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Effect of Minimum Quantity Lubrication (MQL) on Tool Wear, Surface Roughness and Dimensional Deviation in Turning AISI-4340 Steel

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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 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. The use of cutting fluid generally causes economy of tools and it becomes easier to keep tight tolerances and to maintain workpiece surface properties without damages. Due to these problems, 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 lubrication (MQL).

This paper deals with the experimental investigation on the role of MQL on cutting temperature, tool wear, surface roughness and dimensional deviation in turning of AISI-4340 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: MQL, tool wear, surface roughness and dimensional deviation

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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]. In high speed machining, conventional cutting fluid application fails to penetrate the chip-tool interface and thus cannot remove heat effectively [3,4]. 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 at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent [6,7].

However, the advantages caused by the cutting 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 machine operators may be affected by the adverse effects of cutting fluids, such as by skin and breathing problems [8].

For the companies, the costs related to cutting fluids represent a large amount of the total machining costs. Several research workers [9,10] state that the costs related to cutting fluids are frequently higher than those related to cutting tools. 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 lubrication (MQL).

Dry machining is now of great interest and actually, some researchers meet with success in the field of environmentally friendly manufacturing [9,11]. 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

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become a powerful tool and, in fact, they already play a significant role in a number of practical applications [12-16]. Minimum quantity lubrication (MQL) 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 less than the amount commonly used in flood cooling condition. The concept of minimum quantity lubrication, sometimes referred to as near dry lubrication [9] or micro-lubrication [17], 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.

Significant progress has been made in dry and semidry machining recently, and minimum quantity lubrication (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 [18]. Lugscheider et al. [19] used this technique in reaming process of gray cast iron and aluminum alloy with coated carbide tools and concluded that it caused a reduction of tool wear when compared with the completely dry process and, consequently, an improvement in the surface quality of the holes. Dhar et al. [20] also used this technique in turning process of medium carbon steel and concluded that, in some cases, a mixture of air and soluble oil has been shown to be better than the overhead flooding application of soluble oil.

The drilling of aluminum-silicon alloys is one of those processes where dry cutting is impossible [21] 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 cutting time. Therefore, in this process a good alternative is the use of the MQL technique [22, 23].

The review of the literature suggests that minimum quantity lubrication provides several benefits in machining. The main objective of the present work is to experimentally investigate the role of minimum quantity lubrication (MQL) on cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4340 steel at industrial speed-feed condition by uncoated carbide insert (SNMM 120408) and compare the effectiveness of MQL with that of dry and wet machining.

2. EXPERIMENTAL INVESTIGATIONS

Experiments have been carried out by plain turning a 125 mm diameter and 760 mm long rod of AISI-4340 steel in a powerful and rigid lathe (Lehmann Machine Company, USA, 15hp) at different cutting velocities (V_c) and feeds (S_o) under dry, wet and minimum quantity lubrication (MQL) conditions. The machinability characteristics of that work material mainly in respect of cutting temperature, cutting forces, tool wear, surface roughness and dimensional deviation have been investigated to study the role of MQL. 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

Machine tool	:	Lathe Machine (Lehman Machine Company, USA) 15 hp
Work specimen		
Materials	:	AISI-4340 steel (C=0.36%, Cr=1.45%, Mn=0.92%, Mo=0.52%, Ni=2.87%, V=0.20%)
Size	:	φ125 X 760 mm
Cutting tool (insert)		
Cutting insert	:	Carbide, SNMM 120408 (P-30 ISO specification), Drillco
Tool holder	:	PSBNR 2525M12(ISO specification), Drillco
Working 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	:	0.10, 0.13, 0.16 and 0.20 mm/rev
Depth of cut, t	:	1.0 mm and 1.5 mm
MQL supply	:	Air: 7.0 bar, Lubricant: 60ml/h (through external nozzle)
Environment	:	Dry, wet (flood cooling) and minimum quantity lubrication (MQL)

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, a MQL delivery system has been designed, fabricated and used. The schematic view of the MQL set up is shown in Fig.1. 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.2. The MQL jet has been used mainly to target the rake and flank surface and to protect the auxiliary flank to enable better dimensional accuracy

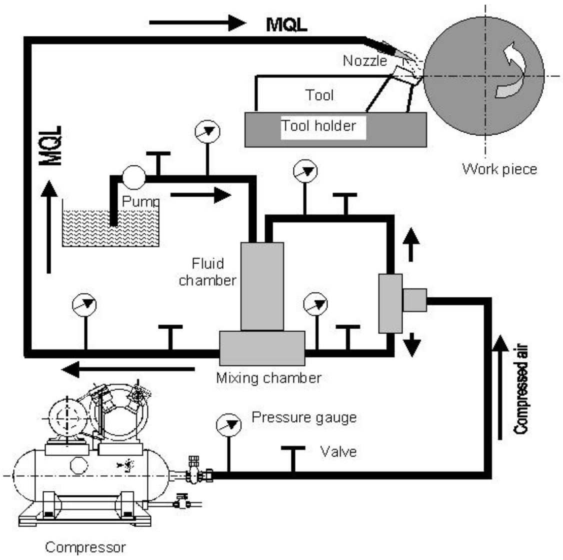
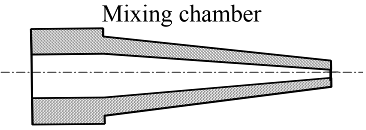


Figure 1. Schematic view of MQL unit.

Mixing chamber



Nozzle tip

Figure 2. Photographic view of the experimental set-up.

MQL is expected to provide some favorable effects mainly through reduction in cutting temperature. The simple but reliable tool-work thermocouple technique [24] 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 conditions.

The effectiveness, efficiency and overall economy of machining any work material by the given tool depends largely only on the machinability characteristics of the tool-work material under the recommended condition. Machinability is usually judged by (i) cutting temperature which affect product quality and cutting tool performance, (ii) pattern and mode of chip formation, (iii) magnitude of the cutting forces which affects power requirement, dimensional accuracy and vibration, (iv) surface finish and (v) tool wear and tool life. In the present work, cutting temperature, tool wear, surface roughness and dimensional accuracy are considered for studying the role of minimum quantity lubrication.

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 1μm. 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 traveled parallel to the axis of the job. At the end of full cut, the cutting inserts were inspected under the scanning electron microscope (Hitachi, S-2600N, Scanning Electron Microscope, Japan).

3. EXPERIMENTAL RESULTS AND DISCUSSION

The machining temperature at the cutting zone is an important index of machinability and needs to be controlled as far as possible. 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 both dry and MQL conditions has been shown in Fig.3. It is evident from Fig.3 that 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 high pressure MQL jet coming from the opposite direction and enables it to 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. However, it was observed that the MQL jet in its present way of application enabled reduction of the average cutting temperature by about 5 to 10% 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.

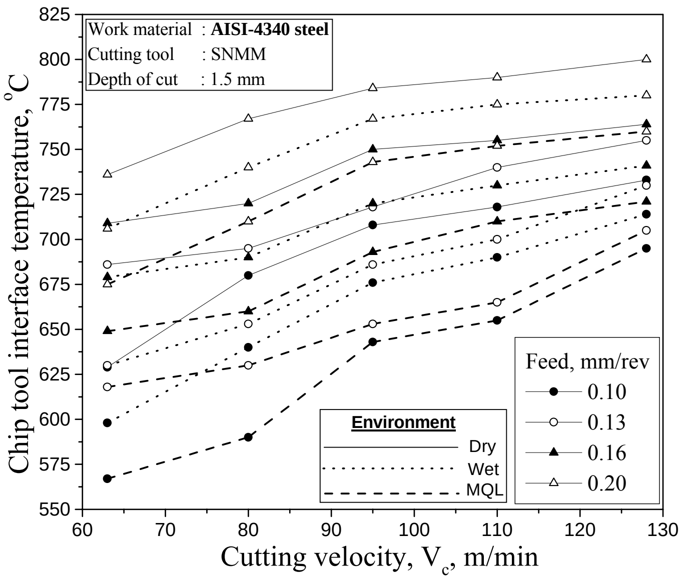


Figure 3. Variation in average chip-tool interface temperature with V_c at different S_o under dry wet and MQL conditions.

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 [4].

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 machining conditions undertaken, the tool failure mode has been mostly gradual wear. The geometrical pattern of tool wear that is generally observed in turning by carbide insert is schematically shown in Fig.4. 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 [24]. Therefore, attempts should be made to reduce the rate of growth of flank wear (V_B) in all possible ways without making a concession in MRR.

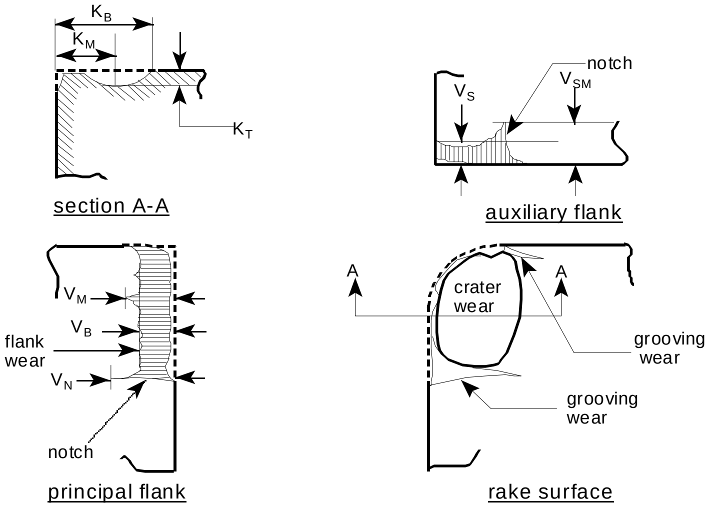


Figure 4. Geometry of wear of turning tool.

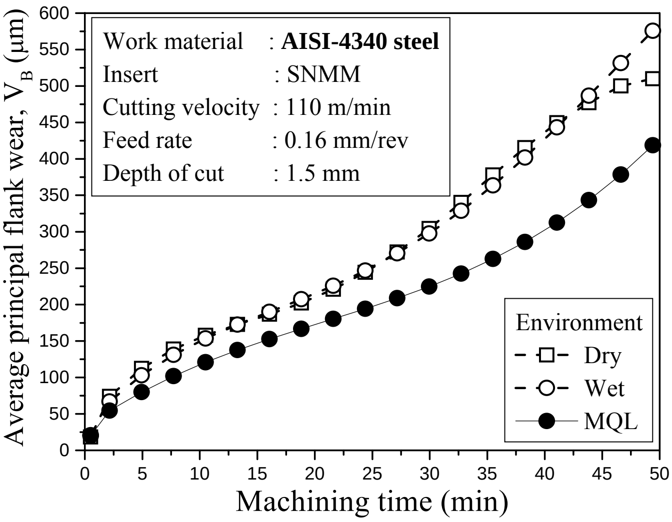


Figure 5. Growth of average principal flank wear, V_B with machining time under dry, wet and MQL conditions.

Fig.5 shows the growth in average flank wear, V_B, on the main cutting edge under dry, wet (conventional cooling with 1:20 soluble oil) and MQL 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.5 also clearly shows that flank wear, V_B particularly its rate of growth decreased by MQL. 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 (Klocke and Eisenblatter 1997). The growth of average auxiliary flank wear, V_S with time of machining of the steel under dry, wet and MQL conditions have been shown in Fig.6. The nature of growth of V_S matches with that of V_B expectedly. The application of MQL has reduced V_S, which is expected to provide better surface finish and dimensional accuracy.

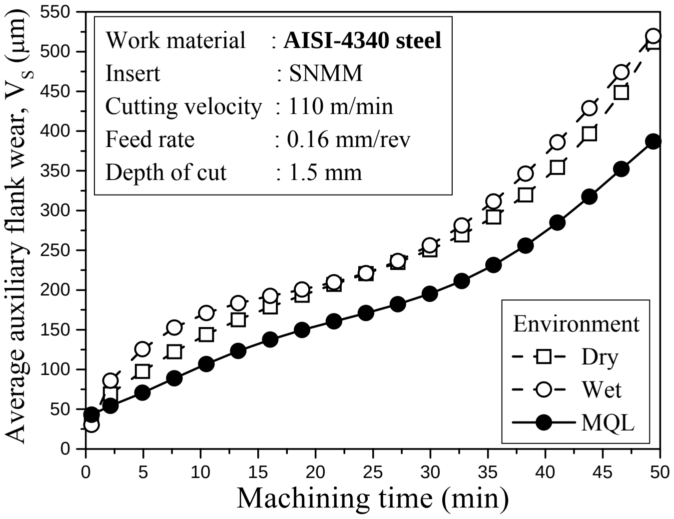


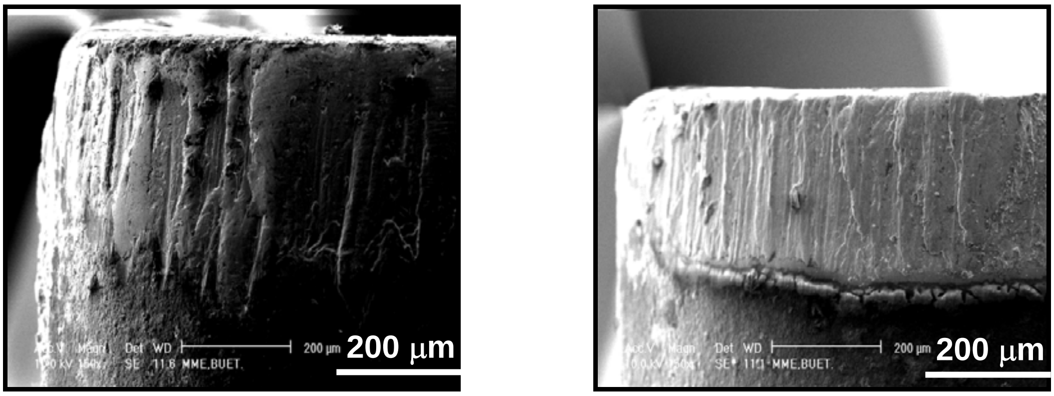
Figure 6. Growth of average auxiliary flank wear, V_S with time under dry, wet and MQL conditions.

The SEM views of the worn out insert after being used for about 45 minutes of machining under dry, wet and MQL conditions are shown in Fig.7. Under all the environments, abrasive scratch marks appeared in the flanks. The examination of the craters revealed deep scratches left by the backside of the chip on the rake surface of the tool. There have also been some indications of adhesive wear in the insert. Some plastic deformation and micro chipping were found to occur under dry and wet machining. Severe groove wear and notch wear at the flank surfaces were found in insert under both dry and wet conditions. The notch wear on main cutting edge develops mainly because of oxidation and chemical wear where the thermo-mechanical stress gradient is 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 and mechanism of this wear is abrasive. Effective temperature control by MQL almost reduced the growth of notch and groove wear on the main cutting edge. It has also enabled the reduction in the auxiliary notch wear. Further the figure clearly shows reduced average flank wear, average auxiliary flank wear and crater wear under MQL condition.

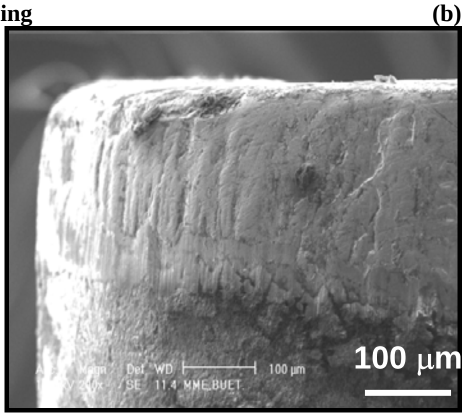
Surface finish is also an important index of machinability or grindability because performance and service life of the machined/ground component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface microcracks, if any, particularly when that component is to be used under dynamic loading or in conjugation 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 (i) regular feed marks left by the tool tip on the finished surface (ii) irregular deformation of the auxiliary cutting edge at the tool-tip due to chipping, fracturing and wear (iii) vibration in the machining system and (iv) built-up edge formation, if any.

Fig.8 shows the variation in surface roughness with machining time under both dry and MQL environments. As MQL reduced average auxiliary flank wear and notch wear on auxiliary cutting edge, surface roughness also grew very slowly under MQL conditions. It appears from Fig.8 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.



(a) Dry machining **(b) Wet machining**



(c) MQL machining

Figure 7. SEM views of the worn out insert after machining 45 minutes under (a) dry, (b) wet and (c) MQL conditions

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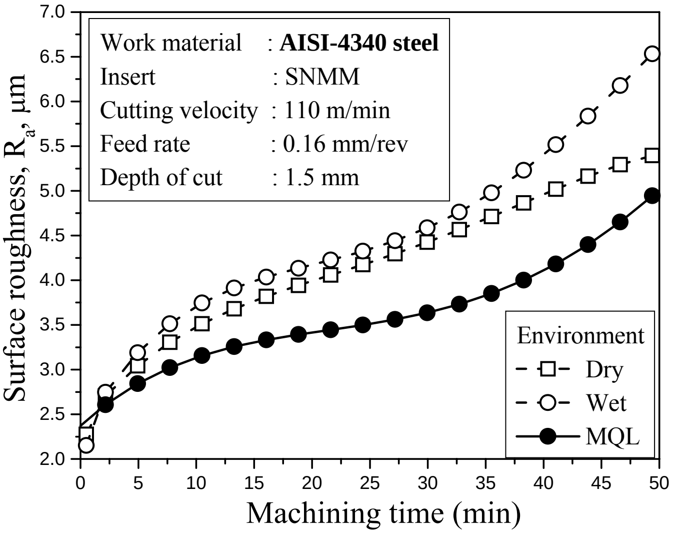

Figure 8. Surface roughness with progress of machining under dry, wet and MQL conditions.

Fig.9 shows the effect of MQL on the dimensional accuracy of the turned job. MQL provided better dimensional accuracy in respect of 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 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 system and thermal expansion of the job during machining followed by cooling. Therefore, if the machine-fixture-tool-work 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.

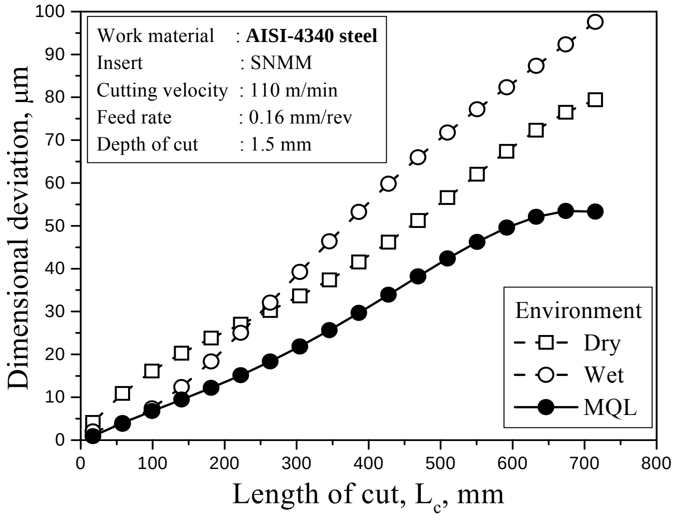

Figure 9. Dimensional deviation observed after one full pass turning of the rod under dry, wet and MQL conditions.

4. CONCLUSIONS

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

i. The cutting performance of MQL machining is better than that of dry and conventional machining with flood cutting fluid supply because MQL provides the benefits mainly by reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges.

ii. MQL jet provided reduced tool wear, improved tool life and better surface finish as compared to dry and wet machining of steel.

iii. 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 lead to improvement in tool life or enhancement of productivity allowing higher cutting velocity and feed.

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