface Finish of Turned Parts," Machining Science and Technology, Vol. 17, No. 1, pp. 145-162, 2013.
15. Sreejith, P., "Machining of 6061 Aluminium Alloy with MQL, Dry and Flooded Lubricant Conditions," Materials Letters, Vol. 62, No. 2, pp. 276-278, 2008.
16. Zhong, W., Zhao, D., and Wang, X., "A Comparative Study on Dry Milling and Little Quantity Lubricant Milling based on Vibration Signals," International Journal of Machine Tools and Manufacture, Vol. 50, No. 12, pp. 1057-1064, 2010.
17. Kilickap, E., Huseyinoglu, M., and Ozel, C., "Empirical Study Regarding the Effects of Minimum Quantity Lubricant Utilization on Performance Characteristics in the Drilling of Al 7075," Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 33, No. 1, pp. 52-57, 2011.
18. Hadad, M. and Sadeghi, B., "Thermal Analysis of Minimum Quantity Lubrication-MQL Grinding Process," International Journal of Machine Tools and Manufacture, Vol. 63, No. pp. 1-15, 2012.
19. Tawakoli, T., Hadad, M. J., and Sadeghi, M. H., "Influence of Oil Mist Parameters on Minimum Quantity Lubrication-MQL Grinding Process," International Journal of Machine Tools and Manufacture, Vol. 50, No. 6, pp. 521-531, 2010.
20. Lee, P. H., Nam, J. S., Li, C., and Lee, S. W., "An Experimental Study on Micro-Grinding Process with Nanofluid Minimum Quantity Lubrication (MQL)," Int. J. Precis. Eng. Manuf., Vol. 13, No. 3, pp. 331-338, 2012.
21. Rahman, M., Senthil Kumar, A., and Salam, M., "Experimental Evaluation on the Effect of Minimal Quantities of Lubricant in Milling," International Journal of Machine Tools and Manufacture, Vol. 42, No. 5, pp. 539-547, 2002.
22. Cai, X. J., Liu, Z. Q., Chen, M., and An, Q. L., "An Experimental Investigation on Effects of Minimum Quantity Lubrication Oil Supply Rate in High-Speed End Milling of Ti-6Al-4V," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 226, No. 11, pp. 1784-1792, 2012.
23. Attanasio, A., Ceretti, E., Gelfi, M., and Giardini, C., "Experimental Evaluation of Lubricant Influence on Residual Stress in Turning Operations," International Journal of Machining and Machinability of Materials, Vol. 6, No. 1, pp. 106-119, 2009.

24. Ji, X., Zhang, X., and Liang, S. Y., "Predictive Modeling of Residual Stress in Minimum Quantity Lubrication Machining," The International Journal of Advanced Manufacturing Technology, Vol. 70, No. 9-12, pp. 2159-2168, 2014.

25. Ji, X., Zhang, X. P., Li, B. Z., and Liang, S. Y., "Predictive Modeling of Minimum Quantity Lubrication: Cutting Force, Temperature and Residual Stress," Applied Mechanics and Materials, Vol. 365, No. pp. 1181-1184, 2013.

26. Zhang, C. Y., "Study on the Mechanism of MQL Cutting and Its Application Fundament," Ph.D. Thesis, Department of Mechanical Manufacturing and Automation, Jiangsu University, 2008.