To appear in *HNICEM '03*

Minimum Quantity Lubrication in Finish Hard Turning

Ronan Autret, Graduate Research Assistant
Steven Y. Liang, Professor
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

Abstract

Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. Typically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Minimum quantity lubrication (MQL) presents itself as a viable alternative for hard machining with respect to tool wear, heat dissertation, and machined surface quality. This study compares the mechanical performance of minimum quantity lubrication to completely dry lubrication for the turning of hardened bearing-grade steel materials based on experimental measurement of cutting forces, tool temperature, white layer depth, and part finish. The results indicate that the use of minimum quantity lubrication leads to reduced surface roughness, delayed tool flank wear, and lower cutting temperature, while also having a minimal effect on the cutting forces.

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 (7.5%), 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/m^3, per the U.S. Occupational Safety and Health Administration (OSHA) [4], and is 0.5 mg/m^3 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/m^3 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 thus 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 hard turned parts, 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 hard cutting conditions, involving high thermal and mechanical loads. In the study, the minimum quantity lubrication is provided with a spray of air and vegetable oil. During each test, surface roughness, white layer depth, tool wear, cutting forces, and temperature are measured and compared. The following sections describe the experimental set-up, procedure, data, and analysis.

Experimental Set-up and Parameters

Figure 1 shows the use of a minimum quantity lubrication applicator (Unist Lubricator) on a slant bed horizontal lathe (Hardinge T42SP) at the Georgia Institute of Technology. The coolant used was a triglyceride and propylene glycol ester solution dispensed at a flow rate of 50 ml/hour under the nozzle pressure of 20psi. The workpiece material is high carbon steel bars hardened to 62 to 64 RHC. The cutting tool used was low content CBN tool (Kennametal KD5625) with rake angle of -6^o, chamfer length of 0.12 mm, horn radius of 0.03 mm, and nose radius of 0.8 mm.

During machining, cutting forces were measured with a tool post dynamometer as seen in Figure 1. Shown in Figure 2 is the use of a K-type thermocouple mounted under the cutter insert shim to measure temperature. This system actually measures the temperature under the insert, at the tip but between the shim and the insert. The temperature (Temp) at the thermocouple location can be related to the temperature (Tc), as measured by inferred imaging method, at the tip of the tool by

$$\mathrm{Temp}(t) = \frac{1}{k} T_C(t - \tau) \tag{1}$$

where k is an attenuation factor with a value on the order of 8, and δ is a time delay often observed to be about 4 sec.

Figure 1 Minimum quantity lubrication applicator fitted to a horizontal lathe (on left). Dry machining (on center). Minimum quantity lubrication machining (on right).

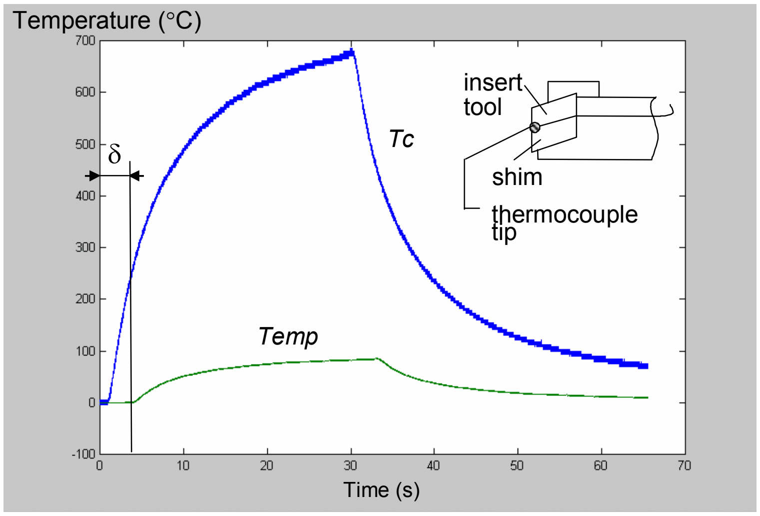


Figure 2 Tool shim thermocouple measurement of cutting temperature

Results

Figure 3 shows the increase of cutting forces with respect to feed. However, the use of minimum quantity lubrication does not affect the force level in any noticeable way. Therefore, the thermal softening of material does not seem to occur with such a small amount of fluid. Figure 4 gives the rise of temperature at tool shim corresponding to various feed. The temperature rise is defined as the change of temperature during the first second of machining. It is seen that the temperature drops on the order of 5 to 10% with the use of minimum quantity lubrication. This effect is also qualitative appreciated in comparing the dry to minimum quantity lubrication as shown in Figure 1. The application of minimum quantity lubrication is observed to alleviate the high temperature on chip.

The resulting surface finishes are shown in Figure 5. Under the depth of cut of 0.012 inch and feed of 0.006 in/rev, the chip formation is smooth with no side flow present, making the feed marks clearly distinguishable. The effect of minimum quantity lubrication is to lower the Ra finish by about 50% with all fresh tools and under the given set of cutting conditions. However, the same amount of finish improvement was not consistently observed when other feed conditions were tested. Generally, the effect of minimum quantity lubrication is more noticeable under stronger – higher feed and deeper cut – conditions.

Tests were also performed with certain wearlands on the tool flank. These wearlands were naturally developed to various lengths during machining. The purpose of the tests were to evaluate the effect of tool wear on the performance of minimum quantity lubrication as well as assess the resulting tool performance under minimum quantity lubrication. Figure 6 shows the cutting forces with dry and minimum quantity lubrication conditions under the influence of tool flank wear. Note that the material removal rate was relatively high, and the decrease of cutting forces in all feed, tangential, and thrust directions are attributed to the existence of crater wear. The use of minimum quantity lubrication in this case does not lead to noticeable force difference.

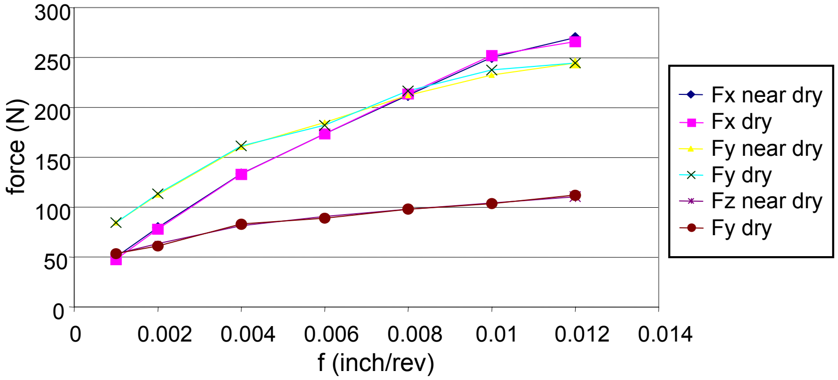


Figure 3 Forces under various feed. Cutting speed = 450sfpm and depth of cut = 0.012 inch.

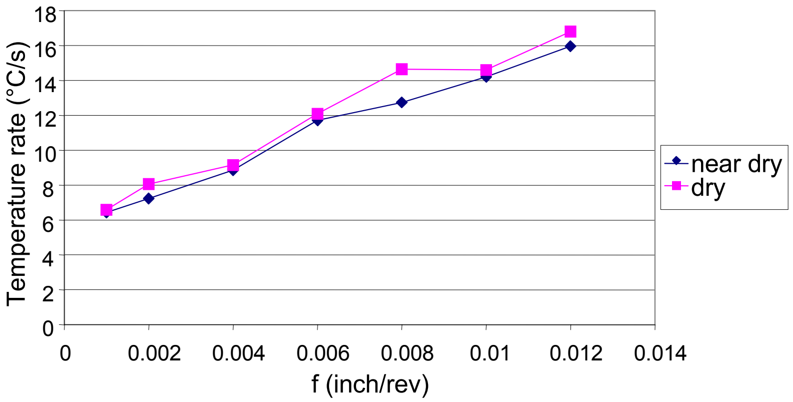
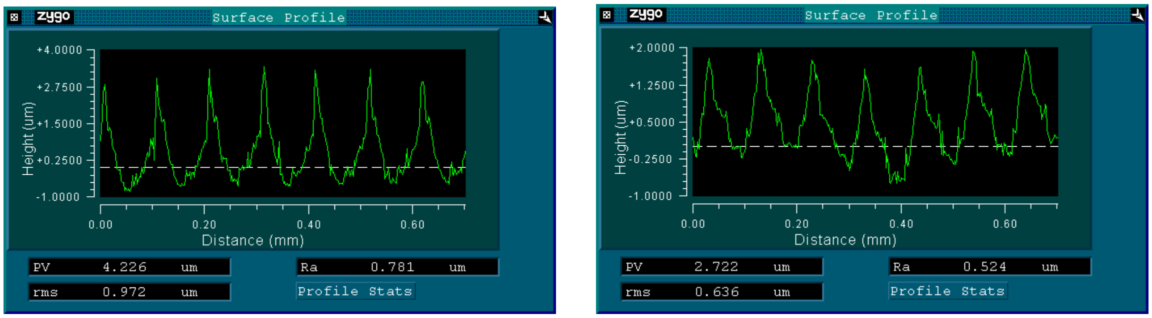


Figure 4 Temperature rate under various feed. Cutting speed = 450sfpm and depth of cut = 0.012 inch.



PV 4.226 um
rms 0.972 um
Ra 0.781 um

PV 2.722 um
rms 0.636 um
Ra 0.524 um

Figure 5 Resulting workpiece surface profile with feed = 0.006 in/rev, cutting speed = 450sfpm and depth of cut = 0.012 inch. Dry cutting on left and minimum quantity lubrication on right.

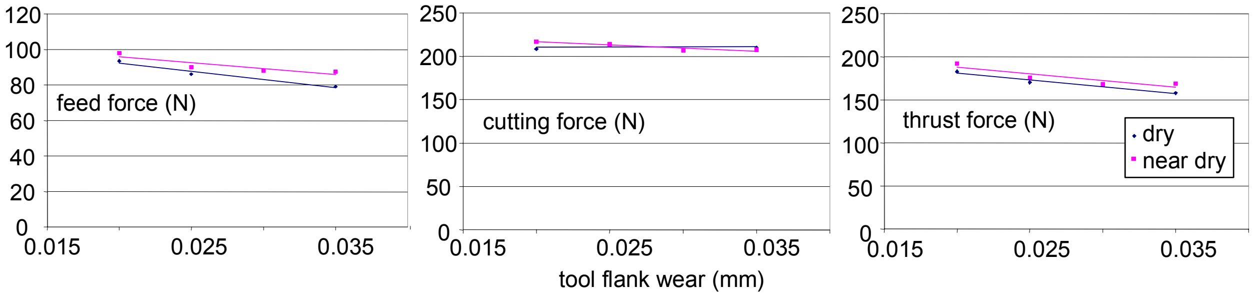


Figure 6 Cutting forces versus maximum flank wear for cutting speed = 700 sfpm, feed = 0.008 in/rev, depth of cut = 0.01 in.

Temperatures after two minutes of cutting were measured with tool worn to different extents. This temperature is not the temperature right at the tool-workpiece contact point, but rather the temperature under the tool shim where the thermocouple is located. The tested condition did not permit white layers to take place on the workpiece. Under two different cutting conditions, the steady state temperature is seen in Figure 7, to be lower by about 20 to 30 degrees while minimum quantity lubrication is used. Since temperature is an important factor governing the thermal damage on tool, the life of the cutter is expected to change according to lubrication condition.

Figure 8 shows the progression of tool wearland under two different cutting conditions. Measurements of tool wear were taken after each cut. The initial chipping of tool in one of the cutting condition is given in Figure 9, which shows the evident effect of MQL in reducing the loss of tool material on flank. In two different cutting conditions, it is seen that the rate of tool wear is reduced if minimum quantity lubrication is applied. The eventual termination point of the test determines the tool life, which is caused primarily by chipping on the tool rake. The minimum quantity lubrication postponed such chipping so that the flank wear was allowed to progress to a greater length before the tool failed. In terms of machining time, it is further noted that the use of minimum quantity lubrication contributed to the prolonging of tool life by 35% to 50%. This effect is more pronounced under greater material removal rates.

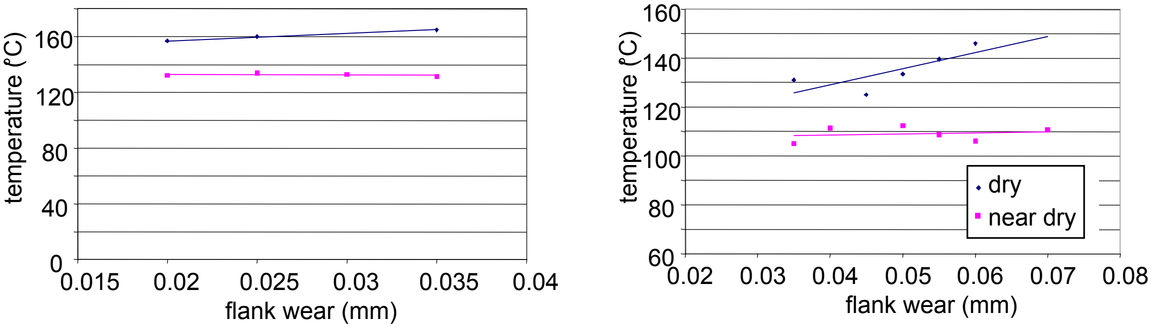


Figure 7 Steady state (after 2 minute machining time) cutting temperature versus maximum flank wear for cutting speed = 700 sfpm, feed = 0.008 in/rev, depth of cut = 0.01 in (on left) and cutting speed = 500 sfpm, feed = 0.004 in/rev, depth of cut = 0.012 in (on right).

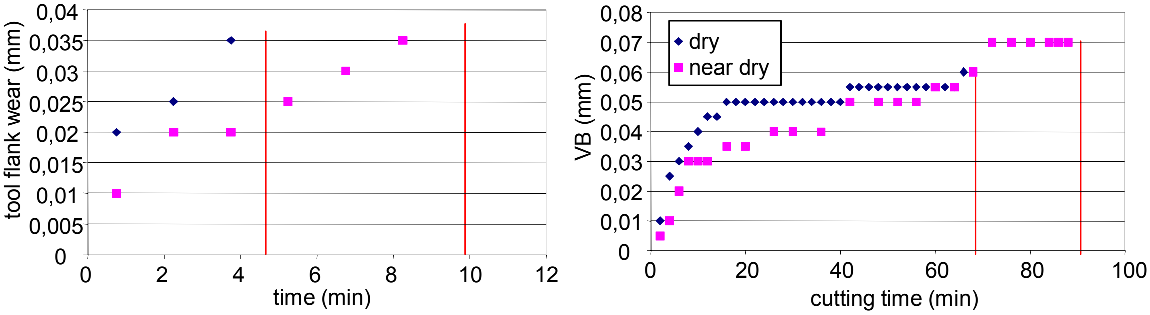


Figure 8 Tool flank wear progression in time for cutting speed = 700 sfpm, feed = 0.008 in/rev, depth of cut = 0.01 in (on left) and cutting speed = 500 sfpm, feed = 0.004 in/rev, depth of cut = 0.012 in (on right).

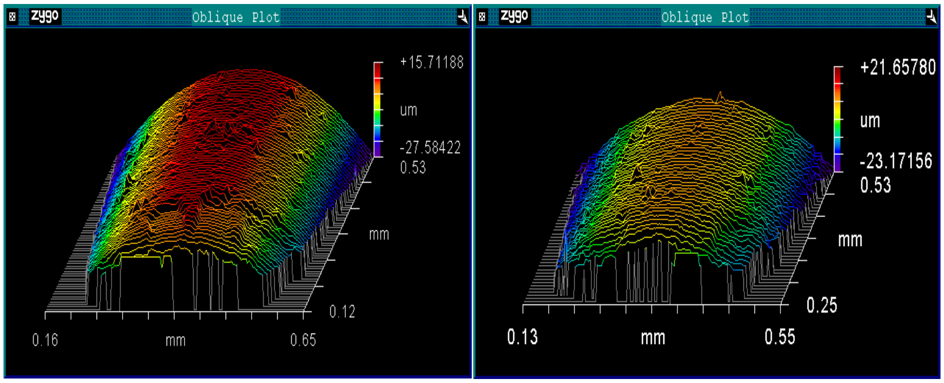


Figure 9 The initial chipping of cutter in day (left) and MQL (right) cutting after 40 seconds. Cutting speed = 500 sfpm, feed = 0.004 in/rev, depth of cut = 0.012 in

Based on the Taylor's model, cutting tool life (T) can be generally described in term of cutting velocity as

$$T = \exp(C) V_C^{a} \tag{2}$$

With the data given in Table 1 the Taylor's model coefficients C and a can be calculated as given in Table 2.

Table 1 Tool life test results

Test	Vc (sfpm)	F (in/rev)	Ap (in)	T in MQL (min)	T in Dry (min)
1	500	0.004	0.01	90	68
2	700	0.008	0.01	9.75	5.25

Table 2 Taylor's coefficients

Coefficient	MQL	Dry
a	-6.60	-7.61
C	45.54	51.52

Tests were performed to confirm the dynamic behavior of temperature and force in response to minimum quantity lubrication. During testing, the total length of cut (8 inches) along the bar specimen was divided into three consecutive sections. The first section was cut completely dry, the minimum quantity lubrication was applied at the start of the second section, and at the tool entrance into the third section, the minimum quantity lubrication was turned off so that a dry cutting condition resumes. The profile of tool shim temperature and the 3-D forces with respect to cutting time are shown in Figure 10. The steady state temperature drops by about 15% as a result of minimum quantity machining application, while the time it takes to reach such a steady state temperature is on the order of 20 to 30 seconds. The forces exhibit no apparent difference with or without the use of minimum quantity lubrication. These observations are generally consistent with other steady state testing results.

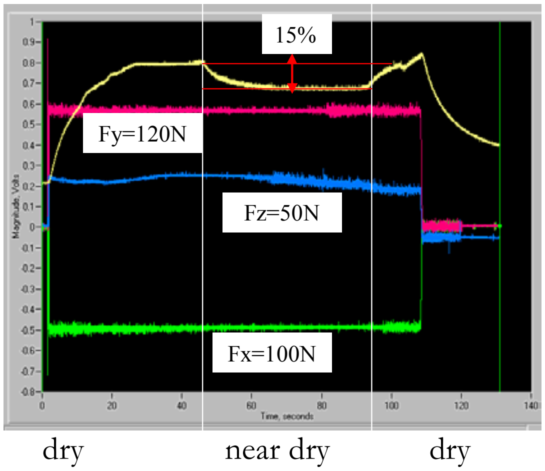


Figure 10 Variation of temperature and cutting forces in response to intermittent application of minimum quantity *lubrication. Cutting speed = 500 sfpm, feed = 0.002 in/rev, depth of cut = 0.0075 in.*

Conclusions

An experimental study has been performed to examine the effect of minimum quantity lubrication over completely dry condition in the turning of hardened high carbon steel materials with low content CBN cutters. The process attributes analyzed herein have included the surface roughness, cutting temperature, cutting forces, and tool life. A range of feeds, speeds, and depths of cut were tested with a water soluble propylene glycol ester solution as cutting fluid at a constant flow rate and a nozzle pressure.

In the context of resulting surface roughness, no noticeable difference can be concluded with the use of near-dry over completely dry condition. However, the improvement of surface finish can be more obviously felt by near-dry machining under greater depths of cut and feeds. In the context of steady-state cutting temperature, a 10 to 30% reduction is consistently observed when minimum quantity lubrication condition is applied as opposed to completely dry. It is expected to be a result of increase in the evaporative heat transfer at the cutting zone. In the contest of cutting forces, there is no significant difference with or without the use of minimum quantity lubrication. The thermal softening effect of workpiece in completely dry machining condition is not overwhelming, therefore, the benefit of using completely dry over minimum quantity lubrication is not readily justified. In the context of tool life, the study has shown a significant increase of tool life – over 30% -- by minimum quantity lubrication over a wide range of cutting conditions. This effect is in close coupling to the reduction of cutting temperature.

It can thus be concluded that the use of cutting fluid at minute amounts can potentially protect the tool while holding the cutting forces relatively unchanged in comparison to completely dry cutting. Other machining performance issues in terms of chip flushing and environmental consciousness have not been included in this study. Further research in these directions is suggested.

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