

EFFECT OF MINIMUM QUANTITY LUBRICANT ON TEMPERATURE CHIP AND CUTTING FORCE IN TURNING MEDIUM CARBON STEEL

S. M. A. Choudhury¹, N. R. Dhar² and M. M. A. Bepari³

¹Ph. D. Student and ²Professor

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

Email: smac@bttb.net.bd, nrdhar@ipe.buet.ac.bd

³Professor

Department of Material & Metallurgical Engineering
Bangladesh University of Engineering & Technology, Dhaka, Bangladesh.

Email: mohar@mme.buet.ac.bd

ABSTRACT

Machining is inherently characterized by generation of heat and high cutting temperature. At such elevated temperature the cutting tool if not enough hot hard may lose their form or stability quickly, wear out rapidly, resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases though in different degrees with the increase of cutting velocity, feed and depth of cut. As a result, higher production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material. Metal cutting fluids change the performance of machining operations because of their lubrication, cooling, and chip flushing functions. But metal cutting fluid cannot control the high cutting temperature in high production machining. Besides, they are major source of pollution from machining industries. Minimum quantity of lubricant is an alternative method for desirable control of cutting temperature. This study compares the mechanical performance of minimum quantity lubrication to completely dry lubrication for the turning of medium carbon steel based on experimental measurement of cutting temperature, chips, cutting forces and part finish. The results indicate that the use of minimum quantity lubrication leads to reduced cutting forces, lower cutting temperature and favourable chip-tool interaction.

Keywords: MQL, Chip formation, Cutting temperature and Cutting forces

1. INTRODUCTION

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” [1] or “microlubrication” [2], 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 [3]. 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 (PEL) for metalworking fluid aerosol concentration is 5 mg/m³ as per the U.S. Occupational Safety and Health Administration (OSHA) [4], and is 0.5 mg/m³ according to the U.S. National Institute for Occupational Safety and Health (NIOSH) [5]. The oil mist level in U.S. automotive parts manufacturing facilities has been estimated to be generally on the order of 20-90 mg/m³ with the use of traditional flood cooling and lubrication [6]. This suggests an opportunity for improvement of several orders of magnitude.

On the other hand, completely dry cutting has been a common industry practice for the machining of hardened steel parts. These parts typically exhibit a very high specific cutting energy. Traditional beliefs indicate that completely dry cutting of them, as compared to flood cutting, lowers the required cutting force and power on the part of the machine tool as a result of increased cutting temperature. However, achievable tool life and part finish often suffer under completely dry condition. Therefore, the permissible feed and depth of cut have to be restricted. Under these considerations, the concept of minimum quantity lubrication presents itself as a

possible solution for hard turning in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, provided that the minimum quantity lubrication parameters can be strategically tuned. However, there has been no documented study so far that investigates the feasibility of using minimum quantity lubrication in hard machining processes.

The purpose of this research is to study the effects of minimum quantity lubrication condition on the cutting performance of medium carbon steel, as compared to completely dry cutting. An approach based on the tool work combination method has been performed to identify the ideal testing parameters range. The study helps to provide an understanding of the behavior of the tool and the workpiece under minimum quantity lubricant conditions. In the study, the minimum quantity lubrication is provided with a spray of air and vegetable oil. During each test, cutting temperature, chip reduction coefficient, cutting forces and surface roughness are measured and compared. The following sections describe the experimental condition, experimental results and discussion and conclusion.

2. EXPERIMENTAL CONDITIONS

Fig.1 shows the use of a minimum quantity lubrication applicator on a horizontal lathe (China, 10hp). The coolant used was water soluble cutting oil dispensed at a flow rate of 100 ml/hour under the nozzle pressure of 20 bars. The workpiece material is medium carbon steel. The cutting tool used was SNMG tool (Widia P-30) with inclination angle of -6° , orthogonal rake angle of -6° , orthogonal clearance angle of 6° , auxiliary cutting edge angle of 15° , principal cutting edge angle of 75° , and nose radius of 0.8 mm. The conditions of the present experiments are given in Table-1.



Fig 1: Photographic view of the experimental set-up

Cutting temperature has been measured by a tool-work thermocouple technique, as shown in Fig. 2, with due care to avoid generation of parasitic emf and electrical short circuit. The cutting forces were measured with a force dynamometer (Kistler) mount on carriage via a custom designed turret adapter (Kistler) for the tool holder creating a very rigid tooling fixture. The charge signal generated at the dynamometer was amplified using charge amplifiers (Kistler). The amplified signal is

acquired and sampled by using data acquisition on a laptop computer at a sampling frequency of 2000 Hz per channel. Time-series profiles of the acquired force data reveal that the forces are relatively constant over the length of cut and factors such as vibration and spindle run-out were negligible. The surface roughness was measured with a Taylor-Hobson Surtronic 3+ profilometer using a cut-off length of 0.8 mm.

Table 1: Experimental conditions

Machine tool	: 10 HP Lathe, China
Work specimen	
Material	: Medium carbon steel
Cutting tools (inserts)	
material, grade	: TTR (P30), Widia India Ltd
configurations	: SNMG 120408 TTR
Processes parameters	
cutting velocity (V_c)	: 104, 148, 178 and 208 m/min
feed rate (S_o)	: 0.10, 0.14, 0.18 and 0.22 mm/rev
depth of cut (t)	: 1.50 mm
Environments	: dry and MQL

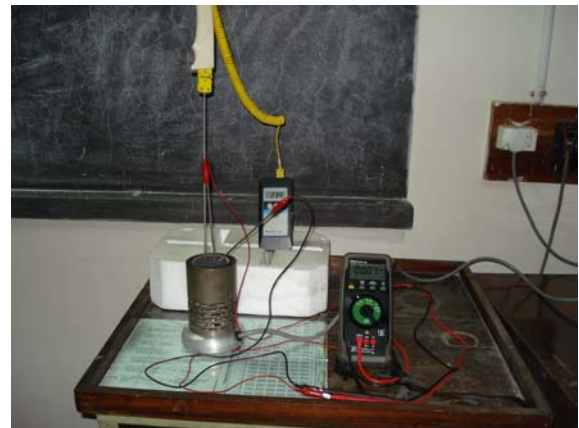


Fig 2: Tool work thermocouple calibration set up

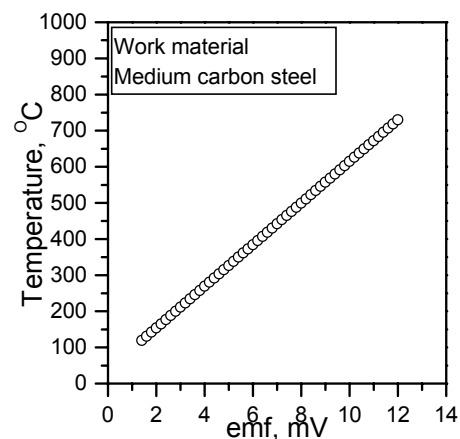


Fig 3: Tool-work thermocouple calibration curve

The calibration of the work-tool thermocouple has been carried out by graphite block embedded with an

electrically heated porcelain tube served as the heat sink. Fig.2 shows the calibration setup employed for the thermocouple used in the present investigation. Fig.3 shows the calibration curve obtained for the tool-work pair with tungsten carbide (P30 Grade, WIDIA) as the tool material and medium carbon steel as the work material. In the present case, almost linear relationship is obtained between the temperature and emf. A multiple correlation coefficient of 0.994 was obtained.

3. EXPERIMENTAL RESULTS AND DISCUSSION

During machining any ductile materials, heat is generated at the (i) primary deformation zone due to shear and plastic deformation, (ii) chip-tool interface due to secondary deformation and sliding and (iii) work-tool interfaces due to rubbing. All such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. Therefore, attempts are made to reduce this detrimental cutting temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate effectively as expected at the chip-tool interface where the temperature is maximum. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V_c when the chip-tool contact becomes almost fully plastic or bulk.

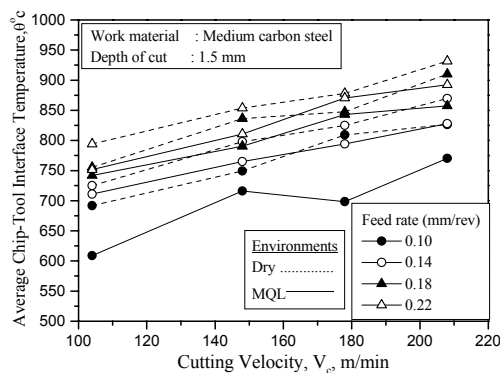


Fig 4: Variation of cutting temperature with V_c and S_o under different environments

However, it was observed that the minimum quantity lubricant jet in its present way of application enabled reduction of the average cutting temperature by about 10 to 20% depending upon the levels of the process parameters, V_c and S_o and the types of the cutting inserts. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

Fig.4 clearly shows that the machining temperature significantly increased with the increase in cutting

velocity and feed, though in different degrees, under all the conditions undertaken expectedly for increased energy input. Minimum quantity lubricant has enabled a significant reduction in machining temperature, though in different degrees for different levels of process parameter undertaken. Such effects may be reasonably attributed to reduction in chip-tool contact length, reduction in forces due to restricted contact cutting effect and also by enhanced heat transfer under minimum quantity lubricant cooling.

The value of chip reduction coefficient, ξ is an important index of chip formation and specific energy consumption for a given tool-work combination. In machining conventional ductile metals producing continuous chips, the value of ξ is generally greater than 1.0 because the chip thickness becomes greater than uncut chip thickness due to almost all sided compression and friction at the chip-tool interface. Larger value of ξ means larger cutting forces and friction and is hence undesirable. The effect of increase in V_c and S_o and the change in environment on the value of chip reduction coefficient, ξ obtained during turning of the present medium carbon steel is shown in Fig.5 which depicts the reduction of cutting zone temperature by the application of minimum quantity lubricant reduced the value of ξ . The form and colour of the steel chips became favorable for more effective cooling and improvement in nature of interaction at the chip-tool interface.

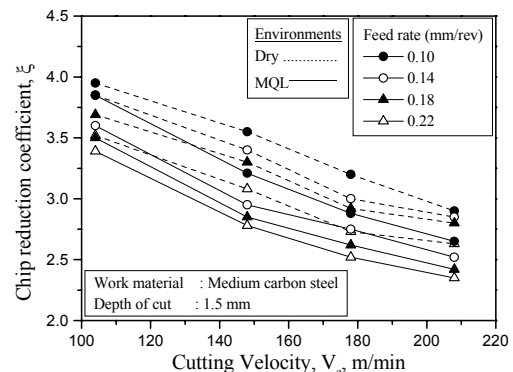


Fig 5: Variation of chip reduction coefficient with V_c and S_o under different environments

The nature of variation in the cutting forces P_z and P_x observed during turning the medium carbon steel rod by SNMG insert at different V_c and S_o under both dry and minimum quantity lubrication conditions are shown in Fig.6 and Fig.7 respectively.

The magnitude and pattern of the cutting forces is one of the most important machinability indices because that plays vital roles on power and specific energy consumption, product quality and life of the salient numbers of the Machine-Fixture-Tool systems. Design of the Machine-Fixture-Tool-Work systems also essentially need to have the knowledge about the expected characteristics of the cutting forces. Therefore, it is reasonably required to study and assess how the cutting forces and tool life are affected by cryogenic cooling with liquid nitrogen, which

is primarily aimed at environment friendly machining.

Fig.6 and Fig.7 are clearly showing that both P_z and P_x have uniformly decreased with the increase in V_c more or less under all the feeds, for both the environments undertaken as usual due to favourable change in the chip-tool interaction resulting in lesser friction and intensity or chances of built-up edge formation at the chip-tool interface. In machining ductile metals like steels by carbide tools, which are not chemically inert like ceramics, the chip material under elevated temperature and high pressure sticks in their layer on the tool surface by adhesion and diffusion and often resulting in gradual piling of the strain hardened layers forming built-up edge near the cutting edge. After growing to certain size, the built-up edge gets separated from the tool by the increased transverse force. Both the formation and frequent separation of built-up edge are detrimental because it not only raises and fluctuates the cutting forces but also impairs the finished surface and reduces tool life.

It is evident from Fig.6 and Fig.7 that both P_z and P_x decreased appreciably due to application of minimum quantity lubrication jet more or less at all the V_c - S_0 combinations. This improvement can be reasonably attributed to reduction in the cutting temperature particularly near the main cutting edge where seizure of chips and formation or tendency of formation of built-up edge is more predominant.

Minimum quantity lubricant reduced the cutting forces by about 5% to 20%. P_x decreased more predominantly than P_z . Favorable change in the chip-tool interaction and retention of cutting edge sharpness due to reduction of cutting zone temperature seemed to be the main reason behind reduction of cutting forces by the minimum quantity lubricant jet.

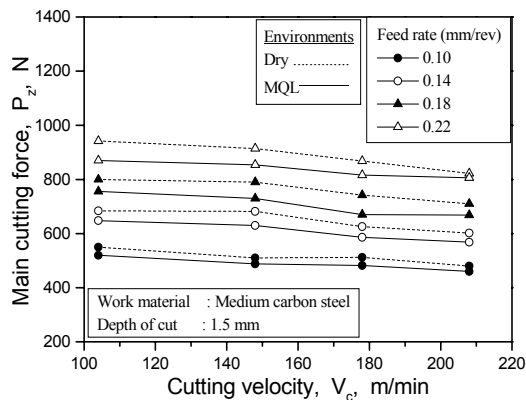


Fig 6: Variation in the main cutting force, P_z with V_c and S_0 under different environments

During machining, the shear strength of the ductile type work material at the cutting zone in one hand increases due to compression and straining and on the other hand decreases due to softening by the cutting temperature if it is sufficiently high. But again along with softening, the chip material becomes sticky for which the friction force and hence the cutting force may tend to increase. The overall effect of all such factors on the

magnitude of the cutting forces will depend on the nature of the work material and the level of the cutting temperature. Therefore, it seems that minimum quantity lubricants had ultimately favorable effect on the behavior of the present steel in respect of cutting forces for which minimum quantity lubricant enabled reduction in the cutting forces to some extent even when built-up edge was not visible.

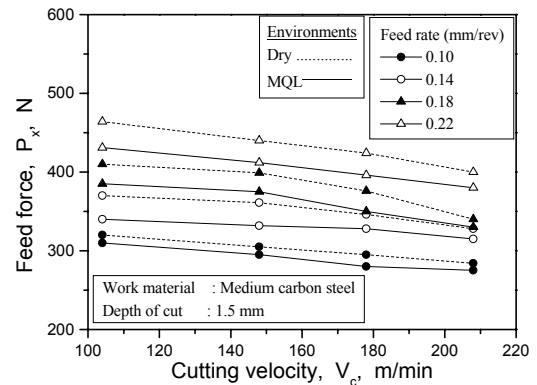


Fig 7: Variation in the feed force, P_x with V_c and S_0 under different environments

Surface roughness is another important index of machinability which is substantially influenced by the machining environment for given tool-work pair and speed-feed conditions.

Surface roughness has been measured after a few seconds of machining with the sharp tool while recording the cutting forces. The surface roughness attained after 45 seconds of machining of the medium carbon steel by the sharp SNMG insert at various V_c - S_0 combinations under dry and minimum quantity lubrication conditions is shown in Fig.8.

Fig.8 shows the variation of R_a values of surface roughness after 45 seconds at different V_c - S_0 combinations under dry and minimum quantity lubrication conditions by the SNMG insert. Assuming sinusoidal distribution of surface roughness caused only by feed marks, the R_a values for the present insert having 0.8 mm nose radius have been evaluated and found to be around 0.8 μm , 1.4 μm , 2.2 μm and 3.8 μm for S_0 equal to 0.10, 0.14, 0.18 and 0.22 mm/rev respectively. But the actual values of R_a have been much larger than the aforesaid values excepting when V_c and S_0 are very large. This indicates that in the present machining conditions, the effects of chipping, wear and notching of the auxiliary flank near the tool tips on surface roughness are prevalent. Built-up edge formation is also quite likely to have some role on surface roughness in machining the present steels by carbide inserts.

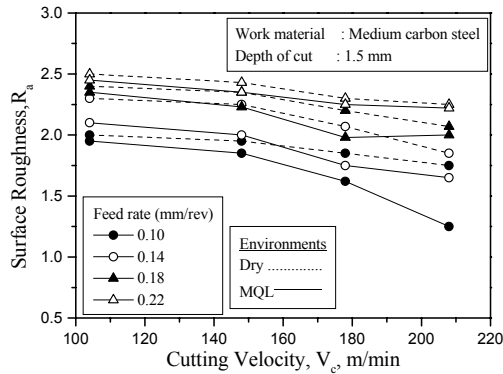


Fig 8: Variation of surface roughness, R_a with V_c and S_o under different environments

In the present conditions, particularly with the increase in V_c and S_o , the actual R_a value has been even lower than the corresponding R_a value expected only due to feed marks as can be seen, for instance, in Fig.8. This might be due to either truncation of the feed marks or flattening of the radiused tip of the cutting insert by more rapid break-in wear due to intensive temperature and pressure. Simultaneous action of both the factors is also possible.

Fig.8 clearly shows that surface roughness as such increased with the increase in feed, S_o and decreased with the increase in V_c . Reduction in R_a with the increase in V_c may be attributed to smoother chip-tool interface with lesser chance of built-up edge formation in addition to possible truncation of the feed marks and slight flattening of the tool-tip. Increase in V_c may also cause slight smoothing of the abraded auxiliary cutting edge by adhesion and diffusion type wear and thus reduced surface roughness.

It is evident in Fig.8 that minimum quantity lubricant could provide marginal improvement in surface finish at the beginning of machining with the fresh cutting edges. The slight improvement in surface finish by minimum quantity lubricant might be due to reduction in break-in wear and also possibly reduction or prevention of built-up edge formation depending upon the work material and cutting condition.

4. CONCLUSIONS

- (i) The present minimum quantity lubricant systems enabled reduction in average chip-tool interface temperature upto 20% depending upon cutting conditions and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.
- (ii) Due minimum quantity lubricant application, the form and colour of the steel chips became favorable for more effective cooling and improvement in nature of interaction at the chip-tool interface.

- (iii) Minimum quantity lubricant reduced the cutting forces by about 5% to 20%. P_x decreased more predominantly than P_z . Favorable change in the chip-tool interaction and retention of cutting edge sharpness due to reduction of cutting zone temperature seemed to be the main reason behind reduction of cutting forces by the Minimum quantity lubricant jet.
- (iv) Surface finish also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of Minimum quantity lubricant

5. ACKNOWLEDGEMENT

This research work has been funded by Directorate of Advisory Extension and Research Services (DAERS), BUET, Dhaka, Bangladesh. The authors are also grateful to the Department of Industrial and Production Engineering and department of Mechanical Engineering, BUET for providing the facilities to carryout the experiment.

6. REFERENCES

1. Klocke, F., Eisenblatter, G., "Dry Cutting," Annals of the CIRP, 46 (2), pp. 519-526, 1997.
2. MaClure, T. F., Adams, R. and Gugger, M. D, Comparison of Flood vs. Micro-lubrication on Machining Performance, website: <http://www.unist.com/techsolve.html>, 2001.
3. Brockhoff, T. and Walter, A., "Fluid Minimization in Cutting and Grinding," Abrasives, October 1998, pp. 38-42, 1998.
4. Aronson, R. B. "Why Dry Machining", Manufacturing Engineering, pp. 33-36, January 1995.
5. U.S. Department of Health and Human Services, Occupational Exposure to Metalworking Fluids, NIOSH Publication No. 98-102, January 1998.
6. Bennett, E.O. and Bennett, D.L., "Occupational Airway Diseases in the Metalworking Industry," Tribology International, 18/3, pp. 169-176, 1985.