**Proceedings of the
International Conference on Mechanical Engineering 2005
(ICME2005) 28- 30 December 2005, Dhaka, Bangladesh**

ICME05-AM-32

THE INFLUENCE OF MINIMUM QUANTITY OF LUBRICATION (MQL) BY VEGETABLE OIL-BASED CUTTING FLUID ON MACHINABILITY OF STEEL

N. R. Dhar and M. W. Islam

Department of Industrial & Production Engineering,
Bangladesh University of Engineering & Technology (BUET)
Dhaka, Bangladesh.

ABSTRACT
The growing demands for high productivity of machining need use of high cutting velocity and feed rate. Such machining inherently produces high cutting temperature, which not only reduces tool life but also impairs the product quality. Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions but the use of cutting fluid has become more problematic in terms of both employee health and environmental pollution. Because of them some alternatives has been sought to minimize or even avoid the use of cutting fluid in machining operations. Some of these alternatives are dry machining and machining with minimum quantity of lubrication (MQL). This paper deals with experimental investigation on the role of MQL on cutting temperature, tool wear, surface finish and dimensional deviation in turning of AISI-1040 steel at industrial speed-feed combinations by uncoated carbide insert. The encouraging results include significant reduction in cutting temperature, tool wears and dimensional inaccuracy by MQL mainly through favorable chip-tool and work-tool interaction.

Keywords: MQL, Cutting temperature, Tool wear and Dimensional deviation

1. INTRODUCTION
High production machining of steel inherently generates high cutting zone temperature. Such high temperature causes dimensional deviation and premature failure of cutting tools. It also impairs the surface integrity of the product by inducing tensile residual stresses and surface and subsurface microcracks in addition to rapid oxidation and corrosion [1,2]. Currently, this problem is tried to be controlled by reducing heat generation and removing heat from the cutting zone through optimum selection of machining parameters, proper cutting fluid application and using heat resistant cutting tools.

High cutting zone temperature is generally tried to be controlled by employing flood cooling by soluble oil. In high speed–feed machining, conventional cutting fluid application fails to penetrate the chip-tool interface and thus cannot remove heat effectively [3-4] and the use of cutting fluid has become more problematic in terms of both employee health and environmental pollution. Addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip–tool interface to provide lubrication and cooling [5]. However, high-pressure jet of soluble oil, when applied [6] at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent. High-pressure coolant injection technique [7] not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid by 50%. The increasingly stricter environmental regulations and their enforcement are eliminating much of the flexibility in the use of cutting fluids. It is a long way before the cutting fluids can be considered totally harmless and acceptable. The cost associated with the use of cutting fluids is estimated to be several billion dollars per year [8]. Consequently, elimination on the use of cutting fluids, if possible, can be a significant economic incentive. Considering the high cost associated with the use of cutting fluids and projected escalating costs when the stricter environmental laws are enforced, the choice seems obvious. Because of them some alternatives has been sought to minimize or even avoid the use of cutting fluid in machining operations. Some of these alternatives are dry machining and machining with minimum quantity of lubrication.

Dry machining operations are now of great interest and, actually, they meet with success in the field of environmentally friendly manufacturing [9]. In reality, however, they are sometimes less effective when higher machining efficiency, better surface finish quality and severer cutting conditions are required. For these situations, semi-dry operations utilizing very small amounts of cutting lubricants are expected to become a powerful tool and, in fact, they already play a significant role in a number of practical applications [10-13]. Minimum quantity lubrication refers to the use of cutting fluids of only a minute amount-typically of a flow rate of 50 to 500 ml/hour which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition, where, for example, up to 10 liters of fluid can be dispensed per minute. The concept of minimum quantity lubrication, sometimes referred to as near dry lubrication [9] or microlubrication [14], has been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. The minimization of cutting fluid also leads to economical benefits by way of saving lubricant costs and workpiece/tool/machine cleaning cycle time.

A recent survey conducted on the production of the European automotive industry revealed that the expense of cooling lubricant comprises nearly 20% of the total manufacturing cost [15]. In comparison to cutting tools, the cooling lubricant cost is significantly higher. As a result, the need to reduce cutting fluids consumption is strong. Furthermore, the permissible exposure level for metal-working fluid aerosol concentration is 5 mg/m^3, per the U.S. Occupational Safety and Health Administration (OSHA)[16], and is 0.5 mg/m^3 according to the U.S. National Institute for Occupational Safety and Health (NIOSH) [17]. The oil mist level in U.S. automotive parts manufacturing facilities has been estimated to be generally on the order of 20-90 mg/m^3 with the use of traditional flood cooling and lubrication [18]. This suggests an opportunity for improvement of several orders of magnitude. The minimal quantity lubrication (MQL) system is probably the most representative application of semi-dry machining.

The review of the literature suggests that MQL provides several benefits in machining. The purpose of this research work is to experimentally investigate the influence of MQL on cutting temperature, tool wear and dimensional deviation in turning AISI 1040 steel at industrial speed–feed conditions by carbide inserts and compare the effectiveness of MQL with that of dry machining.

2. EXPERIMENTAL CONDITIONS AND PROCEDURE

For the present experimental studies, AISI 1040 steel rod of initial diameter 125 mm and length 620mm was plain turned in a BMTF Lathe, Bangladesh, 4 hp by uncoated carbide insert at industrial speed-feed combinations under both dry, wet and MQL conditions. The experimental conditions are given in Table-1. The ranges of the cutting velocity (V_c) and feed rate (S_o) were selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut, being less significant parameter, was kept fixed.

Table 1: Cutting conditions of turning test

Machine tool	BMTF Lathe, Bangladesh, 4 hp
Workpiece	AISI-1040 steel
Cutting tool	Carbide, SNMM, Drillco
Tool holder	PSBNR 2525M12, Drillco
Tool geometry	-6, -6, 6, 6, 15, 75, 0.8 (mm)
Process parameters	
Cutting velocity, V_c	63, 80, 95, 110 and 128 m/min
Feed rate, S_o	.10, 0.13, 0.16 and 0.20 mm/rev
Depth of cut, t	1.0 mm
MQL supply	Air: 2.5 bar, lubricant: 200ml/h through external nozzle
Environment	Dry, Wet and Minimum Quantity Lubrication (MQL)

For cooling, MQL in the form of thin but high speed was impinged from a specially designed nozzle along the auxiliary cutting edge of the insert. The MQL jet has been used mainly to target the rake surface and flank surface along the auxiliary cutting edge and to protect the auxiliary flank to enable better dimensional accuracy. MQL is expected to provide some favorable effects mainly through reduction in cutting temperature. The simple but reliable tool-work thermocouple technique with proper calibration has been employed to measure the average cutting temperature during turning at different V_c-S_o combinations by the uncoated carbide insert under dry, wet and MQL condition [19,20]. The cutting insert was withdrawn at regular intervals to study the pattern and extent of wear on main and auxiliary flanks for all the trials. The average width of the principal flank wear, V_B was measured using in inverted metallurgical microscope (Olympus, Model MG) fitted with micrometer of least count 1μm. The photographic view of the experimental setup is shown in Fig.1. A precision dial gauge monitored the variation in finished diameter along the job-axis.

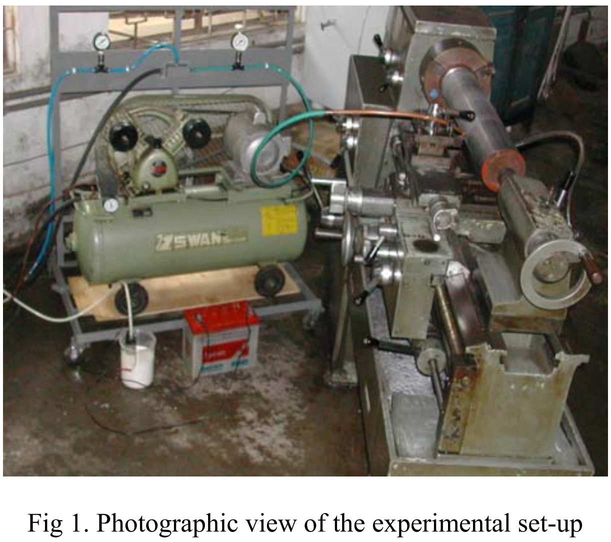

Fig 1. Photographic view of the experimental set-up

3. EXPERIMENTAL RESULTS AND DISCUSSION

MQL is expected to provide some favorable effects mainly through reduction in cutting temperature. The effect of MQL on average chip-tool interface temperature (θ_{avg}) at different V_c and S_o under dry and MQL condition has been shown in Fig.2.

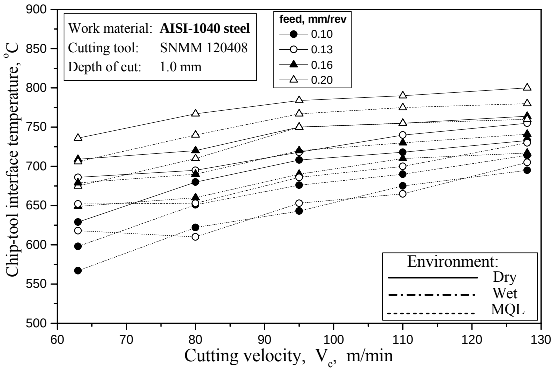

Fig 2. Variations in θ_{avg} at different V_c and S_o under dry, wet and MQL conditions.

Apparently, more drastic reduction in θavg is expected by employing MQL but actually it is not so because the MQL could not reach the intimate chip–tool contact zone. However, during machining at lower V_c when the chip-tool contact is partially elastic, where the chip leaves the tool, MQL is dragged in that elastic contact zone in small quantity by capillary effect and is likely to enable more effective cooling. With the increase in V_C the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip-tool interface. MQL cooling effect also improved to some extent with the decrease in feed particularly at lower cutting velocity. Possibly, the thinner chips, specially at lower chip velocity, are slightly pushed up by the MQL jet coming from opposite direction and enables it come closer to the hot chip–tool contact zone to remove heat more effectively. Further, at high velocity, the coolant may not get enough time to remove the heat accumulated at the cutting zone resulting in less reduction in temperature under MQL condition at high cutting velocity.

Productivity and economy of manufacturing by machining are significantly influenced by life of the cutting tools. Cutting tools may fail by brittle fracturing, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears. With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces, as schematically shown in Fig.3 due to continuous interaction and rubbing with the chips and the work surfaces, respectively. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems. The life of carbide tools, which mostly fail by wearing, is assessed by the actual machining time after which the average value (V_B) of its principal flank wear reaches a limiting value, like 0.3 mm. Therefore, attempts should be made to reduce the rate of growth of flank wear (V_B) in all possible ways without sacrifice in MRR.

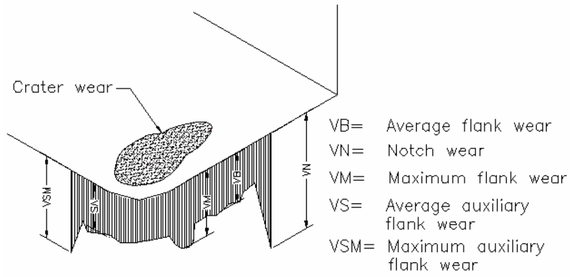

Fig 3. Geometry of wear of turning tool

Figure 4 clearly reveals that MQL has reduced V_B remarkably in machining AISI 1040 steel. This is reasonably attributed to extremely lubrication provided by the MQL jet, which could, at least partially, reach the work-tool interfaces, unlike chip-tool interface. The deep grooves parallel to the cutting edges of the insert are likely to help entry of larger fraction of the MQL jet at the flank surfaces.

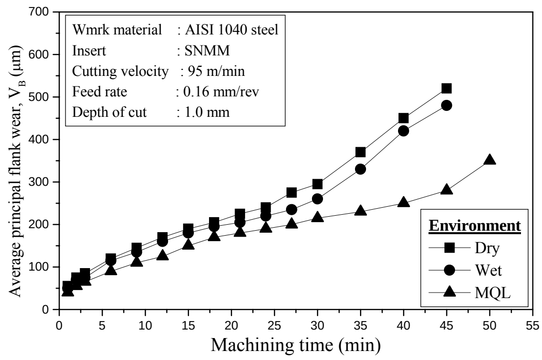

Fig 4. Growth of average flank wear, V_B with time under dry, wet and MQL conditions

In machining research, a cutting tool is generally said to have failed when its V_B reaches a specific value, mostly 0.3 mm. It is very important to note in Fig.4 that tool life has improved from 31 min to 48 min, i.e. almost by one and half times increase in tool life have been possible by MQL. Fig.4 also depicts how flank notch wear, V_N remarkably decreased due to MQL. Deep notching, if forms, not only raises cutting forces but also may cause catastrophic tool failure prematurely and randomly, which is extremely harmful and undesirable for the present days' sophisticated and expensive manufacturing systems. So, proper MQL is expected also to enhance reliability and safely of machining processes and systems.

Surface roughness is another important index of machinability, which is substantially influenced by the machining environment for given tool-work pair and speed-feed combinations. The variation in surface roughness observed with progress of machining of the steel by the insert at a particular set of V_c, S_o and t under dry, wet and MQL conditions have been in shown in Fig.5. As MQL reduced average auxiliary flank wear and notch wear on auxiliary cutting edge, surface roughness also grew very slowly under MQL conditions. Conventionally applied cutting fluid did not reduce tool wear compared to dry machining. But the surface roughness deteriorated drastically under wet machining compared to dry, which may possible be attributed electrochemical interaction between insert and work piece. It appears from Fig.5 that surface roughness grows quite fast under dry machining due to more intensive temperature and stresses at the tool-tips, MQL appeared to be effective in reducing surface roughness. However, it is evident that MQL improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.

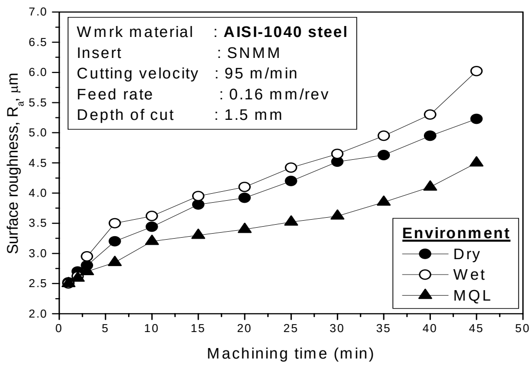

Fig 5. Surface roughness with progress of machining under dry, wet and MQL conditions

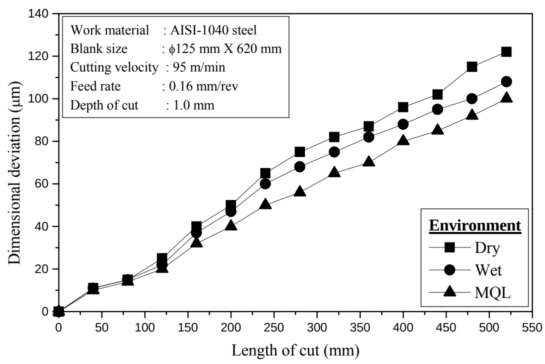

Fig 6. Dimensional deviations observed after one full pass under dry, wet and MQL conditions

MQL provided remarkable benefit in respect of controlling the increase in diameter of the finished job with machining time as can be seen in Fig.6. The finished job diameter generally deviates from its desired value with the progress of machining, i.e. along the job-length mainly for change in the effective depth of cut due to several reasons which include wear of the tool nose, over all compliance of the machine-fixture-tool-work (MFTW) system and thermal expansion of the job during machining followed by cooling. Therefore, if the MFTW system were rigid, variation in diameter would be governed mainly by the heat and cutting temperature. With the increase in temperature the rate of growth of auxiliary flank wear and thermal expansion of the job will increase. MQL takes away the major portion of heat and reduces the temperature resulting decrease in dimensional deviation desirably.

4. CONCLUSIONS

Based on the results of the present experimental investigation the following conclusions can be drawn:

- The cutting performance of MQL machining is better than that of conventional machining with flood cutting fluid supply.
- The present MQL systems enabled reduction in average chip-tool interface temperature upto 10% and even such small reduction enabled significant improvement in the major machinability indices.
- The most significant contribution of application of MQL in machining the steel by the carbide insert undertaken has been the high reduction in flank wears, which would enable remarkable improvement in tool life. Such reduction in tool wear might have been possible for retardation of abrasion and notching, decrease or prevention of adhesion and diffusion type thermal sensitive wear at the flanks and reduction of built-up edge (BUE) formation which accelerates wear at the cutting edges by chipping and flaking. Deep notching and grooving, which are very detrimental and may cause premature and catastrophic failure of the cutting tools, are remarkably reduced by MQL.
- Dimensional accuracy also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of MQL. MQL also provided better surface finish.

5. ACKNOWLEDGEMENT

This work has been funded by Directorate of Advisory Extension and Research Services (DAERS), Committee for Advanced Studies & Research (CASR), BUET, Dhaka, Bangladesh, sanction DEARS/CASR/ R-10/ 2004/D-944 (30) dated 28/02/ 2004. The authors are also grateful to the Department of Industrial and Production Engineering, BUET for providing the facilities to carryout the experiment.

6. REFERENCES

1. Leskover, P. and Grum, J., 1986, “The Metallurgical Aspect of Machining”, Ann. CIRP 35, pp. 537-550.
2. Tonshoff, H.K. and Brinkomeier, E., 1986, “Determination of the Mechanical and Thermal Influences on Machined Surface by Microhardness and Residual Stress Analysis”, Ann. CIRP 29, pp.519-532.

3. Shaw, M. C., Pigott, J. D. and Richardson, L.P., 1951, "Effect of Cutting Fluid upon Chip–Tool Interface Temperature", Trans. ASME 71, pp. 45-56.
4. Paul, S., Dhar, N.R. and Chattopadhyay, A.B., 2000,"Beneficial Effects of Cryogenic Cooling over Dry and Wet Machining on Tool Wear and Surface Finish in Turning AISI 1060 Stee"l", *Proc. of the Int. Conf. on Advanced Manuf. Technology, ICAMT-2000*, Malaysia, pp. 209-214.
5. Cassin, C., and Boothroyed, G., 1965,"Lubrication Action of Cutting Fluids", J. Mech. Eng. Science, 7(1) pp. 67-81.
6. Mazurkiewicz, M., Kubala, Z., and Chow, J., 1989, "Metal Machining With High Pressure Water-Jet Cooling Assistance-A New Possibility", J. Eng. Ind. 111, pp. 7-12.
7. Alaxender, A., Varadarajan, A.S., and Philip, P. K., 1998,"Hard Turning with Minimum Cutting Fluid: A Viable Green Alternative on the Shop Floor", *Proceedings of the 18th All India Conference on MTDR*, India, pp. 152-155.
8. "Ecologically Improved Manufacturing" at http//www.ifw.unihannover.de/BEREICH3/Forschen/310 2e.htm.
9. Klocke, F., and Eisenblatter, G., 1997, *Dry Cutting*, Annals of the CIRP, 46/2, pp.519-526.
10. Heisel, U., et al., 1994, "Application of Minimum Quantity Cooling Lubrication Technology in Cutting Processes", Prod. Eng, Vol .II/1, pp.49-54.
11. Sutherland, J. W., et al., 2000, "An Experimental Investigation of Air Quality in Wet and Dry Turning", Ann. of CIRP, 49/1, pp.61-64.
12. McCabe, J. and Ostaraff, M. A., 2001 "Performance Experience with Near-Dry Machining of Aluminum", Lubr. Eng., 57/12, pp. 22-27.
13. Suda, S., et al., 2001, "Evaluation of Machinability with MQL System and Effectiveness in Production Lines", *Proceedings of the International Tribology Conference*, Nagasaki, pp.203-208.
14. MaClure, T. F., Adams, R., and Gugger, M. D., 2001, "Comparison of Flood vs. Microlubrication on Machining Performance, website: http://www.unist.com/techsolve.html.
15. Brockhoff, T., and Walter, A., 1998, "Fluid Minimization in Cutting and Grinding, Abrasives", pp. 38-42.
16. Aronson, R. B., 1995, "Why Dry Machining", Manufacturing Engineering, pp. 33-36.
17. U.S. Department of Health and Human Services, January 1998, "Occupational Exposure to Metalworking Fluids", NIOSH Publication No. 98-102.
18. Bennett, E. O., and Bennett, D. L., 1998, "Occupational Airway Diseases in the Metalworking Industry", Tribology International, 18/3, pp. 169-176.
19. Dhar, N. R., Islam, M. W., Islam, S., and Mithu, M. A. H., 2004 "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. [in press]
20. Islam, M. W., 2004 "Experimental Study of Effect of Minimum Quantity Lubrication (MQL) in Turning AISI 1040 Steel", M. Eng. Dissertation, BUET, Dhaka, Bangladesh.