Proceedings of the
International Conference on Mechanical Engineering 2007
(ICME2007) 29- 31 December 2007, Dhaka, Bangladesh

ICME2007-AM-33

AN EXPERIMENTAL STUDY OF EFFECT OF HIGH-PRESSURE COOLANT ON TOOL WEAR, TOOL LIFE AND ROUGHNESS IN TURNING 16MnCr5 STEEL BY SNMG INSERT

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ABSTRACT

The growing demand for high productivity machining and grinding particularly high strength and heat resistance materials need use of high cutting velocity and feed. Such machining and grinding inherently generate very large amount of heat and high cutting temperature, which not only reduces tool life but also impairs the product quality. Conventional cooling methods are not only ineffective but also deteriorate the working environment by producing harmful gasses and smokes. Attempts have already been initiated to control the pollution problem by cryogenic cooling which also helps rid of recycling and disposal of conventional fluids and possible damage of the machine parts by corrosion etc. Industries are reasonably interested to know how, apart from environment friendless, high-pressure coolant affects machinability of any material, which have significant role on efficiency and overall economy of manufacturing by machining. The present work deals with experimental investigation in the role of high-pressure coolant on visible product quality and tool wear in plain turning of 16MnCr5 steel rod at different cutting velocities and feeds by uncoated carbide (SNMG) insert. The encouraging results include significant reduction in dimensional inaccuracy, surface roughness and tool wear rate by high-pressure coolant mainly through reduction in the cutting zone temperature and favorable change in the chip-tool interaction.

Keywords: High-pressure coolant, Tool wear, Surface roughness and Product quality

1. INTRODUCTION

Metal cutting is one of the most important processes carried out in industries consists in separating a layer of metal from the parent work-piece to obtain a machine part of the required shape and dimension and with a specified quality of surface finish by effecting a relative motion between tool and work-piece. The metal cutting process accompanied by deformation of metal in compression, tension and shear by a great deal of friction, a large consumption of energy and heat generation. The mechanical energy necessary for the machining operation is transformed into heat, leading to conditions of high pressure, high temperatures and severe thermal/frictional conditions at the tool-chip interface. The greater the energy consumption, the more severe are the thermal/frictional conditions, consequently making the metal cutting process more and more inefficient in terms of tool life, dimensional accuracy and material removal rate. Most of the mechanical energy used to form the chip becomes heat, which generates high temperatures in the cutting region. High cutting temperature adversely affects tool life, dimensional and form accuracy and surface integrity of the product. The machining process should be carried out at high speeds and feeds and least cutting effort and at lowest cost. High production machining can be defined as that speed above which shear-localization develops completely in the primary shear zone, is associated with generation of large amount of heat and cutting 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 micro-cracks in addition to rapid oxidation and corrosion [1, 2]. Tool failure is an important factor which affects productivity and manufacturing efficiency. Investigation shows that the tool flank face temperature can attain large values especially in high speed machining [3]. As a consequence of these high temperatures, abrasion is considered as being the dominant damage mechanism for tools at high cutting speeds. A good agreement is found with respect to measurements of flank wear and tool life. The temperature rise in the cutting tool tends to soften it and cause loss of keenness in the cutting edge leading to its failure. The cutting force, heat and abrasive wear are thus the basic features of the metal cutting processes. Good machinability is associated with moderate cutting forces, the formation of rather small chips, not excessive tool abrasion and good surface finish.

With the advent of highly hard and stiff carbide tools and other new methods of machining, the efficiency of the metal cutting operations has improved to a certain extent under normal cutting conditions. However, improving the performance of metal cutting operations in high speed machining and in the case of machining difficult-to-machine i.e hard and tough materials is still a major concern.

It was found that the efficiency of metal cutting operations depends to a large extent on the effectiveness of the cooling/lubrication provided. An over head flood of water soluble cutting fluid directed over the back of the chip is the most common method of applying the cutting fluid. However, this method loses its effectiveness at higher cutting speeds. Conventional coolants undergo film boiling at around 350^{o}C and loose their cooling property at such elevated temperature [4-7]. In machining, the chip-tool interface is mainly plastic in nature. Even addition of extreme pressure additives to conventional cutting fluid can not provide desirable lubrication and cooling of chip-tool interface. Moreover, the conventional cutting fluid severely pollutes the environment by producing harmful smokes and gasses, contaminates soil and water which has been a serious concern of the modern society [8].

Possibility of controlling high cutting temperature in high production machining by some alternative methods has been reported. Cutting forces and temperature were found to reduce while machining steel with tribologically modified carbide inserts [9]. Cryogenic machining with liquid nitrogen [10, 11] and machining with minimum quantity lubrication (MQL) has improved machinability of steel to a certain extent under normal cutting conditions [12, 13]. It has also been reported that though the machining of steel with liquid nitrogen improves the machinability index [10, 11]; it is not used in industrial practices due to high cost of liquid nitrogen. In industry, such high cutting temperature and its detrimental effects also can be reduced by using heat and wear resistance cutting tool materials like high performance ceramics. Though high performance ceramics (CBN, PCBN, diamond and PCD) are extremely heat and wear resistive, they are not used in general practice due to their high cost. Those are justified for very special work materials and requirements where other tools are not effective.

The penetration of the cutting fluid either in the form of flood or mist to the chip-tool interfaces becomes difficult at high cutting speeds because of high relative velocity of chip over the cutting face of the tool. This tends to retard the motion of the cutting fluid. In order that a cutting fluid works effectively at higher cutting speed if high velocity stream of fluid is used.

A good number of attempts [14-18] were made in the past to improve cooling/lubrication in machining and by the use of a high pressurized coolant/lubricant jet. In general, all attempts to apply pressurized cutting fluid can be classified into three groups, namely, coolant/lubricant jet injected into tool-chip interface through an external nozzle [14, 17], jet delivered into the clearance between flank and machined surface [15], and jet injected directly through the tool rake face into tool-chip interface [16, 17]. The results achieved by these investigators were very encouraging. Cutting forces were reduced, surface quality and tool life improved, thereby increasing the metal removal rate, and improving the overall performance of the machining operation. From all these investigations, it was evident that applying cutting fluid in the form of a jet at higher pressures into the cutting zone is more beneficial than conventional cooling techniques and a high pressure coolant/ lubricant jet injected into the tool-chip interface provides effective cooling/lubrication and consequently improves the machining performance of the tool.

A high pressure water jet brought as a coolant/lubricant through a hole in the rake face of tool reduces secondary shear, lowers interface temperatures, and changes chip shape [18]. Until now, investigations carried out in this direction were, in general, limited to low pressures where the cutting fluid is not capable of penetrating deep enough into the tool-chip interface to dissipate heat as quickly as possible from the appropriate regions in the cutting zone. Further, all these investigations were limited to stationary single edge cutting tool operations under low speed-feed-doc conditions. However, there is a great need to improve machining performance by improving cooling methods in the case of high speed, feed and depth of cut conditions especially while machining difficult-to machine materials.

The success of implementing this technology across the metal removal industries will therefore depend on increased research activities providing credible data for in depth understanding of high-pressure coolant supplies at the chip-tool interface and integrity of machined components. The review of the literature suggests that high pressure cooling provides several benefits in machining. The main objective of the present work is to experimentally investigate the role of high pressure coolant jet cooling/lubrication with water insoluble cutting oil having a viscosity grade 68 (hydro clear straight run cutting oil, VG-68) on cutting tool wear, tool life and surface finish in turning 16MnCr5 steel by uncoated carbide insert (SNMG 120408) and compare the effectiveness of high pressure coolant with that of dry machining.

2. EXPERIMENTAL INVESTIGATION

Experiments have been carried out by plain turning a φ200 x 580 mm rod of 16MnCr5 steel in a powerful and rigid lathe at different cutting velocities (Vc) and feeds (So) under both dry condition and high-pressure coolant condition to study the role of highly pressurized water insoluble coolant (Hydro clear straight run cutting oil, VG 68) on the machinability characteristics of that work material mainly in respect of tool wear, tool life and surface roughness. The experimental conditions have been given in Table-1.

Nozzle is placed 15 mm apart from the tool tip to minimize the interference of the nozzle with the flowing chips and to reach quite close to the chip tool contact zone, which may cause unfavorable metallurgical changes. Effectiveness of cooling and the related benefits depend on how closely the high pressure coolant jet can reach the chip-tool and the work-tool interfaces where, apart from the primary shear zone, heat is generated. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view tool configuration namely SNMG-120408 has been undertaken for the present investigation. The insert was clamped in a PSBNR-2525 M12 type tool holder.

The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The final arrangement made and used has been shown along with photographic view of experimental set-up in Fig.1.

Table 1: Experimental conditions

Machine tool	:	Lathe Machine (China), 10 hp
Work specimen		
Material	:	16MnCr5 steel (AISI 4320)
Hardness (BHN)	:	201
Size	:	Φ200 X 580 mm
Cutting insert	:	SNMG insert, Sandvik
Tool holder	:	PSBNR 2525 M12, Sandvik
Tool geometry	:	-6^o, -6^o, 6^o, 15^o, 75^o, 0. 8 mm
Process parameters		
Cutting velocity	:	93,133, 186, 266 and 193 m/min
Feed rate	:	0.10, 0.14, 0.18 and 0.22 mm/rev
Depth of cut	:	1.0 mm and 1.50 mm
High pressure coolant	:	80 bar, Coolant: 6.0 l/h through external nozzle
Environments	:	Dry and high pressure coolant (HPC) condition

The high pressure coolant jet is directed along the diagonal of the cutting edges to reach both the principal and auxiliary flanks and partially under the flowing chips so that it can easily penetrate on to the chip tool interface overcoming the retardation tendency of the jet due to high relative velocity of the chip. Wedge action of the jet assist penetration by curling and segmenting the chips.

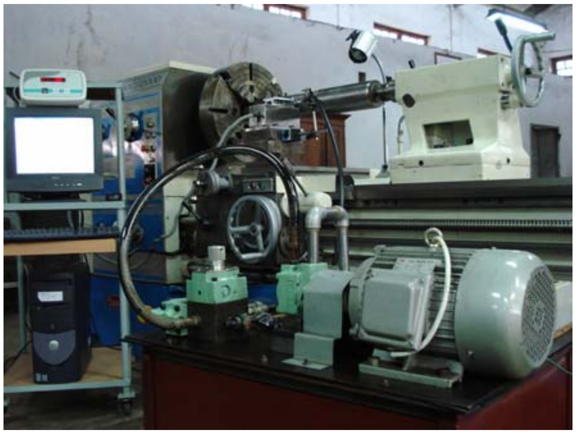


Fig 1:Photographic view of experimental set-up

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

The average cutting temperature was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration [19]. A graphite block was used as a uniform heat source that gains heat from an electric crucible. A carbide rod and a strip of work material joined together at one edge and embedded in the graphite block and the other edges were connected with the terminals of a millivoltmeter. A temperature probe was placed in such a way that the probe and the aforesaid junction be equidistant from the wall of the crucible.

Cutting tool wear at both the principal and auxiliary flanks, and surface roughness were measured at regular intervals in an optical microscope(Carl Zeiss) and a Taly surf (surtronic 3^+) roughness checker respectively while turning by the selected insert at a selected V_c-S_o-t condition under both dry and HPC cooling conditions.

3. EXPERIMENTAL RESULTS AND DISCUSSION

During metal cutting considerable amount of heat is produced due to friction between tool and work and plastic shearing of metal in the form of chips. This heat reduces the hardness of the cutting tool, makes it less wear resistant and changes its dimensions. Heat also leads to changes in the dimensions of machined surfaces. These temperature deformations of the tool and work reduce the machining accuracy.

Heat generation during machining can be categorised as (i) due to shear and plastic deformation. Heat generation in this shear zone is the maximum (ii) chip-tool interface due to secondary deformation and sliding of flowing chips and (iii) work-tool interfaces due to rubbing or burnishing friction. The heat in this zone goes on increasing with time as the wear land on the tool develops and goes on increasing.

In normal cutting condition all such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode; cutting forces, tool life and product quality. High production machining needs to increase the process parameters further for meeting up the growing demand and cost competitiveness. Cutting temperature is increased with the increase in process parameter. Therefore, attempts are made to reduce this detrimental cutting temperature.

Most machining operations can be carried out advantageously by using a cutting fluid. During metal cutting heat and wear are inevitably produced due to friction and shearing action that takes place as the chip being formed. Both heat and wear are undesirable in order to obtain a reasonable tool life and surface finish. One way of improving metal cutting operation is by using a cutting fluid. The cutting fluid can benefit metal cutting in several ways but by far the most important is heat removal and reduce heat generation.

For effective cooling it is necessary to penetrate the fluid as much as possible to the chip-tool interface where the temperature is the maximum. Conventional cutting fluid application even though extreme pressure additives are added with it, may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface. 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 penetration of the cutting fluid to the chip-tool interface becomes difficult at high cutting speeds because of high relative velocity of chip over the cutting face of the tool. This tends to retard the motion of the cutting fluid. In order that a cutting fluid works effectively at higher cutting speed if high velocity stream of fluid is used.

The reduction in cutting temperature, tool wear, surface roughness and improvement in efficiency of metal cutting operation with the aid of high pressure coolant jet cooling/lubrication could be due to several reasons. The penetration of the coolant jet into tool-chip interface results in the formation of a hydro-wedge which provides hydrodynamic lubrication by serving as a boundary lubricant preventing to a large extent the intimate contact between tool and chip. In the case of dry machining, the intimate metallic contact between chip and tool results in an extreme secondary deformation zone, encouraging tool wear. The greater the area of contact, the higher is the friction at the tool-chip interface. In the case of high pressure coolant jet cooling, the formation of hydro-wedge at tool-chip interface tends to keep the chip away from the tool rake face and thereby promoting self-breakage effect. The presence of much bigger serrations on the contact surface in the case of dry machining as compared to high pressure coolant jet cooling is an indication of intense shearing action in the case of dry machining. The improvement in the effectiveness of the cooling/lubrication at higher pressures can be related to formation and growth of hydro-wedge. An increase in coolant pressure is accompanied by a corresponding growth in hydro-wedge which tends to keep the chip farther and farther away from tool-chip contact surface.

The cutting temperature generally increases with the increase in Vc and So, though in different degree, due to increased energy input and it could be expected that high pressure coolant would be more effective at higher values of Vc and So. But actually it had been otherwise as can be shown in Fig. 2. However, it was observed that the high pressure coolant jet in its present way of application enabled reduction of the average cutting temperature by about 8-23 % depending upon the levels of the process parameters. Even such apparently small reduction in the cutting temperature is expected to have some favorable influence on other machinability indices.

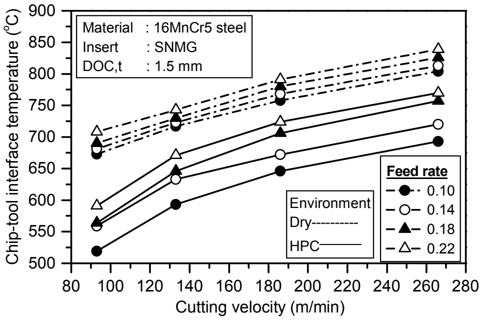


Fig 2: Variation in average chip-tool interface temperature at different V_c and S_o under dry and HPC environment

Cutting tools usually reach the end of their useful life either by breaking or by wearing. Breaking is usually caused by over loading. Tool wear refers to abrasion on the flank below the cutting edge and abrasion of tool face just back of cutting edge. Cutting tool life is one of the major and significant indices for assessing productivity and economy of manufacturing. High strength and tougher cutting tools are usually failed by gradual wear at its flank surface. Other modes of tool failure are brittle fracturing and catastrophic wear. Premature failure of cutting tools by mechanical breakage and plastic deformation can be successfully overcome by providing adequate strength, toughness and hot hardness in tool materials and by controlling tool geometry. Hardness is essential so that the cutting edge can penetrate into work-piece material. Poor toughness causes breaking of the cutting edge. Heat resistance enables the cutting edge to maintain its hardness when it gets heated due to friction on chip removal. Turning carbide inserts having enough strength; toughness and hot hardness generally fail by gradual wears on the flank below the cutting edge resulting from the abrasive contact with the machined surface. With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces due to continuous rubbing with the chips and the work surfaces. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems. The life of carbide tools, which mostly fail by wearing, is assessed by the actual machining time after which the average value (VB) of its principal flank wear reaches a limiting value, like 300 µm. Therefore, attempts should be made to reduce the rate of growth of flank wear (VB) in all possible ways without much sacrifice in MRR.

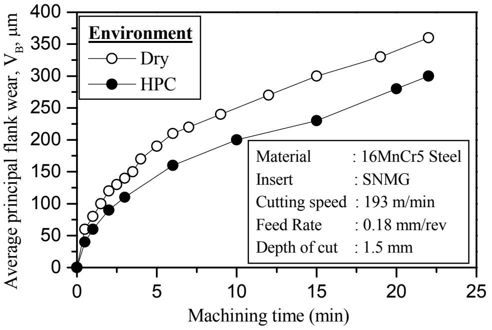


Fig 3:Growth of principal flank wear (V_B) under dry and HPC environment

Fig.3 clearly shows that flank wear, VB particularly its rate of growth decreased by HPC jet cooling. The cause behind reduction in VB observed may reasonably be attributed to substantial reduction in the flank temperature by HPC jet cooling particularly the jet impinged along the auxiliary cutting edge, 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 big.

Auxiliary flank wear (V_S), is responsible for machined rough surface as well as dimensional inaccuracy sizeably due to HPC jet cooling. Auxiliary flank wear basically depends upon the rigidity of Machine- Tool-Fixture-Work system as well as vibration of the machine tool. Fig. 4 shows that there is a very little change in auxiliary flank wear; cause behind it may be the vibration of machine tool under dynamic loading condition.

It can be observed from Fig.5 that the width of principal flank wear is much higher and distinct in the case of dry machining as compared to that in the case of high pressure coolant jet cooling indicating a longer tool life in the case of high pressure coolant jet cooling.

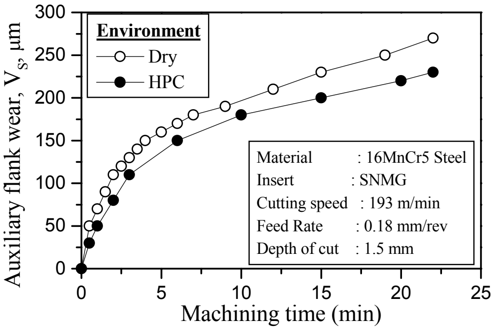
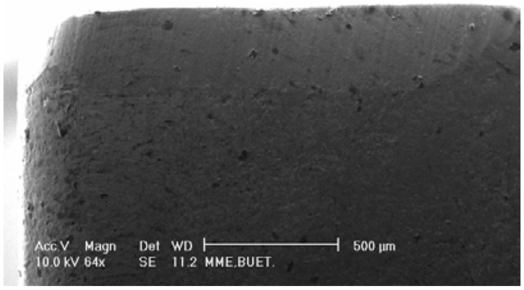


Fig 4:Growth of auxiliary flank wear (V_S) under dry and HPC environment

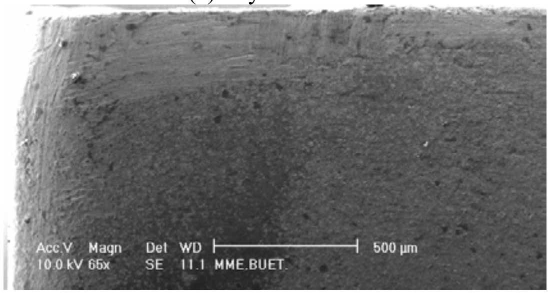
Tool rejection criteria for finishing operation were employed in this investigation. The values were established in accordance with ISO Standard 3685 for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of rejection criteria:

i. Average flank wear ≥ 0.3 mm.
ii. Maximum flank wear ≥ 0.4 mm.
iii. Nose wears ≥ 0.3 mm.

For the present investigation average flank wear was considered for rejection criteria. Machining was continued up to the period when principal flank wear reached to the limiting value 300 µm. The bar chart of Fig.7 shows the effective life of insert at different cutting velocity and feed under both the environments.

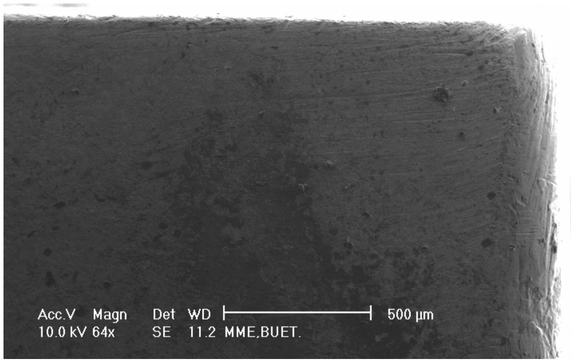


(a) Dry condition

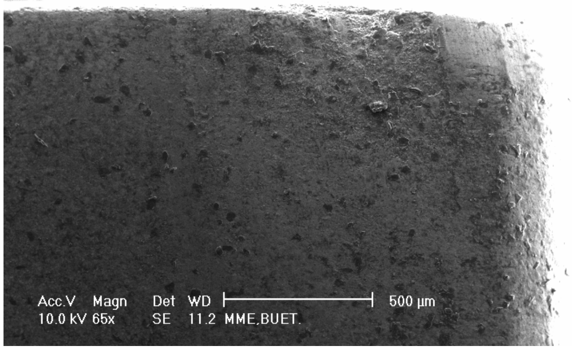


(b) HPC condition

Fig 5:SEM view of worn out insert showing the pattern and extent of tool wear on principal flank



(a) Dry condition



(b) HPC condition

Fig 6:SEM view of worn out insert showing the pattern and extent of tool wear on auxiliary flank

Surface roughness is one of the important factors in all areas of tribology and in evaluating the quality of a machining operation. Surface roughness is formed as a result of the repetition of the cutting tool tip moving along the work-piece at the desired feed rate during machining processes.

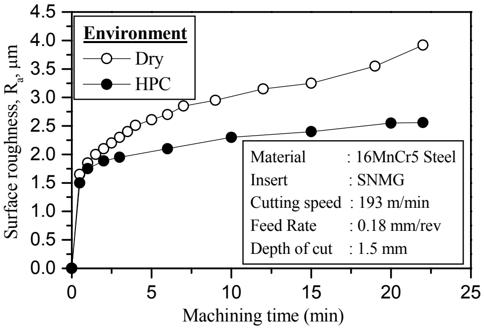


Fig 7:Variation in surface roughness (R_a) under dry and HPC environment

The nature and extent of surface roughness in turning is mainly caused by the feed marks in the longitudinal direction of the turned job depend mainly upon the value of feed, tool geometry, nose radius and condition of the auxiliary cutting edge. The level of feed So directly and almost proportionately governs the surface roughness in machining by single point tools but the value of cutting velocity also affect the nature, pattern and extent of surface finish, though indirectly through deformation of the tool nose profile, BUE formation and vibration.

Fig.8 visualizes that surface roughness of regular pattern would inherently occur in plain turning even in absence of tool nose wear, vibration and built-up edge depending upon the tool nose radius and magnitude of the feed. Surface roughnesses gradually decreased primarily with the machining time, then rapidly increase in dry machining and decreased gradually in HPC machining as can be seen in Fig.8. This can be attributed that HPC jet cooling not only reduced cutting temperature but also reduce the possibility of formation of built-up edge by welding of metal to the insert at elevated temperature due to reduction in cutting temperature.

An improvement in the surface quality indicates an enhanced dimensional accuracy which is very crucial while manufacturing precision components. The quality of the surface obtained is fundamentally a geometric and kinematics reproduction of the cutting edge. As already stated, with the application of high pressure coolant jet, the rate of tool wear is reduced which contributes to the improvement in surface finish.

4. CONCLUSIONS

i. High pressure coolant (HPC) jet cooling enabled sizeable reduction in the cutting zone temperature.
ii. HPC jet cooling in its present way of application has substantially reduced flank wear and hence improved tool life.
iii. Surface finish significantly improved by HPC jet cooling in turning 16MnCr5 steel.

5. ACKNOWLEDGEMENT

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

6. REFERENCES

1. Leskover P. and Grum, J., 1986, “The metallurgical aspect of machining”, Annals of CIRP, 35(1):537-550.
2. Tonshoff, H.K. and Brinkomeier, E., 1986, “Determination of the mechanical and thermal influences on machined surface by microhardness and residual stress analysis”, Annals of CIRP, 29(2):519-532.
3. Ackroyd, B., 2001, “Exploration of Contact Conditions in Machining.” *Proceedings of Institution of Mechanical Engineers: Part B- Journal of Engineering Manufacturing,* pp. 215(4):493-507.
4. Shaw, M. C., Pigott, J. D. and Richardson, L.P., 1951, “The effect of cutting fluid upon chip-tool interface temperature”, Transaction of ASME, 71:45-56.
5. Merchant, M. E., 1958, “The physical chemistry of cutting fluid action”, Am. Chem. Soc. Div. Petrol

Chem., 3(4A):179-189.

6. Cassin and Boothroyed, G., 1965, "Lubrication action of cutting fluids", Journal of Mechanical Engineering and Science, 7(1):67-81.
7. Kitagawa, T., Kubo, A. and Maekawa, K., 1997, "Temperature and wear of cutting tools in high speed machining of inconel 718 and Ti-6V-2Sn", Wear, 202:142-148.
8. Ecologically improved manufacturing processes at home page http://www.ifw.uni-hannover.de/BEREICH3/ Forschen/ 310_2e.htm.
9. Farook, A., Varadarajan, A.S. and Philip, P.K., 1998, "Machinability Studies on Steel using Hard Metal Inserts with Soft Material Deposit" *Proceddings of the 18th AIMTDR*, pp.152-155.
10. Dhar, N. R., Paul, S. and Chattopadhyay, A. B., 2002, "Role of Cryogenic Cooling on Cutting Temperature in Turning Steel", Transaction of the ASME, 123:146-154.
11. Dhar, N. R., Paul, S. and Chattopadhyay, A. B., 2002, "The Effects of Cryogenic Cooling on Chips and Cutting Forces in Turning of AISI 1040 and AISI 4320 Steels", Journal of Engineering Manufacture (IMechE-2002), .216(B):713-724.
12. Dhar, N. R., Kamruzzaman, M. and Ahmed Mahiuddin, 2006, "Effect of Minimum Quantity Lubrication (MQL) on Tool Wear and Surface Roughness in Turning AISI-4340 Steel" Journal of Materials Processing Technology, 172:299-304.
13. Dhar, N. R., Islam, M. W., Islam, S. and 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, 171:93-99.
14. Pigott, R. J. S and Colwell, A. T., 1952, "Hi-jet system for increasing tool life", SAE Q. Trans. 6(3):, 547-564.
15. Ramaiyengar, H. S., Salmon, R.and Rice, W. B., 1964, "Some effects of cutting fluids on chip formation in metal cutting ", Trans. ASME, 86: 36-38.
16. C. S. Sharma, W. B. Rice and R. Salmon, 1971, "Some effects of injecting cutting fluids directly into the chip-tool interface" , Engng Ind. Trans. ASME 93: 441-444.
17. Wrethin R., Rotberg J. and Ber A., 1992, "Influence of High Pressure Flushing, Through the Rake Face Cutting Tool", Annals of CIRP, 41(1):101-106.
18. Mazurkiewicz, M., Kubula, Z. and Chow, J., 1989, "Metal Machining with High-Pressure Water-Jet Cooling Assistance-A New Possibility", Journal of Engineering for Industry, 111:7-12.
19. Kamruzzaman, M., 2006, "Effect of high pressure coolant on machinability of steel", Ph.D. dissertation (continuing), Bangladesh University of Engineering & Technology.