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Effect of High-Pressure Coolant on Temperature, Chip, Force, Tool Wear, Tool Life and Surface Roughness in Turning AISI 1060 Steel

M. KAMRUZZAMAN[1], Nikhil Ranjan DHAR[1♠]

[1] Department of Industrial & Production Engineering, ,Bangladesh University of Engineering & Technology(BUET), Dhaka-1000, Bangladesh.

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ABSTRACT

Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. 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. However, the conventional types and methods of application of cutting fluid have been found to become less effective with the increase in cutting speed and feed when the cutting fluid cannot properly enter the chip-tool interface to cool and lubricate due to bulk plastic contact of the chip with the tool rake surface. Besides that, often in high production machining the cutting fluid may cause premature failure of the cutting tool by fracturing due to close curling of the chips and thermal shocks. Because of them some alternatives has been sought to minimize these problems. Some of these alternatives are cryogenic machining, minimum quantity lubricant machining and machining with high-pressure coolant jet. This paper deals with experimental investigation on the role of high-pressure coolant on cutting temperature, chips, cutting forces, tool wear, tool life and surface finish in turning of AISI 1060 steel at industrial speed-feed combinations by uncoated carbide inserts. The encouraging results include significant reduction in cutting forces, tool wear, surface roughness and significant improvement in tool life by high-pressure coolant jet mainly through reduction in the cutting zone temperature and favorable change in the chip-tool and work-tool interaction.

Key Words: *High-pressure coolant, Temperature, Chip reduction coefficient, Force, Tool wear, Tool life and Surface roughness.*

1. INTRODUCTION

In machining operations, mechanical work is converted to heat through plastic deformation involved in chip formation and through friction between the tool and work piece. Machining under high speed-feed condition is associated with generation of large amount of heat and cutting temperature. Some of this heat conducts into cutting tool, resulting in high tool temperature near cutting edge. Elevated tool temperature has negative impact on tool life. The temperature of the tool plays an important role in the thermal distortion and dimensional accuracy of the machined parts, as well as on the tool life. It also weakens 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]. Tools become softer and wear more rapidly by abrasion as temperature is increased, and in many cases constituents of the tool may diffuse into the chip or react chemically with the work piece or cutting fluid. Generally such problems are tried to be controlled by profuse cooling with soluble oil.

Coolants are used to reduce the amount of heat and friction at the point where a tool cuts into a metal work piece. This heat reduction allows the cutting tool to operate at higher speeds and reduces tool wear. However, at the lower pressures typically used to deliver cutting fluid, the coolant cannot effectively remove the majority of heat at the cutting point, as the bulk contact within chip-tool under high cutting speed and feed condition prevents the fluid from entering into

♠Corresponding author, e-mail: nrdhar@ipe.buet.ac.bd

the chip-tool interface where temperature is maximum [3-8]. Actually under high speed machining, if conventional coolant is used from overhead position it experiences nothing but dry machining as coolant don't get access into the chip-tool interface. Moreover, reaching to the boiling temperature cutting fluid creates vapor barrier for the fluid to enter into the interface. Instead, the coolant washes over the tool, tool holder and work piece, cooling the surfaces to some extent, but not removing the intense heat within the cutting area itself. In fact, most of this heat is conducted to the material around the shear zone and to the tooling, thus keeping the temperature at the cutting point higher than desired. Conventional cutting fluid application pollutes environment (air pollution, water pollution and soil contamination), produces nerve-racking obnoxious gases and corrodes machine slide ways [3]. Besides, when cutting fluid comes in physical contact with operators it creates skin irritation, skin cancer, bronchitis etc [3]. The cost of disposal of used coolant has increased substantially due to tougher environmental legislations which incurs increased production cost.

Some alternative possible solutions have been reported to control high cutting temperature in high production machining. 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 under dry cutting [9]. Though high performance ceramics (CBN, PCBN, diamond and PCD) are extremely heat and wear resistant, still 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. Cutting forces and temperature were found to be reduced while machining steel with tribologically modified carbide inserts [6]. Cryogenic machining with liquid nitrogen [10-12] and machining with minimum quantity lubrication (MQL) [13, 14] has improved machinability of steel to a certain extent under normal cutting conditions. It has also been reported that though the machining steel with liquid nitrogen improves the machinability index [11, 12]; still it is not used in industrial practices due to high cost of liquid nitrogen and sharp increment of notch wear under nitrogen rich atmosphere.

By directing the coolant stream more precisely along with the optimum amount of pressure, more heat can be removed dramatically from the cutting zone. This degree of cooling also enables the cutting tool to remove greater amount of metal, thus improving machine tool cycle time. Additionally, the high-pressure coolant stream helps breaking up chips and removing them from the cutting area more efficiently, which means the cutting tool spends less time for breaking metal chips. However, high pressure jet of soluble oil, if applied at the chip-tool interface, the wedge formation by the jet may lift up the chip, segregating it and could break the vapor barrier and reduce cutting temperature and improve tool life [15-23]. The combination of reduced heat and more efficient evacuation of chips prolong tool life and makes replacement more predictable because the cutting tool wears out naturally rather than failing prematurely because of excessive heat or chip damage.

Application of pressurized coolant jet for effective cooling without polluting the environment is becoming more popular day by day [16, 18]. But in addition to pollution control, the industries also reasonably insist economic viability through technological benefits in terms of product quality, tool life and saving power consumption by the application of pressurized jet cooling. So it has become essential to study the role of high- pressure cooling on cutting temperature, chips, cutting force, tool wear, tool life and surface quality of the product in machining where high cutting temperature is the major concern.

The main objective of the present work is to experimentally investigate the role of high- pressure coolant jet (jet of water insoluble hydro-clear straight run cutting oil, VG 68) on cutting temperature, chips, cutting force, tool wear, tool life and surface finish in turning AISI 1060 steel by two types of carbide inserts of different geometry namely SNMG and SNMM under different cutting velocities and feeds.

2. EXPERIMENTAL INVESTIGATION

Experiments have been carried out by turning a hollow bar of AISI 1060 steel (Ø178 mm X 580 mm) on a lathe (China, 10 hp) by uncoated carbide inserts (SNMG and SNMM) at different cutting speeds (V) and feeds (f) under both dry and high-pressure coolant condition. Keeping in view less significant role of depth of cut on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.0 and 1.5 mm, which would adequately serve the present purpose. All these parameters have been selected as per tool manufacturer's recommendation as well as industrial practices for machining steel with carbide insert. The experimental conditions have been given in Table-1.

Table 1. Experimental conditions.

Machine tool	: Lathe (China), 10 hp
Work specimen	
Material	: AISI 1060 steel
Hardness (BHN)	: 195
Size	: Ø178 X 580 mm
Cutting insert	: SNMG & SNMM insert, Sandvik
Tool holder	: PSBNR 2525 M12, Sandvik
Tool geometry	: -6°, -6°, 6°, 15°, 75°, 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/rot
Depth of cut	: 1.0 mm and 1.50 mm
High pressure coolant	: 80 bar, Coolant: 6.0 l/min through external nozzle
Environments	: Dry and high-pressure coolant (HPC)

The photographic view of the experimental set-up along with motor-pump assemble, flow control valve, relief valve and directional control valve is shown in Fig.1. The coolant needs to be supplied at high pressure and impinged at high speed through the nozzle (Ø 0.50 mm) at the chip-tool interface. Considering the conditions required for the present work and uninterrupted supply of coolant at constant pressure (40 bar) over a reasonably long cut, a high-pressure coolant delivery system has been designed, fabricated and used. The thin but high velocity stream of coolant was projected along the auxiliary cutting edge of the insert, so that the coolant reaches as close to the chip-tool and the work-tool interfaces as possible. The positioning of the nozzle tip with respect to the cutting insert has been settled in such a way that coolant jet is directed along the auxiliary cutting edge to reach at both the flanks and partially under the flowing chips to cover the entire heat affected zone as shown in Figure 1 (right top).

Nozzle position

Figure 1. Photographic view of the experimental set-up.

The average cutting temperature was measured under all the machining conditions undertaken by tool-work thermocouple technique with proper calibration [24].The thickness of the chips directly and indirectly indicates the nature of chip-tool interaction influenced by the machining environment. The chip samples were collected during short run and long run machining for the V-f combinations under dry and high-pressure coolant conditions. The thickness of the chips was repeatedly measured by a slide caliper to determine the value of chip reduction coefficient, ξ (ratio of chip thickness after and before cut).

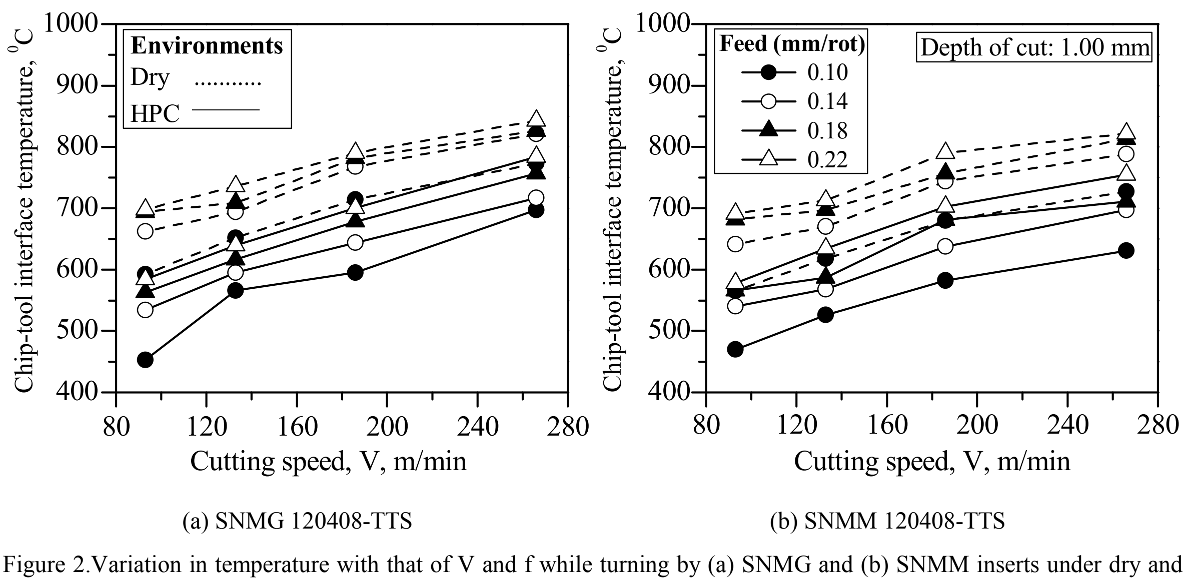
The cutting forces were measured with a force dynamometer (Kistler) mount on carriage via a custom designed turret adapter (Kistler) for the tool holder creating a very rigid tooling fixture. The charge signal generated at the dynamometer was amplified using charge amplifiers (Kistler). The amplified signal is acquired and sampled by using data acquisition on a laptop computer at a sampling frequency of 2000 Hz per channel. Time-series profiles of the acquired force data reveal that the forces are relatively constant over the length of cut and factors such as vibration and spindle run-out were negligible.

The cutting insert was withdrawn at regular intervals to study the pattern and extent of wear on main and auxiliary flanks under both dry and high-pressure coolant conditions. The average width of the principal flank wear, VB and auxiliary flank wear, VS were measured using metallurgical microscope (Carl Zeiss, 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^+, Rank Taylor Hobson Limited) using a sampling length of 0.8mm.

The pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining the AISI 1060 steel over long period have been observed under SEM to see the actual effects of different environments on wear of the carbide inserts of present two configurations.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Heat generation while machining has significant influence on machining indices. It can increase tool wear and thereby reducing tool life [4]. It gives rise to thermal softening of cutting tool. It is commonly accepted that both the wear and failure mechanisms which develop in cutting tools are predominantly influenced by temperature and it also results in modification to the properties of workpiece and tool material such as hardness. In order to predict the wear and failure characteristics of a tool, it is necessary to quantify the temperatures which develop during the cutting operation. In machining operations, mechanical work is converted to heat through the plastic deformation involved in chip formation and through friction between the tool and workpiece or flowing chips. Three regions of heat generation in turning are the shear zone, the chip-tool interface and the tool-workpiece interface zone [8]. During machining heat is generated at the primary deformation zone due to shearing of metal, secondary deformation zone and the flank (clearance) surfaces due to rubbing, but the temperature becomes maximum at the chip-tool interface. The cutting temperature measured in the present work refers mainly to the average chip-tool interface temperature. Any cutting fluid applied conventionally cannot reduce this chip-tool interface temperature effectively because the fluid can hardly penetrate into that interface where the chip-tool contact is mostly plastic in nature particularly at higher cutting speed and feed. High energy jet impinging beneath the flowing chip acts as a wedge that lifts up the chip facilitating chip breakage by reducing curl radius as well as plastic contact and coolant reach to the interface. Coolant having high cooling capacity cools the interface expectedly, effectively and lubricate between the chip-tool and work-tool contact thus reduce frictional heat generation. However, the high-pressure coolant jet could have reduced the cutting temperature quite significantly though in different degrees for different cutting speed and feed combinations and different tools as shown in Figure 2.

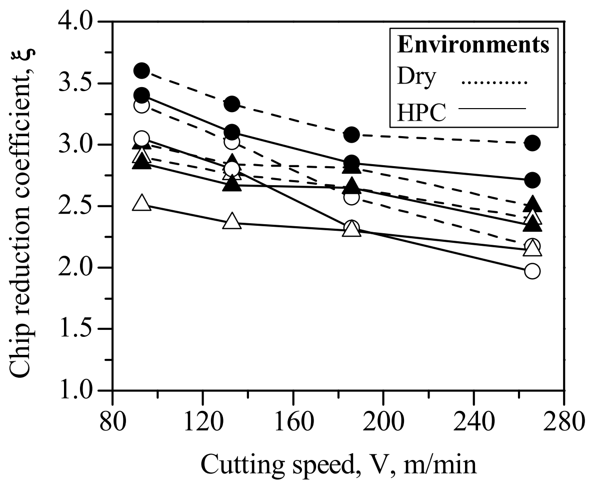


(a) SNMG 120408-TTS (b) SNMM 120408-TTS

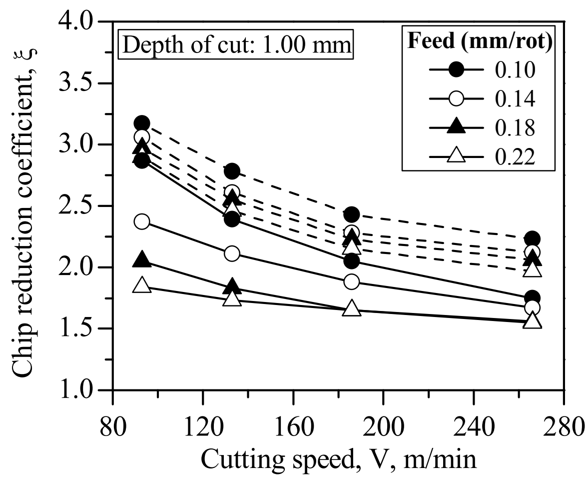
Figure 2.Variation in temperature with that of V and f while turning by (a) SNMG and (b) SNMM inserts under dry and high-pressure coolant conditions.

Traditionally cutting temperature increases with the increase of cutting speed and feed. It is clear from Figure 2 that cutting temperature increases with the increase of cutting velocity and feed for both the inserts under both the environments but temperature under high-pressure coolant condition is lower than that of under dry environment. It is an indication of effective cooling and lubrication of high-pressure coolant jet. In this experiment, under low speed (93 m/min and 133 m/min) and low feed (0.10 mm/rot and 0.14 mm/rot) conditions temperature reduction rate is more in comparison with that of under high speed (186 m/min and 266 m/min) and high feed (0.18 mm/rot and 0.22 mm/rot) conditions. The presence of the grooves along the cutting edges, the hills on the tool rake surface and reduced chip-tool contact length may have helped the jet to come closer to the chip-tool interface and thus effectively cool that interface. The cooling effect has been found different for the different geometry of the two inserts as expectedly. The difference in the effectiveness of high- pressure cooling observed under different V and f can be reasonably attributed to variation in the nature and extent of chip-tool contact. Besides, tool geometry plays a significant role on cooling the cutting zone. Jet injected towards the interface of SNMG insert more effectively reduces the cutting temperature than those of SNMM insert which has no inbuilt groove to easy entrance of coolant.

Temperature is drastically reduced under low speed-feed condition and apparently a small reduction is observed under high speed-feed condition. Even such apparently small reduction in the cutting temperature is expected to have some favorable influence on other machinability indices. With the increase in cutting speed, plastic contact is increased and made the jet less effective to enter into the interface. Due to this, temperature reduction rate is lower under high speed-feed condition.



(a) SNMG 120408-TTS

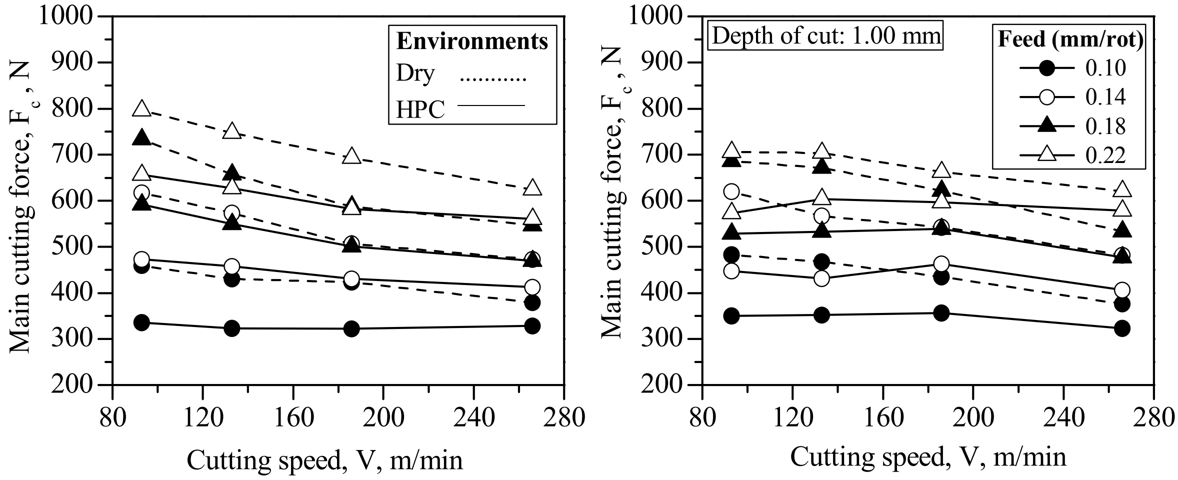


(b) SNMM 120408-TTS

Figure 3.Variation in chip reduction coefficient, ξ with that of V and f while turning by (a) SNMG and (b) SNMM inserts under dry and high-pressure coolant conditions.

Chip reduction coefficient (ξ) is the ratio of cut chip thickness to uncut chip thickness. Though it is called chip reduction coefficient, actually the value of ξ is more than 1 due to all sided compression of the chip while machining. Traditionally the value of ξ decrease with the increase in cutting velocity and feed. Lower value of ξ indicates intimate chip-tool interaction. From Figure 3 it is clear that the value of ξ in all through the speed-feed range for both the inserts under high-pressure coolant environment is lower than that of dry environment which indicates more intimate interaction than dry.

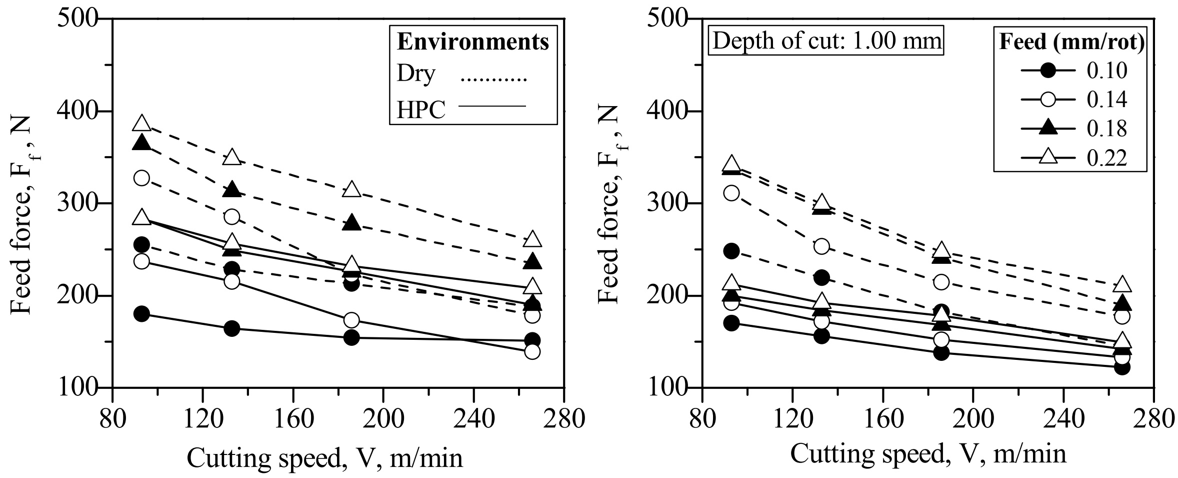
The heat influence on the cutting forces is mainly because of the following reasons-the friction co-efficient is tightly dependent upon temperature and the properties of cut material also depend on temperature. Besides, force is a function of ξ as well as chip tool interaction. Cutting force usually decreases with increase in cutting speed and increase with increase in feed, as ξ decrease under those situations. Formation of built up edge causes fluctuation of cutting force as well as energy consumption. Figure 4 clearly depicts that cutting force decreases with increase in cutting speed and increased with increase in feed like usual manner and employment of high-pressure coolant decreased the cutting force under all the treatments. Less chance of built up edge formation under high-pressure coolant environment is evident as a very small fluctuation of force is observed.



(a) SNMG 120408-TTS (b) SNMM 120408-TTS

Figure 4. Variation in main cutting force, F_c with that of V and f while turning by (a) SNMG and (b) SNMM inserts under dry and high-pressure coolant conditions.

Figure 5 clearly shows that F_f have decreased uniformly with the increase in V under all the feeds for both the inserts and environments as usual due to favorable change in the chip-tool interaction resulting in lesser friction and intensity or chances of built-up edge formation at the chip-tool interface. The built-up edge if formed have been separated from the tool by transverse force and flushed away with the strong stream of high-pressure coolant jet. The formation of built-up edge not only fluctuate the cutting forces but also weaken the finished surface and as a result tool life is reduced. Reduction in chip-tool contact length and reduction in curl radius of the chips might have contributed in reducing the cutting forces.



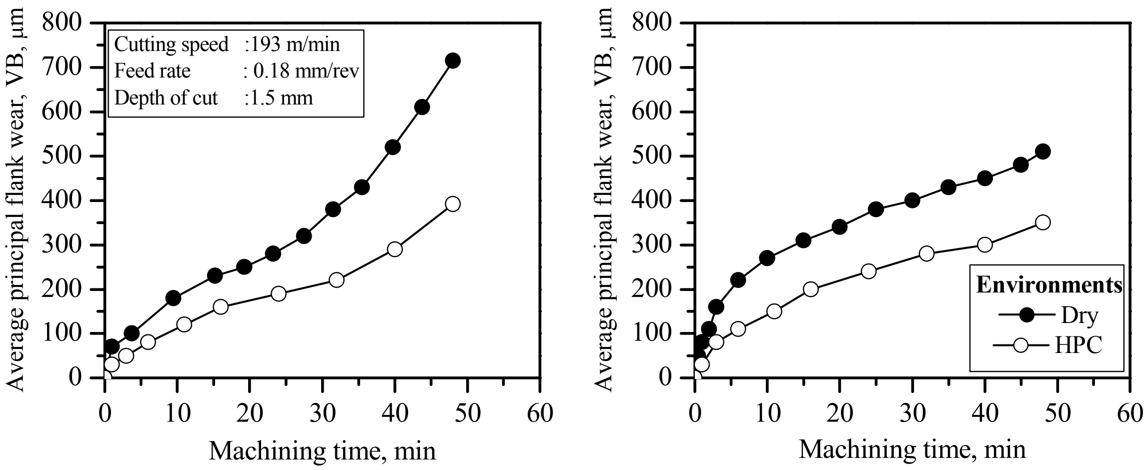
(a) SNMG 120408-TTS (b) SNMM 120408-TTS

Figure 5.Variation in feed force, F_f with that of V and f while turning by (a) SNMG and (b) SNMM inserts under dry and high-pressure coolant conditions.

Cutting tools are subjected to an extremely severe rubbing process. They are in metal-to-metal contact with the chip and work piece under of very high stress condition at high temperature. The situation is further aggravated due to the existence of extreme stress and temperature gradients near the surface of the tool. During cutting, cutting tools remove the material from the component to achieve the required shape, dimension and finish. However, wears are occurring during the cutting action, and it will result in the failure of the cutting tool. Cutting tools may fail due to the plastic deformation, mechanical breakage, cutting edge blunting, and tool brittle fracture or due to the rise in the interface temperatures. Under high temperature, high pressure, high sliding velocity and mechanical or thermal shock in cutting area, cutting tool has normally complex wear appearance, which consists of some basic wear types such as crater wear, flank wear, thermal crack, brittle crack, fatigue crack, insert breakage, plastic deformation and build-up edge. The dominating basic wear types vary with the change of cutting conditions. Crater wear and flank wear are the most common wear types.

Tool wear influences cutting power, machining quality, tool life and machining cost. When tool wear reaches a certain value, increasing cutting force, vibration and cutting temperature cause surface integrity deteriorated and dimension error greater than tolerance. A wear land increases the tendency of a tool to dynamic instability. A cutting operation which is quite free of vibration when the tool is sharp may be subjected to an unacceptable chatter mode when the tool wears and the life of the cutting tool comes to an end. Then the cutting tool must be replaced or ground and the cutting process is interrupted. Time for tool sharpening, replacement and adjusting machine tool increases cost and decreases the productivity. Hence tool wear relates to the economic of machining and prediction of tool wear is of great significance for the optimization of cutting process. When the tool wear reach certain extent usually 300 μm for finishing operation and 400 μm for roughing cut as per ISO standard, the tool or edge has to be replaced to guarantee the ordinary cutting action.

Flank wear is caused by the friction between the newly machined work piece surface and the tool flank face. It is responsible for a poor surface finish, a decrease in the dimensional accuracy of the tool and an increase in cutting force, temperature and vibration. Hence the width of the flank wear land, VB, is usually taken as a measure of the amount of wear and a threshold value of the width is defined as tool reshape criterion. Fig. 6 shows a variation of flank wear with cutting time, showing the initial wear, steady wear, and gradual wear periods.



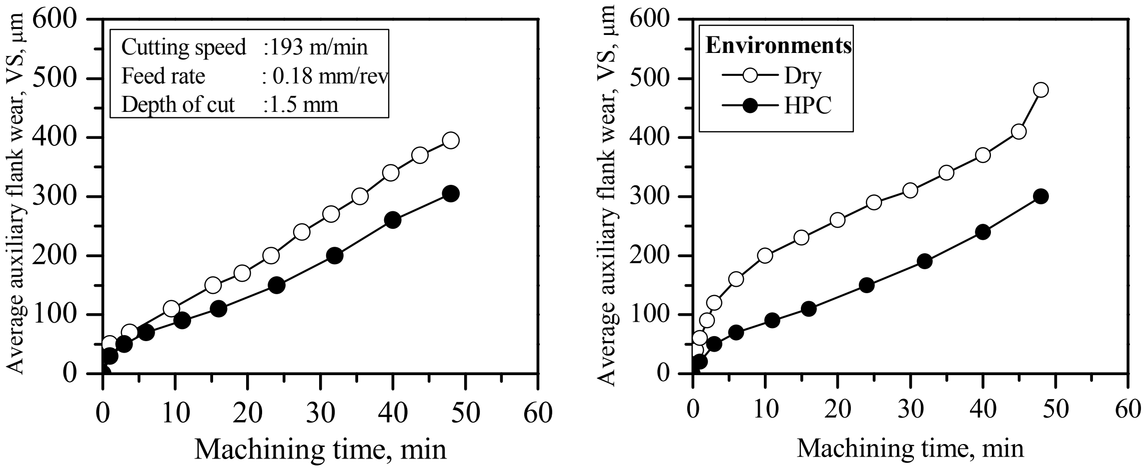
(a) SNMG 120408-TTS

(b) SNMM 120408-TTS

Figure 6. Growth of average principal flank wear (VB) in (a) SNMG and (b) SNMM inserts under dry and high-pressure coolant conditions.

During the machining trials, mainly the growths of average principal flank wears and average auxiliary flank wears have been monitored. Fig. 6 shows the growth in average principal flank wear, VB, on the main cutting edge while machining AISI 1060 steel using uncoated carbide insert of different geometry under both the environments. The gradual growth of VB, observed under both the environments for both the inserts indicates steady machining without any premature tool failure by chipping, fracturing etc. establishing proper choice of domain of process parameters. These phenomenon along with effective temperature control under high-pressure coolant condition enabled reduced rate of tool wear.

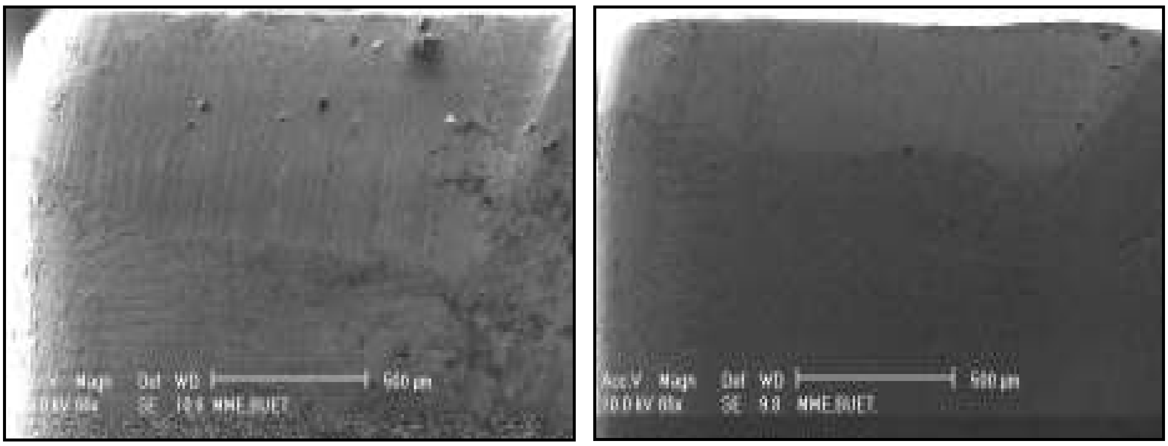
Another important tool wear criteria is average auxiliary flank wear, VS, which governs the surface finish on the job as well as dimensional accuracy. Irregular and higher auxiliary flank wear lead to poor surface finish and dimensional inaccuracy. The growth of, VS has been depicted in Figure7 for both the inserts. The application of high-pressure coolant jet along the auxiliary cutting edge has reduced VS effectively. The pattern and extent of wear that developed on the principal and auxiliary flank surfaces of the tool after being used for machining over long period have been observed under SEM to see the actual effects of environments on wear of the carbide inserts of two configurations.



(a) SNMG 120408-TTS (b) SNMM 120408-TTS

Figure 7. Growth of average auxiliary flank wear (VS) in (a) SNMG and (b) SNMM inserts under dry and high-pressure coolant conditions.

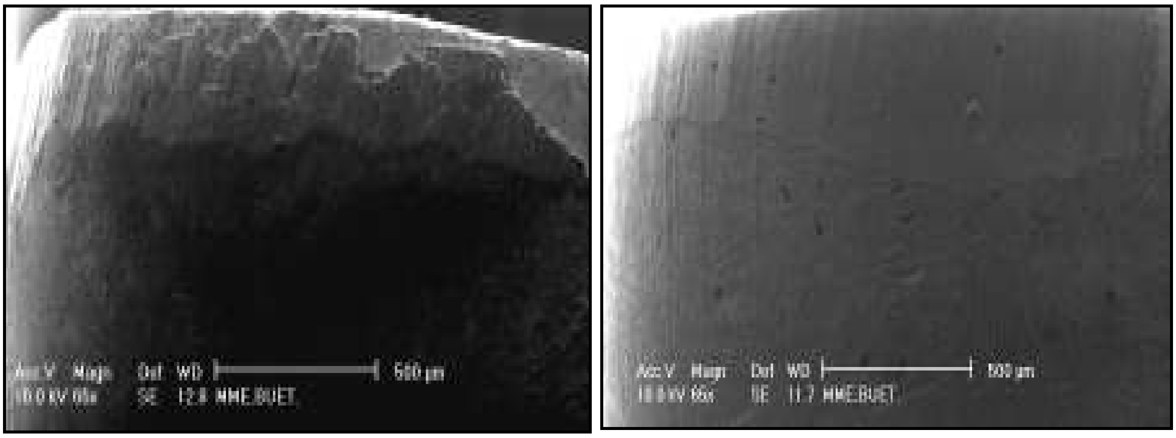
The SEM views of the worn out inserts after 48 minutes of machining steel under dry and high-pressure coolant conditions are shown in Fig.8 and Fig.9. Under both the environments, abrasive scratch marks appeared in the flanks. Some plastic deformation and micro chipping were found to occur under dry machining. Almost no groove wear and notch wear at the flank surfaces were found on insert under both the conditions.



Dry condition, 48 min High-pressure coolant condition, 48 min

Figure 8. SEM views of principal flank wear of the worn out SNMG insert.

Effective temperature control by high-pressure coolant and oil film lubrication completely eliminate notch and groove wear on the main cutting edge. It has also enabled the elimination in the auxiliary notch wear. Further the figures clearly show reduced average principal flank wear and average auxiliary flank wear under high-pressure coolant condition.



Dry condition, 48 min   High-pressure coolant condition, 48 min

Figure 9. SEM views of principal flank wear of the worn out SNMM insert.

Cutting tool life is one of the major and significant indices for assessing productivity and economy of manufacturing a product. High strength and tougher cutting tools are usually failed by gradual wear at its flank surfaces. Other modes of tool failure are brittle fracturing and catastrophic wear. Carbide inserts having enough strength; toughness and hot hardness generally fail by gradual wears. 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 fails 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 taken to reduce the rate of growth of flank wear (VB) in all possible ways without much sacrifice in MRR. The rate of growth of flank wear was decreased substantially by high-pressure coolant jet cooling. The cause behind reduction in VB may be attributed to substantial reduction in the flank temperature by high-pressure coolant jet cooling particularly the jet impinged along the auxiliary the 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 of growth of flank wear, the tool life would be much higher if high-pressure coolant jet is properly applied. Figure 10 and Figure 11 are representing a bar chart of tool life. Depending upon the process parameters percent increase in tool life for SNMG insert is 33 to 62 with an average 50; on the other hand that for SNMM insert is 65 to 155 with an average 110. It is noticeable that SNMM insert gives a better life under high-pressure coolant condition.

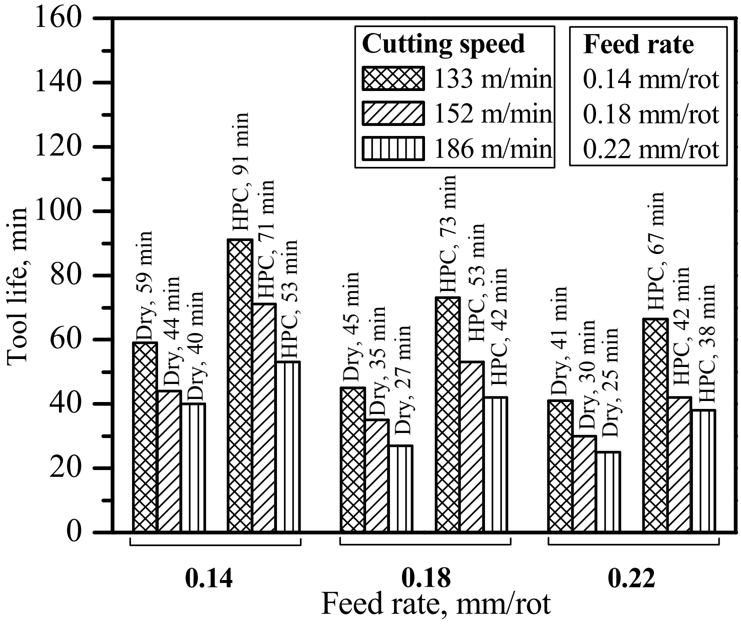


Figure 10. Variation in tool life of SNMG insert with different cutting feeds at different cutting speeds under both dry and high-pressure coolant conditions based on limiting flank wear criteria VB=300 µm.

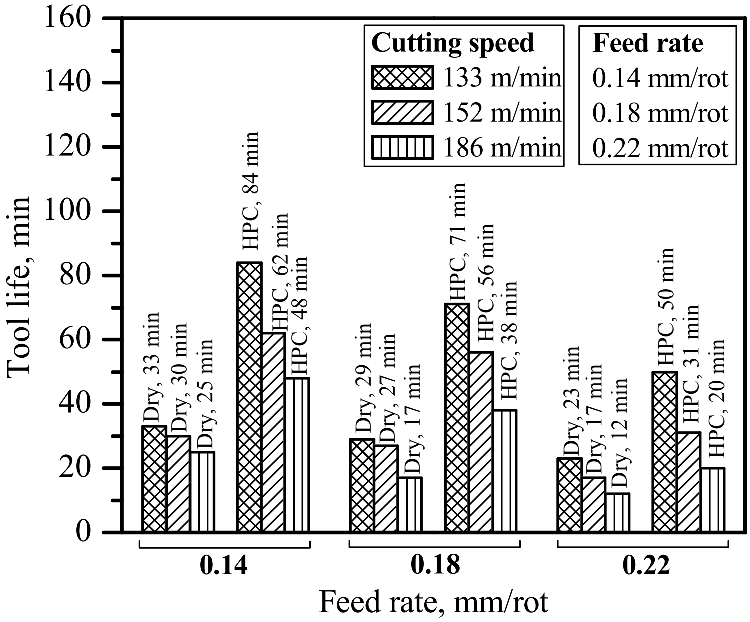
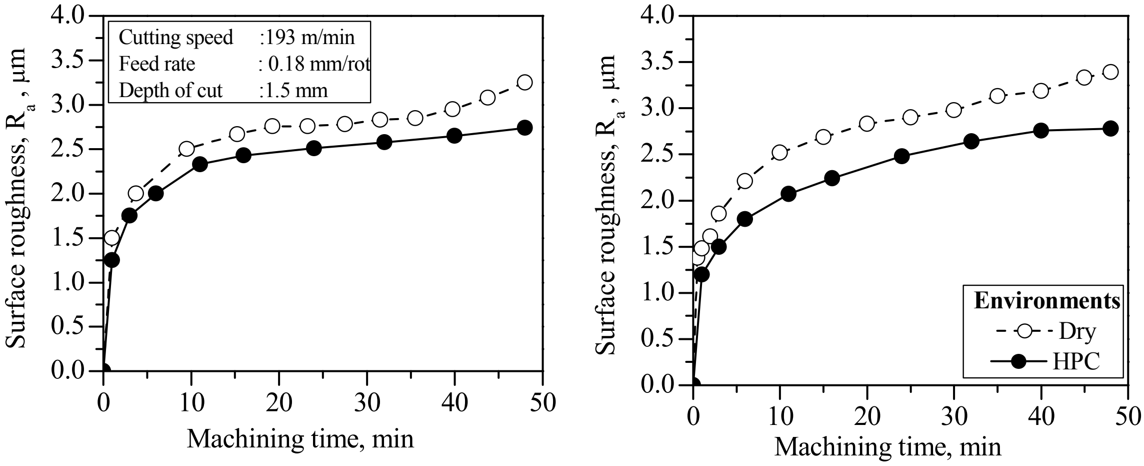


Figure 11. Variation in tool life of SNMM insert with different cutting feeds at different cutting speeds under both dry and high-pressure coolant conditions based on limiting flank wear criteria VB=300 µm.

In metal cutting, severe deformations take place in the vicinity of the cutting edge of the tool because of the high temperatures. These elevated temperatures have a negative impact on tool life and quality of surface. The nature and extent of surface roughness in the longitudinal direction of the turned job depend mainly upon the geometry and condition of the auxiliary cutting edge including a part of the rounded nose.



(a) SNMG 120408-TTS **(b) SNMM 120408-TTS**

Figure 12. Progress of surface roughness, R_a with machining time while turning steel by (a) SNMG and (b) SNMM inserts under dry and high-pressure coolant conditions.

Surface roughness gradually increased as usual with machining time which can be seen in Fig. 12 due to gradual increase in auxiliary flank wear (VS). Again it may be noted that the rate of increase in surface roughness decreased to significant extent when machining was carried out under high-pressure coolant condition which not only reduced the VS but also reduced possibility of built-up edge formation due to reduction in temperature. Higher surface roughness was produced under dry machining due to more intensive temperature and stresses at the tool-tips. High-pressure coolant appeared to be more effective in reducing surface roughness. However, it is evident that high-pressure coolant substantially 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. Oil film lubrication and efficient cooling provided by high-pressure coolant jet significantly reduce surface roughness.

4. CONCLUSIONS

i. High-pressure coolant jet enabled substantial reduction in cutting zone temperature and favorable chip-tool interaction under all the investigated speed-feed combinations. Under lower speed and feed condition temperature reduction is more than under high speed-feed condition because of easy entrance of high velocity jet overcoming the bulk contact.

ii. The present way of application of cutting fluid enabled in reducing the main cutting force and feed force due to improved and intimate chip-tool interaction. Reduction in ξby effective cooling decreased chip load as well as cutting forces on cutting tool.

iii. High-pressure coolant with the present technique has significantly reduced flank wears and hence is expected to provide improved tool life. High-pressure coolant helps to retain the sharp edge of the cutting tool for a long time by effectively reducing the cutting temperature and ensure efficient cooling.

iv. Surface finish significantly improved under high-pressure coolant condition in turning AISI 1060 steel. It provided more efficient chip removal and heat reduction. Consequently the work piece surface is less blemished by chips or distorted by excess heat.

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