Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Performance evaluation of minimum quantity lubrication by vegetable oil in terms of cutting force, cutting zone temperature, tool wear, job dimension and surface finish in turning AISI-1060 steel*

KHAN M.M.A.[†1], DHAR N.R.[2]
([1]Department of Industrial and Production Engineering, Shahajalal University of Science and Technology, Sylhet, 3114, Bangladesh)
([2]Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh)
[†]E-mail: muhshin92@yahoo.com
Received Mar. 21, 2006; revision accepted Aug. 25, 2006

Abstract: In all machining processes, tool wear is a natural phenomenon and it leads to tool failure. 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 fluid 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. The minimization of cutting fluid also leads to economical benefits by way of saving lubricant costs and workpiece/tool/machine cleaning cycle time. The concept of minimum quantity lubrication (MQL) 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. This paper deals with experimental investigation on the role of MQL by vegetable oil on cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-1060 steel at industrial speed-feed combinations by uncoated carbide insert. The encouraging results include significant reduction in tool wear rate, dimensional inaccuracy and surface roughness by MQL mainly through reduction in the cutting zone temperature and favorable change in the chip-tool and work-tool interaction.

Key words: Minimum quantity lubrication (MQL), Cutting force, Chip-tool interface temperature, Tool wear, Surface roughness, Dimensional deviation
doi:10.1631/jzus.2006.A1790 **Document code:** A **CLC number:** TG312

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 (Leskover and Grun, 1986; Tönshoff and Brinkomeier, 1986). In high speed machining, conventional cutting fluid application fails to penetrate the chip-tool interface and thus cannot remove heat effectively (Shaw *et al*., 1951; Paul *et al*., 2000). 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 (Cassin and Boothroyed, 1965). However, high-pressure jet of soluble oil, when applied at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent (Mazurkiewicz *et al*., 1989; Alexander *et al*., 1998).

However, the advantages caused by the cutting

* Project (No. DEARS/CASR/R-01/2001/D-934 (30)) supported by Directorate of Advisory Extension and Research Services (DAERS), Committee for Advanced Studies & Research (CASR), BUET, Dhaka, Bangladesh

fluids have been questioned lately, due to the several negative effects they cause. When inappropriately handled, cutting fluids may damage soil and water resources, causing serious loss to the environment. Therefore, the handling and disposal of cutting fluids must obey rigid rules of environmental protection. On the shop floor, the operators may be affected by the bad effects of cutting fluids, such as by skin and breathing problems (Sokovic and Mijanovic, 2001).

For the companies, the costs related to cutting fluids represent a large amount of the total machining costs. Several researchers (Klocke and Eisenblätter, 1997b; Byrne and Scholta, 1993) state that the costs related to cutting fluids are frequently higher than those related to cutting tools. Consequently, eliminating 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. Enormous efforts to reduce or eliminate the use of lubricant in metal cutting are, therefore, being made from the viewpoint of cost, ecological and human health issues (Aronson, 1995; Heisel *et al*., 1994; Honma *et al*., 1996; Klocke and Eisenblätter, 1997a). Dry machining technologies and minimum quantity lubrication (MQL) which uses a fine spray of cooling medium are, therefore, being pursued as alternatives for conventional coolants. However, dry machining and MQL will only be acceptable on condition that the main tasks of coolants in machining processes can be successfully replaced.

Dry machining is now of great interest and actually, they meet with success in the field of environmentally friendly manufacturing (Klocke and Eisenblätter, 1997b; Aronson, 1995). 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 (Klocke and Eisenblätter, 1999; Heisel *et al*., 1994; Wakabayashi *et al*., 1998; Sutherland, 2000; Suda, 2001). MQL refers to the use of cutting fluids of only a minute amount—typically of a flow rate of 50 to 500 ml/h. The concept of MQL, sometimes referred to as near dry lubrication (Klocke and Eisenblätter, 1997b) or micro-lubrication (MaClure *et al*., 2001), 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. However, there has been little investigation of the cutting fluids to be used in MQL machining. Fluids not applied for MQL (Stäbler *et al*., 2003; Sefrin, 1999; Hörner, 1997) are water mixed cooling lubricants and their concentrates, lubricants with organic chlorine or zinc containing additives, lubricants that have to be marked according to the Decree on Hazardous Materials and products basing on mineral base oils in the cooling lubricant>3×10^{-6} benzpyrene. From viewpoints of performance, cost, health, safety and environment, vegetable oils are, therefore, considered as viable alternative to petroleum-based metalworking cutting fluids (Skerlos and Hayes, 2003; Krahenbuhl, 2005) because:

(1) Molecules, being long, heavy, and dipolar in nature, create a dense homogeneous and strong lubricating film that gives the vegetable oil a greater capacity to absorb pressure.

(2) The lubricating film layer provided by vegetable oils, being intrinsically strong and lubricious, improves workpiece quality and overall process productivity reducing friction and heat generation.

(3) A higher flash point yields opportunities for increased rates of metal removal as a result of reduced smoke formation and fire hazard.

(4) The higher boiling point and greater molecular weight of vegetable oil result in considerably less loss from vaporization and misting.

(5) Vegetable oils are nontoxic to the environment and biologically inert and do not produce significant organic disease and toxic effect.

(6) No sign and symptom of acute and chronic exposure to vegetable oil mist have been reported in human (ACGIH, 2001).

Significant progress has been made in dry and semidry machining recently, and MQL machining in particular has been accepted as a successful semidry application because of its environmentally friendly characteristics. Some good results have been obtained with this technique (Dhar and Islam, 2005; Dhar *et al*., 2006; Coelho *et al*., 1995; Tönshoff and Spintig, 1994; Ferraresi, 1974). Lugscheider *et al*.(1997) used this technique in the reaming process of gray cast iron (GG25) and aluminum alloy (AlSI12) with coated carbide tools and concluded that it caused a reduction of tool wear when compared to the completely dry process and, consequently, an improvement in the surface quality of the holes. The drilling of aluminum-silicon alloys is a process where dry cutting is impossible (Derflinger *et al*., 1999), due to the high ductility of the workpiece material. Without cooling and lubrication, the chip sticks to the tool and breaks it in a very short time during cutting. Machado and Wallbank (1997) conducted experiments on turning medium carbon steel (AISI1040) using a Venturi to mix compressed air (the air pressure was of 2.3 bar) with small quantities of a liquid lubricant, water or soluble oil (the mean flow rate was between 3 and 5 ml/min). The mixture was directed onto the rake face of a carbide tool against the chip flow direction. The application of a mixture of air and soluble oil was able to reduce the consumption of cutting fluid, but it promoted a mist in the environment with problems of odors, bacteria and fungi growth of the overhead flooding system. For this reason, the mixture of air and water was preferred. However, even if the obtained results were encouraging, the system needed yet some development to achieve the required effects in terms of cutting forces, temperatures, tool life and surface finish.

Varadarajan *et al*.(2002) developed alternative test equipment for injecting the fluid and used it with success in hard turning for which a large supply of cutting fluid is the normal practice. The test equipment consisted of a fuel pump generally used for diesel fuel injection in truck engines coupled to a variable electric drive. A high-speed electrical mixing chamber facilitated thorough emulsification. The test equipment permitted the independent variation of the injection pressure, the frequency of injection and the rate of injection. The investigations conducted by the authors revealed that a coolant-rich (60%) lubricant fluid with minimal additives was the ideal formulation. During hard turning of an AISI 4340 hardened steel of 46HRC (460 HV), the optimum levels for the fluid delivery parameters were: a rate of 2 ml/min, a pressure of 20 MPa and a high pulsing rate of 600 pulses/min. In comparison, for the same cutting conditions, with dry cutting and wet cutting, the minimum quantity of cutting fluid method has led to lower cutting forces and temperatures, better surface finish, longer tool life. In addition, it was observed that tightly coiled chips were formed during wet turning and during minimal application, while long snarled chips were prevalent during dry turning. It must be noted that during minimal application, the rate of fluid was only 0.05% of that used during wet turning. The major part of the fluid used during minimal quantity application was evaporated; the remnant was carried out by work and chips and was too low in volume to cause contamination of the environment.

Klocke and Eisenblätter (1997a) dealt with drilling tests using minimum cooling lubrication systems, which are based on atomizing the lubricant directly to the cutting zone. Small quantities of lubricant, in order of 10~50 ml/h, were mixed with compressed air for external feeding via a nozzle or for internal feeding via spindle and tool. Internal feed systems with their ability to deliver the mixture very close to the drill-workpiece contact point may achieve very good results in terms of surface finish and tool life.

Lahres *et al*.(1999) presented dry machining of synchronizing cones for automotive application. The work material was austenitic 22Mn6 steel. In the first step of their study, dry machining was compared to machining with coolant and with minimal lubricant system. The used minimal lubricant system worked with special oil, which had food-grade quality. The air volume flow was about 50 L/min and the air volume oil was about 20 ml/h; hence, the produced chips were dry after leaving the contact zone of the cutting process. At this oil volume flow, a single chip can carry a maximum of 1 ml. Therefore, the chips could be considered as being almost dry and passed for metallic recycling without further treatment. The results exhibited an advantage for the minimal lubricant technique and for the dry machining. Wakabayashi *et al*.(1998), by model experiments, suggested that ester supplied onto a rake face of a tool decomposes to carboxylic acid and alcohol and that its carboxylic acid forms a chemisorbed film with lubricity. In actual conditions with high machining load, however, existence of this kind of boundary film is uncertain (Itoigawa *et al*., 2005).

Review of the literature suggests that the concept of MQL presents itself as a possible solution for machining in achieving slow tool wears while maintaining cutting forces/power at reasonable levels, provided that the MQL parameters can be strategically tuned. The main objective of the present work is to experimentally investigate the roles of MQL by vegetable oil-based cutting fluid on chip tool interface temperature, cutting force, tool wear and surface roughness in turning alloy steel (AISI 1060 steel) by the industrially used uncoated carbide tool (SNMM 120408 TTS) at different cutting velocities and feeds combinations as compared to dry machining.

EXPERIMENTAL INVESTIGATIONS

Experiments were carried out by plain turning a 125 mm diameter and 760 mm long rod of AISI-1060 steel in a powerful and rigid lathe (Lehman Machine Company, USA, 15 hp) at different cutting velocities (V_c) and feed rates (S_o) under dry and MQL by vegetable oil conditions to study the role of MQL on the machinability characteristics of that work material mainly in the aspect of cutting temperature, cutting forces, tool wear, surface roughness and dimensional deviation. 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 Experimental conditions

Conditions	Descriptions
Machine tool	Lathe machine, 15 hp
Work specimens	
Material	AISI 1060 steel (0.58% C, 0.85% Mn)
Hardness (BHN)	245
Size	∅125 mm×760 mm
Cutting insert	Uncoated carbide, TTS, SNMM 120408
Tool holder	PSBNR 2525M12
Working tool geometry	
Inclination angle	−6°
Orthogonal rake angle	−6°
Orthogonal clearance angle	6°
Auxiliary cutting edge angle	15°
Principal cutting edge angle	75°
Nose radius	0.8 mm
Process parameters	
Cutting velocity V_c (m/min)	72, 94, 139 and 164
Feed rate S_o (mm/rev)	0.10, 0.13, 0.16 and 0.20
Depth of cut t (mm)	1.5
Cutting fluid	Food-grade vegetable oil; Viscosity: 84 cP at 20 °C; Flash point: 340 °C (open cup)
MQL supply	Air: 7 bar; Flow rate: 60 ml/h (through external nozzle)
Environment	Dry and MQL

hp: horse power, the unit of power; cP: centi-Poise, the unit of viscosity

The MQL needs to be supplied at high pressure and impinged at high speed through the nozzle at the cutting zone. Considering the conditions required for the present research work and uninterrupted supply of MQL at constant pressure over a reasonably long cut, an MQL delivery system was designed, fabricated and used. The thin but high velocity stream of MQL was projected along the cutting edge of the insert, as indicated in a frame within Fig.1, so that the coolant reaches as close to the chip-tool and the work-tool interfaces as possible. The photographic view of the experimental set-up is shown in Fig.1. The MQL jet was used mainly to target the rake and flank surface and to protect the auxiliary flank to enable better dimensional accuracy.

MQL by vegetable oil is expected to provide some favorable effects mainly through reduction in cutting temperature. The simple but reliable tool-work thermocouple technique (Dhar and Islam, 2005) was employed to measure the average cutting temperature during turning at different V_c-S_o combinations by the uncoated carbide insert under dry and MQL conditions.

The effectiveness, efficiency and overall economy of machining any work material by given tool depend largely only on the machinability characteristics of the tool-work material under the recommended condition. Machinability is usually judged by (1) cutting temperature which affects product quality and cutting tool performance, (2) pattern and mode of chip formation, (3) magnitude of the cutting forces which affects power requirement, dimensional accuracy and vibration, (4) surface finish and (5) tool wear and tool life. In the present work, cutting

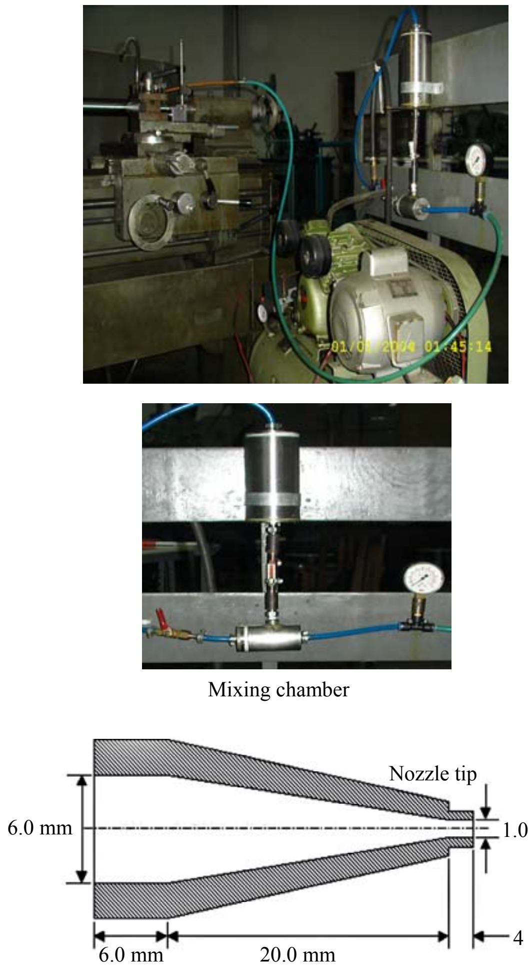


Fig.1 Photographic view of the experimental set-up

temperature, tool wear, surface roughness and product accuracy are considered for studying the role of MQL.

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 and auxiliary flank wear, V_S were measured using metallurgical microscope (Carl Zesis, 351396, Germany) fitted with micrometer of least count 1 μm. The surface roughness of the machined surface after each cut was measured by a Talysurf (Surtronic 3+ Roughness Checker, Taylor Hobson, UK) using a sampling length of 0.8 mm. The deviations in the job diameter before and after cuts were measured by a precision dial gauge, which was travelled parallel to the axis of the job. At the end of full cut, the cutting inserts were inspected under scanning electron microscope (Hitachi, S-2600N SEM, Japan). The tangential or main component, P_z and the axial or feed component, P_x were monitored by a 3D dynamometer (KISTLER, 3D-Dynamometer).

EXPERIMENTAL RESULTS AND DISCUSSION

During machining of ductile materials, heat is generated at: (1) the primary deformation zone due to shear and plastic deformation, (2) the chip-tool interface due to secondary deformation and sliding, and (3) the work-tool interfaces due to rubbing. All such heat sources produce maximum temperature at the chip-tool interface, which substantially influences the chip formation mode, cutting forces and tool life. Therefore, attempts were 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 be expected to cool and lubricate effectively at the chip-tool interface where the temperature is maximum. This is mainly because the flowing chips make mainly in 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 into 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.

However, it was observed that MQL by vegetable oil jet in its present way of application enabled reduction of the average cutting temperature by about 5% to 12% depending upon the levels of the process parameters, V_c and S_o. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

The cutting temperature generally increases with the increase in V_c and S_o, though in different degree, due to increased energy input and it could be expected that MQL by vegetable oil would be more effective at higher values of V_c and S_o. But actually it was otherwise as shown in Table 2.

The percentage reduction in the average cutting temperature gradually decreases with the increase in

Table 2 Reduction in forces and θ_{avg} due to MQL by vegetable oil

Feed rate S_o (mm/rev)	Cutting velocity V_c (m/min)	Percentage reduction		
		P_x	P_z	θ_{avg}
0.10	72	3.22	3.77	7.10
	94	3.40	2.41	8.57
	139	5.36	4.07	8.08
	164	3.27	2.12	5.96
0.13	72	8.82	3.95	7.48
	94	8.73	6.56	6.66
	139	5.49	5.03	7.80
	164	4.13	4.15	8.86
0.16	72	6.49	4.44	9.33
	94	6.40	6.76	11.11
	139	7.43	9.12	13.37
	164	3.03	4.72	12.07
0.20	72	7.66	7.05	8.97
	94	6.80	5.79	10.06
	139	7.07	5.08	10.97
	164	5.26	1.49	11.76

V_c more or less for all the values of S_o when the steel rod was machined under MQL condition. It seems the increased bulk contact of the chips with the tool with the increase in V_c did not allow significant entry of even the MQL jet in case of the SNMM insert whose cutting edge geometry allowed intimate contact of the chip over the chip-tool contact length. Only possible reduction in the chip-tool contact length by the MQL jet, particularly that which comes along the auxiliary cutting edge, could reduce the temperature to some extent particularly when the chip velocity was high due to higher V_c.

The effectiveness of the MQL by vegetable oil was supposed to decrease with the increase in S_o also for more intimate chip-tool contact as shown in Table 2. With the increase in S_o, the chip-tool contact length generally increases but the close curvature of the grooves parallel and close to the cutting edges of the insert reduces the chip-tool contact length and thus possibly helped in reducing the chip-tool interface temperature further.

The cutting tools in conventional machining, particularly in continuous chip formation processes like turning, generally fail by gradual wear by abrasion, adhesion, diffusion, chemical erosion, galvanic action, etc. depending upon the tool-work materials and machining condition. Tool wear initially starts with a relatively faster rate due to what is called break-in wear caused by attrition and microchipping at the sharp cutting edges.

Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature and/or dynamic loading at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness. However, in the present investigations with the tool and work material and the existing machining conditions, the tool failure mode is mostly gradual wear. The geometrical pattern of tool wear that is generally observed in turning by carbide insert is schematically shown in Fig.2. Among the aforesaid wears, the principal flank wear (V_B) is the most important because it raises the cutting forces and the related problems. The life of carbide tool, 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.

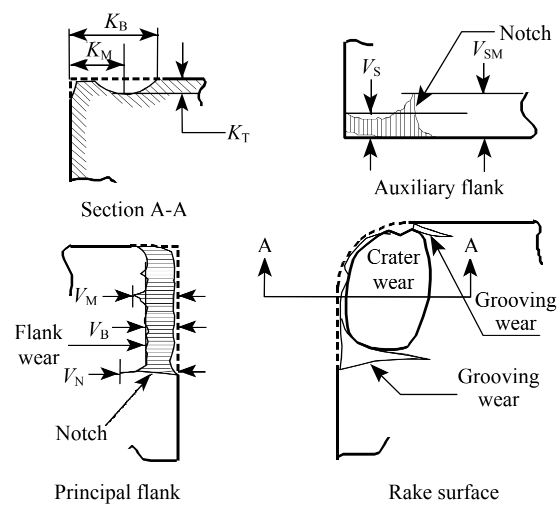


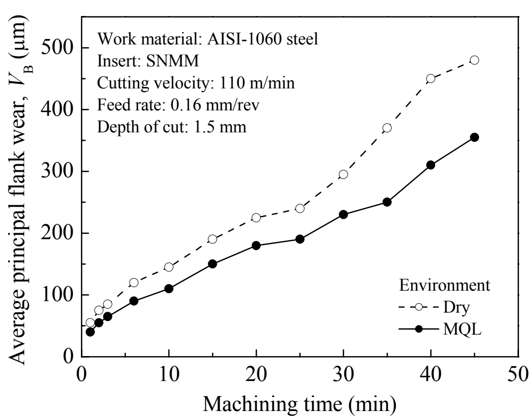
Fig.2 Geometry of wear of turning tool

K_B: average crater wear; K_M: maximum crater wear; K_T: depth of crater wear; V_M: maximum principle flank wear; V_N: notch wear at principle flank; V_{SM}: maximum auxiliary flank wear

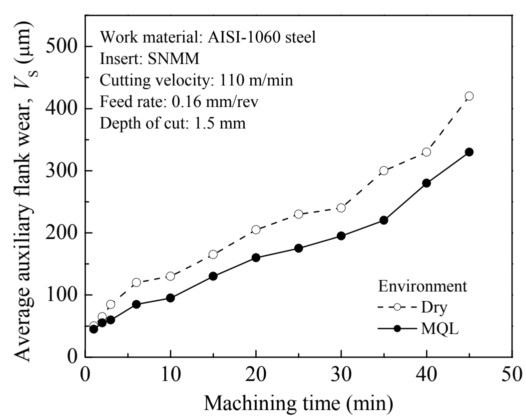
Fig.3a shows the growths in average flank wear, V_B, on the main cutting edge under dry and MQL by vegetable oil conditions. The gradual growth of V_B, the predominant parameter to ascertain expiry of tool life, observed under all the environments indicates steady machining without any premature tool failure by chipping, fracturing, etc. establishing proper choice of domain of process parameters. Fig.3a also clearly shows that flank wear V_B, particularly its rate of growth decreased by MQL by vegetable oil. The cause behind reduction in V_B observed may reasonably be attributed to reduction in the flank temperature by MQL, which helped in reducing abrasion wear by retaining tool hardness and also adhesion and diffusion types of wear which are highly sensitive to temperature. Because of such reduction in rate of growth of flank wear the tool life would be much higher if MQL is properly applied.

Another important tool wear criteria is average auxiliary flank wear, V_S, which governs the surface finish on the job as well as dimensional accuracy. Irregular and higher auxiliary flank wear leads to poor surface finish and dimensional inaccuracy (Lugscheider *et al*., 1997). The growths of average auxiliary flank wear V_S with time of machining of the steel under dry and MQL by vegetable oil conditions are shown in Fig.3b. The nature of growth of V_S matches with that of V_B expectedly. The application of MQL by vegetable oil reduces V_S, which is expected to provide better surface finish and dimensional accuracy.

The SEM views of the worn out insert after being used for about 45 min of machining under dry and MQL by vegetable oil conditions are shown in Fig.4. Under all the environments, abrasive scratch marks appeared in the flanks. Examination of the craters revealed deep scratches left by the backside of the chip on the rake surface of the tool. There were also been some indications of adhesive wear in the insert. Some plastic deformation and micro chipping were found to occur under dry machining. Severe groove wear and notch wear at the flank surfaces were found in the insert under dry condition. The notch wear on the main cutting edge develops mainly because of

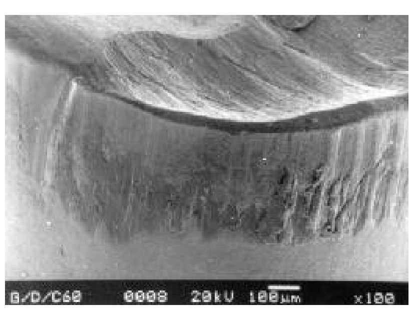


(a)

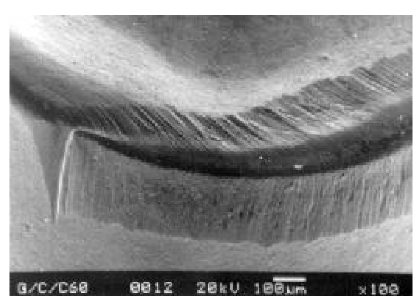


(b)

Fig.3 Growth of average principal flank wear V_B (a) and average auxiliary flank wear V_S (b) with machining time under dry and MQL by vegetable oil conditions



(a)



(b)

Fig.4 SEM Views of the worn out insert after machining 45 min under dry (a) and MQL by vegetable oil (b) conditions

oxidation and chemical wear where the thermo-mechanical stress gradient was also very high. The notch wear on the auxiliary cutting edge develops mainly because of its interaction with the uncut ridges of the work surface with the mechanism of this wear being abrasive. Effective temperature control by MQL by vegetable oil almost reduced the growth of the notch and groove wear on the main cutting edge. It has also enabled the reduction in the auxiliary notch wear. Furthermore, Fig.4 clearly shows reduced average flank wear, average auxiliary flank wear and crater wear under MQL by vegetable oil condition.

Surface finish is also an important index of machinability or grindability because performance and service life of the machined/ground component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface microcracks, if any, particularly when that component is to be used under dynamic loading or in conjunction with some other mating part(s). Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining. Even if it is to be finally finished by grinding, machining prior to that needs to be done with surface roughness as low as possible to facilitate and economize the grinding operation and reduce initial surface defects as far as possible.

The major causes behind development of surface roughness in continuous machining processes like turning, particularly of ductile metals are: (1) regular feed marks left by the tool tip on the finished surface, (2) irregular deformation of the auxiliary cutting edge at the tool-tip due to chipping, fracturing and wear, (3) vibration in the machining system and (4) built-up edge formation, if any.

Fig.5 shows the variation in surface roughness with machining time under dry and MQL by vegetable oil conditions. As MQL reduced average auxiliary flank wear and notch wear on auxiliary cutting edge, surface roughness also grew very slowly under MQL by vegetable oil conditions. 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 by vegetable oil appeared to be effective in reducing surface roughness. However, it is evident that MQL by vegetable oil 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.

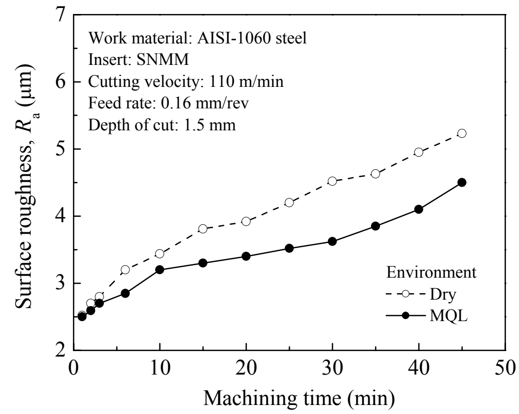


Fig.5 Surface roughness with progress of machining under dry and MQL by vegetable oil conditions

Fig.6 shows the effect of MQL by vegetable oil on the dimensional accuracy of the turned job. MQL provided better dimensional accuracy with respect to controlling the increase in diameter of the finished job with machining time. The finished job diameter generally deviates from its desired value with the progress of machining, i.e. along the job-length mainly due to change in the effective depth of cut for several reasons which include wear of the tool nose, over all compliance of the machine-fixture-tool-work system and thermal expansion of the job during machining followed by cooling. Therefore, if the machine-fixture-tool-work system was rigid, variation in diameter would be governed mainly by the heat and

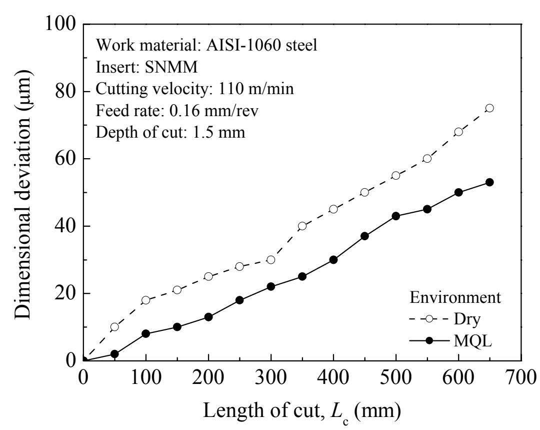


Fig.6 Dimensional deviation observed after one full pass turning of the bar under dry and MQL by vegetable oil conditions

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 from decrease in dimensional deviation.

CONCLUSION

(1) The cutting performance of MQL machining is better than that of dry machining because MQL provides the benefits mainly by reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges.

(2) MQL jet provides reduced tool wear, improves tool life and better surface finish as compared to dry machining of steel.

(3) Surface finish and dimensional accuracy improved mainly due to reduction of wear and damage at the tool tip by the application of MQL. Such reduction in tool wear would either enhance tool life or productivity, allowing higher cutting velocity and feed.

(4) MQL by vegetable oil reduced the cutting forces by about 5% to 15%. P_x decreased more predominantly than P_z. Favourable 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 MQL.

ACKNOWLEDGEMENT

The authors are grateful to the Department of Industrial and Production Engineering, BUET for providing the facilities to carry out the experiment.

References

ACGIH, 2001. Documentation of the Threshold Limit Values and Biological Exposure Indices, 6th Edition. Cincinnati, American Conf. of Governmental Industrial Hygienist.

Alexander, A., Varadarajan, A.S., Philip, P.K., 1998. Hard Turning with Minimum Cutting Fluid: A Viable Green Alternative on the Shop Floor. Proc. of the 18th AIMTDR, p.152-155.

Aronson, R.B., 1995. Why dry machining. *Manf. Engineering*, **114**:33-36.

Byrne, G., Scholta, E., 1993. Environmentally clean machining processes—A strategic approach. *Annals of CIRP*, **42**(1):471-474.

Cassin, C., Boothroyed, G., 1965. Lubrication action of cutting fluids. *J. Mech. Eng. Science*, **7**(1):67-81.

Coelho, R.T., Yamada, S., Aspinwall, D.K., Wise, M.L.H., 1995. The application of polycrystalline diamond (PCD) tool materials when drilling and reaming aluminum based alloys including MMC. *Int. J. Mach. Tools Manuf.*, **35**(5):761-774. [doi:10.1016/0890-6955(95)93044-7]

Derflinger, V., Brändle, H., Zimmermann, H., 1999. New hard/lubricant coating for dry machining. *Surface and Coating Technology*, **113**(3):286-292. [doi:10.1016/S0257-8972(99)00004-3]

Dhar, N.R., Islam, S., 2005. Improvement in Machinability Characteristics and Working Environment by Minimum Quantity Lubrication. CASR Project, BUET.

Dhar, N.R., Islam, M.W., Islam, S., Mithu, M.A.H., 2006. 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*, **171**(1):93-99. [doi:10.1016/j.jmatprotec.2005.06.047]

Ferraresi, D., 1974. Usinagem dos Metais. ABM, Saõ Paulo, p.85.

Heisel, U., Lutz, M., Spath, D., Wassmer, R., Walter, U., 1994. Application of minimum quantity cooling lubrication technology in cutting processes. *Prod. Engineering*, **II**(1):49-54.

Honma, H., Yokogawa, K., Yokogawa, Y., 1996. Study of environment conscious CBN cooling air grinding technology. *J. JSPE*, **62**(11):1638-1642.

Hörner, D., 1997. Cooling Lubricants for Minimum Quantity Lubrication. VDI Conference, p.203. Http://www.engn.umich.edu/alumni/engineer/03FW/research/holography/index.html.

Itoigawa, F., Childs, T.H.C., Nakamuraa, T., Belluco, W., 2005. Effects and mechanisms in minimal quantity lubrication machining of an aluminum alloy. *Wear*, **260**:339-344. [doi:10.1016/j.wear.2005.03.035]

Klocke, F., Eisenblätter, G., 1997a. Machinability investigation of the drilling process using minimal cooling lubrication techniques. *Annals of CIRP*, **46**(1):19-24.

Klocke, F., Eisenblätter, G., 1997b. Dry cutting. *Annals of CIRP*, **46**(2):519-525.

Klocke, F., Eisenblätter, G., 1999. Coated tools for metal cutting-features and applications. *Annals of CIRP*, **48**(2):515-525.

Krahenbuhl, U., 2005. Vegetable Oil-based Coolants Improve Cutting Performance. Http://www.manufacturingcentre.com/tooling/archives/1202/1202oil.asp.

Lahres, M., Doerfel, O., Neumüller, R., 1999. Applicability of different hard coatings in dry machining an austenitic steel. *Surface and Coatings Technology*, **120-121**(1):687-691. [doi:10.1016/S0257-8972(99)00359-X]

Leskover, P., Grun, J., 1986. The metallurgical aspect of machining. *Annals of CIRP*, **35**(1):537-550.

Lugscheider, E., Knotek, O., Barimani, C., Leyendecker, T., Lemmer, O., Wenke, R., 1997. Investigations on hard coated reamers in different lubricant free cutting operations. *Surface and Coatings Technology*, **90**(1-2):172-177. [doi:10.1016/S0257-8972(96)03114-3]

Machado, A.R., Wallbank, J., 1997. The effect of extremely low lubricant volumes in machining. *Wear*, **210**(1-2): 76-82. [doi:10.1016/S0043-1648(97)00059-8]

MaClure, T.F., Adams, R., Gugger, M.D., 2001. Comparison of Flood vs Microlubrication on Machining Performance. Http://www.unist.com/techsolve.html.

Mazurkiewicz, M., Kubala, Z., Chow, J., 1989. Metal machining with high pressure water-jet cooling assistance—A new possibility. *J. Eng. Ind.*, **111**:7-12.

Paul, S., Dhar, N.R., Chattopadhyay, A.B., 2000. Beneficial Effects of Cryogenic Cooling over Dry and Wet Machining on Tool Wear and Surface Finish in Turning AISI 1060 Steel. Proc. of the ICAMT-2000, Malaysia, p.209-214.

Sefrin, H., 1999. Minimum quantity lubrication, application experience in practice. *Tribology and Lubrication Engineering*, **46**(3):261-266.

Shaw, M.C., Piott, J.D., Richardson, L.P., 1951. Effect of cutting fluid upon chip-tool interface temperature. *Trans. ASME*, **71**:45-56.

Skerlos, S., Hayes, K., 2003. Vegetable-based Cutting Fluids: A New Dimension in Research. Http://www.engn.umich.edu/alumni/engineer/03FW/research/holography/index.html.

Sokovic, M., Mijanovic, K., 2001. Ecological aspects of the cutting fluids and its influence on quantifiable parameters of the cutting processes. *Journal of Materials Processing Technology*, **109**(1-2):181-189. [doi:10.1016/S0924-0136(00)00794-9]

Stäbler, D., Schönwald, M., Sefrin, H., Wolf, M., 2003. Hazard Evaluation at the Dry Tooling of Metallic Materials. Final Project Report of the Süddeutsche Metall-Berufsgenossenschaft.

Suda, S., 2001. Evaluation of Machinability with MQL System and Effectiveness in Production Lines. Proc. of the Int. Tribology Conf., Nagasaki, p.203-208.

Sutherland, J.W., 2000. An experimental investigation of air quality in wet and dry turning. *Annals of CIRP*, **49**(1):61-64.

Tönshoff, H.K., Brinkomeier, E., 1986. Determination of the mechanical and thermal influences on machined surface by microhardness and residual stress analysis. *Annals of CIRP*, **35**(2):519-532.

Tönshoff, H.K., Spintig, W., 1994. Machining of holes developments in drilling technology. *Annals of CIRP*, **43**(2):551-561.

Varadarajan, A.S., Philip, P.K., Ramamoorthy, B., 2002. Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning. *Int. J. Mach. Tools Manuf.*, **42**(2):193-200. [doi:10.1016/S0890-6955(01)00119-5]

Wakabayashi, T., Sato, H., Inasaki, I., 1998. Turning using extremely small amount of cutting fluid. *JSME Int. J.*, **41**(1):143-148.