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EFFECTS OF HIGH-PRESSURE COOLANT (HPC) JET ON TEMPERATURE, CHIPS AND FORCES IN TURNING AISI 1060 STEEL AND AISI 4320 STEEL

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ABSTRACT
Usually cutting fluid is used to remove generated heat or to reduce friction. But the conventional types and method of application of cutting fluid have been found to be less effective under high speed machining as it can not enter into the interface efficiently where maximum temperature attains. Moreover, it pollutes the environment. In this situation, high pressure coolant may be the viable solution to control the cutting temperature and. The present work deals with experimental investigation in the role of HPC on tool-chip interface temperature, chips and cutting forces in plain turning of AISI 1060 steel and AISI 4320 steel at different speed-feed combination by two types of carbide inserts of different geometric configurations. High pressure coolant is more effective in respect of reduction in cutting zone temperature, increment in chip thickness ratio. Also cutting force is decreased sizably as chip load and cutting temperature are decreased.

Keywords: Turning, HPC and Forces.

1. INTRODUCTION
During machining generation of heat and high cutting temperature is inherent. At such elevated temperature the cutting tool if not enough hot hard and tough may lose their form stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases with the increase of cutting speed, feed and depth of cut; as a result, high speed machining is constrained by rise in temperature [1]. This problem further intensified with the increase in strength and hardness of the work material [2]. Due to such high temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increase in cutting forces and premature tool failure. On the other hand, the cutting temperature, if it is high and is not controlled, worsens the surface topography and impairs the surface integrity by oxidation and introducing residual stresses, surface and sub-surface micro-cracks and structural changes of the work material [3].

High cutting temperature is conventionally tried to be controlled by employing flood cooling by soluble oil. Machining under high speed-feed condition conventionally applied coolants fails to penetrate into the chip-tool interface and thus cannot remove heat effectively [4-6]. Addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip-tool interface to provide cooling and lubrication [7].

In high speed machining of exotic materials like Inconel and Titanium alloys, cutting fluids failed to reduce cutting temperature and improve tool life effectively [8]. However high pressure jet of water, if applied at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent [9]. In machining ductile metals even with cutting fluid, the increase in cutting speed reduces the ductility of the work material and causes production of long continuous chips, which raises the cutting temperature further [10]. 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 bad effects of cutting fluids, such as by skin and breathing problems [11]. For the companies, the costs related to cutting fluids represent a large amount of the total machining costs. Several research workers [12, 13] state that the costs related to cutting fluids is frequently higher than those related to cutting tools.

Cryogenic cooling by liquid nitrogen jet provides environment friendly, clean technology for suitable control of cutting temperature but it is not cost effective due to high cost of cryogen [3]. In normal cutting condition MQL provides better performance but at higher feed and speed condition performance is not good [6]. Some recent techniques have enabled partial control of the machining temperature by using heat resistant tools like coated carbides, CBN etc. However, CBN tools are very expensive and the practices in the industry are still not wide spread [14].

In line with growing environmental concerns involved in the use of cutting fluids in machining processes, as reported by several researchers and manufacturers [15, 16] of machine tools, strong emphasis is being placed on the development of environmentally friendly technology, i.e., on environmental preservation and the search for conformity with the ISO 14000 standard. On the other hand, despite persistent attempts to eliminate cutting fluids, in many cases cooling is still essential to the economically feasible service life of tools and the required surface qualities. This is particularly true when tight tolerances and high dimensional and shape exactness are required, or when the machining of critical and difficult to cut materials is involved. This makes high pressure coolant, an interesting alternative, because it combines the functionality of cooling, lubrication and reuse of coolants. Lubrication helps to reduce the tool's friction and to prevent the adherence of materials.

The coolant jet under such high-pressure is capable of creating a hydraulic wedge between the tool and the work piece, penetrating the interface deeply with a speed exceeding that necessary even for very high-speed machining. This phenomenon also changes the chip flow conditions [17]. The penetration of the high-energy jet at the tool–chip interface reduces the temperature gradient and minimizes the seizure effect, offering an adequate lubrication at the tool–chip interface with a significant reduction in friction. Excellent chip breakability has been reported when machining difficult-to-cut materials with high-pressure coolant supply [18, 19]. This is attributed to a coolant wedge which forms between the chip and the tool forcing the chip to bend upwards giving it a desirable up curl required for segmentation. Coolant supply at high-pressure tends to lift up the chip after passing through the deformation zone resulting to a reduction in the tool–chip contact length/area. This tends to enhance chip segmentation as the chip curl radius is reduced significantly; hence, maximum coolant pressure is restricted only to a smaller area on the chip. Similar observation with chip segmentation was made while machining steel. It was observed that the power of the coolant jet and the lateral position of the point where the jet hits the line where the chip exits the tool rake face has significant influence on the chip segmentation process with high-pressure coolant supplies [20].

The present work experimentally investigates the role of high pressure coolant (HPC) jet on cutting temperature, chip thickness ratio and cutting force in plain turning of AISI 1060 steel and AISI 4320 steel at industrial speed-feed condition by uncoated carbide inserts with ISO tool designations SNMG 120408 and SNMM 120408 and compares the effectiveness of HPC with that of dry machining as well as among the steels used.

2. EXPERIMENTAL PROCEDURE

The machining was carried out by turning two steel rod of AISI 1060 steel (Size: Ø178 X 580 mm, BHN: 195) and AISI 4320 steel AISI 4320 steel (Size: Ø200 X520 mm, BHN: 201) in a powerful and rigid lathe (10 hp) at different cutting speeds (V) and feed rates (f) under both dry and high pressure coolant (HPC) condition. The ranges of the cutting speed (V) and feed rate (f) were selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut, being less significant parameter, was kept fixed at 1.0 mm. Uncoated carbide inserts with ISO tool designations SNMG 120408 and SNMM 120408 was used for the machining trials. PSBNR2525M12, Sandvik tool holder was used for the experimentation. The experimental conditions are given in Table-1.

Table 1: Experimental conditions

Machine tool	**:** Lathe (China), 7.5 kW
Work material	**:** AISI 1060 and AISI 4320 steel
Tool geometry	**:** -6°,-6°,6°,15°,75°,0.8 (mm)
Tool holder	**:** PSBNR 2525 M12 (Sandvik)
Process parameters	
Cutting speed, V	**:** 93,133, 186 and 266 m/min
Feed rate, f	**:** 0.10, 0.14, 0.18 and 0.22 mm/rev
Depth of cut, d	**:** 1.00 mm
HPC supply	**:** 80 bar with a flow rate of 6.0 l/min
Environment	**:** • Dry and • HPC with VG 68 Cutting oil

Fig 1. Photographic view of experimental set-up

The HPC needs to be supply at high pressure and impinged at high speed through the nozzle at the chip-tool interface. Considering the conditions required for the present research work and uninterrupted supply of HPC at constant pressure (80 bars) over a reasonably long cut, a HPC delivery system has been designed fabricated and used. The thin but high velocity stream of HPC 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 photographic view of the experimental set-up is shown in Fig.1. The HPC jet has been used mainly to target the rake and flank surface and to protect the auxiliary flank to enable better dimensional accuracy.

The average cutting temperature was measured under all the machining conditions undertaken by tool-work thermocouple technique with proper calibration. The calibration curve is shown in Fig.2. 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 speed and feed combinations under dry and HPC conditions. The thickness of the chips was repeatedly measured by a digital slide caliper to determine the value of chip thickness ratio, r_c (ratio of chip thickness before and after 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.

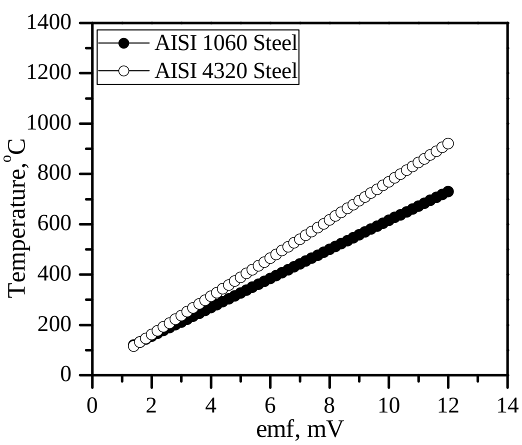
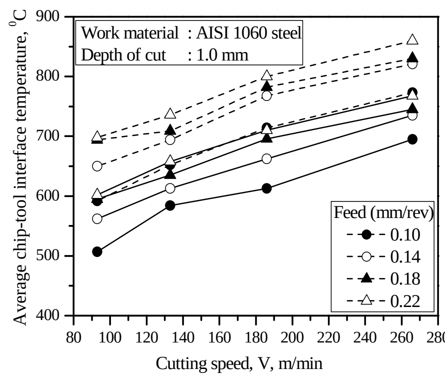


Fig 2. Tool-work thermocouple calibration curve

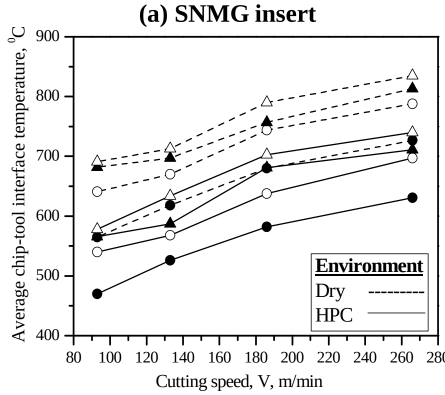
3. RESULTS AND DISCUSSIONS

During machining heat is generated at the primary deformation zone, secondary deformation zone and the flank (clearance) surfaces but temperature becomes maximum at the chip-tool interface by accumulating all the heat sources. The cutting temperature measured or evaluated in the present work refers mainly to that 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 the interface where the chip-tool contact is mostly plastic in nature particularly at higher value of V and f. However, it was observed that during machining of AISI 1060 steel and AISI 4320 steel with SNMG and SNMM inserts the high pressure coolant jet in its present way of application enabled reduction of the average cutting temperature depending upon the levels of the process parameters, V and f and the types of the cutting inserts. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices. SNMM insert provided more reduction than SNMG insert and harder AISI 4320 steel provided lower reduction due to higher cutting temperature.

The cutting temperature generally increases with the increase in V and f, 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 V and f. But actually it had been otherwise as can be shown in Fig.3 and Fig.4.



(a) SNMG insert

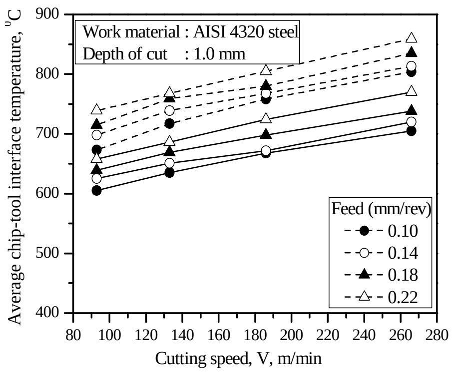


(b) SNMM insert

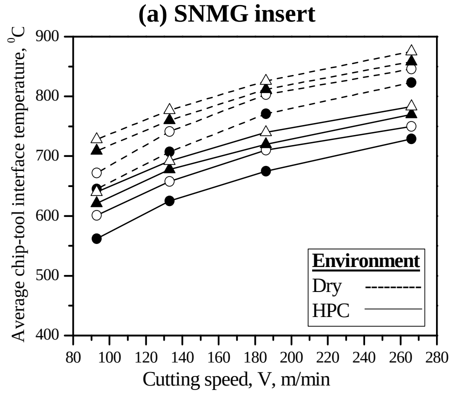
Fig 3. Variation in temperature in turning AISI 1060 steel

The reduction in the average cutting temperature gradually decreased with the increase in speed more or less truly under all the values of feed when the steel rods was machined under HPC by both type insert unlike when machined by the SNMG type (Fig.3 and Fig.4). This indicates that the geometry of the cutting insert plays significant role on the effectiveness of HPC. It seems the increased bulk contact of the chips with the tool with the increase in speed did not allow significant entry of even the high pressure coolant jet in case of the SNMG 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 HPC 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 cutting speed.

Almost all the parameters involved in machining have direct and indirect influence on the thickness of the chips during deformation. The degree of chip thickness which is assessed by chip thickness ratio r_c, plays an important role on cutting forces and hence on cutting energy requirements and cutting temperature. Fig.5 and Fig.6 shows that HPC has increased the value of r_c due to reduction in friction at the chip-tool interface and reduction in deterioration of effective rake angle by built-up edge formation and wear at the cutting edges mainly due to reduction in cutting temperature. It appears from Fig.5 and Fig.6 that the chip thickness ratio increases throughout the V-f range undertaken in case of both the inserts when the material machined under HPC condition. The increasing rate of chip thickness ratio is more when machined steel rod under HPC condition by the SNMM type insert due to chip breaking effect of the hill.



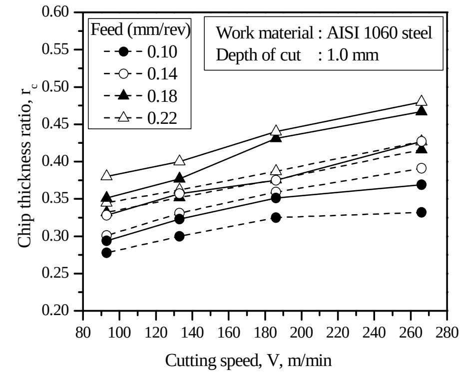
(a) SNMG insert



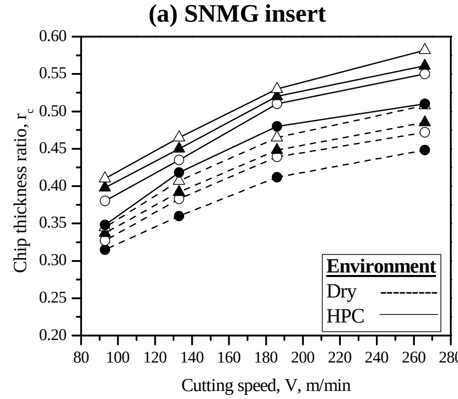
(b) SNMM insert

Fig 4. Variation in temperature in turning AISI 4320 steel

A sample of some chips produced during machining both the steels with both the inserts under lower, moderate and higher speeds and feeds are incorporated in Table 2 and Table 3 to show the actual shape and color of the chips under both the environments. Table 2 and Table 3 show that under dry condition chips are basically blue in color and long ribbon shaped. Chips become lighter in color due to reduction in temperature and shapes become loose arc type due to increase in breakability by the application of high velocity HPC jet.

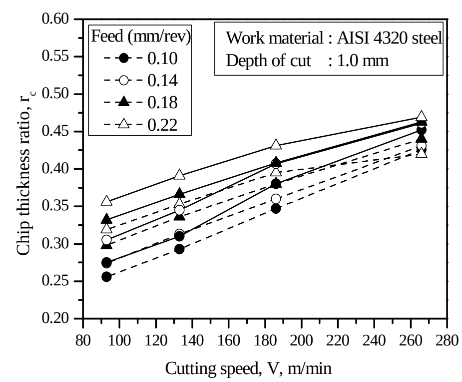


(a) SNMG insert

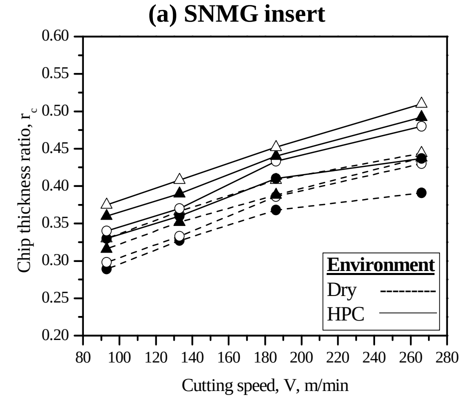


(b) SNMM insert

Fig 5. Variation in r_c in turning AISI 1060 steel



(a) SNMG insert



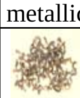
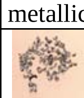
(b) SNMM insert

Fig 6. Variation in r_c in turning AISI 4320 steel

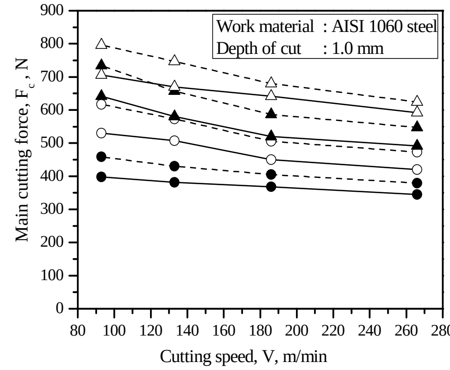
Table 2: Shape and color of chips produced during turning AISI 1060 by different inserts

f (mm/rev)	V (m/min)	Insert			
		SNMG		SNMM	
		Environment		Environment	
		Dry	HPC	Dry	HPC
		shape/ color	shape/ color	shape/ color	shape/ color
0.10	93	 blue	 metallic	 blue	 metallic
0.14	133	 blue	 metallic	 blue	 metallic
0.18	186	 blue	 metallic	 blue	 metallic
0.22	266	 blue	 metallic	 blue	 metallic

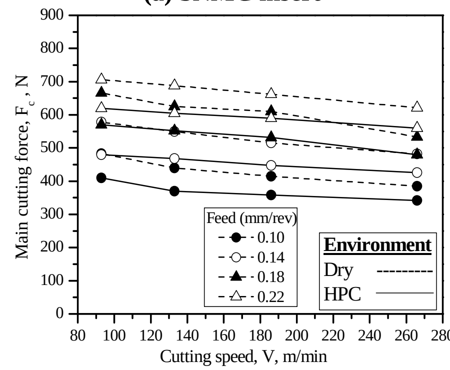
Table 3: Shape and color of chips produced during turning AISI 4320 by different inserts

f (mm/rev)	V (m/min)	Insert			
		SNMG		SNMM	
		Environment		Environment	
		Dry	HPC	Dry	HPC
		shape/ color	shape/ color	shape/ color	shape/ color
0.10	93	 blue	 metallic	 blue	 metallic
0.14	133	 blue	 metallic	 blue	 metallic
0.18	186	 blue	 metallic	 blue	 metallic
0.22	266	 blue	 metallic	 blue	 metallic

The magnitude and pattern of the cutting forces is one of the most important machinability indices because that plays vital roles on power and specific energy consumption, product quality and life of the salient numbers of the Machine-Fixture-Tool systems. Design of the M-F-T-W systems also essentially needs to have the knowledge about the expected characteristics of the cutting forces. Therefore, it is reasonably required to study and assess how the cutting forces are affected by HPC. The force data acquired for the steels machined under both environments with both the inserts are plotted against cutting velocity, shown in figure Fig.7 and Fig.8.

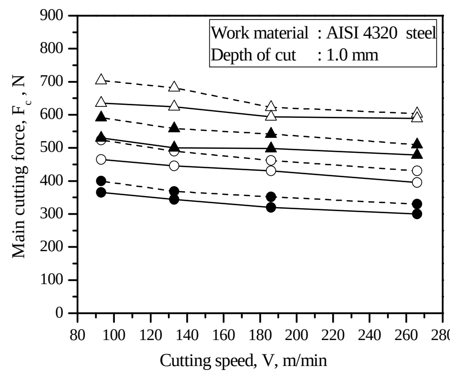


(a) SNMG insert

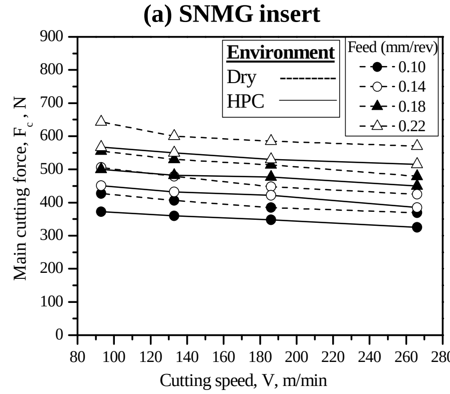


(b) SNMM insert

Fig 7. Variation in main cutting force (F_c) in turning AISI 1060 steel



(a) SNMG insert



(b) SNMM insert

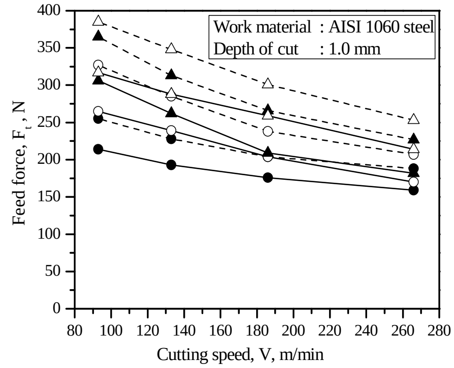
Fig 8. Variation in main cutting force (F_c) in turning AISI 4320 steel

Fig.7 and Fig.8 are clearly showing that F_c have uniformly decreased with the increase in cutting speed more or less under all the feeds, for both the inserts and environments undertaken 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. It is evident from Fig.7 and Fig.8 that F_c decreased appreciably due to application of high pressure coolant jet more or less at all the speed-feed combinations when machined steel rods by the SNMM insert. This is the indication of effectiveness of HPC due to the geometry of the cutting insert. It seems that increased bulk contact of the chips with the tool with the increase in speed did not allow significant entry of even the HPC jet in case of the SNMG insert whose cutting edge geometry allowed intimate contact of the chip over the chip-tool contact length.

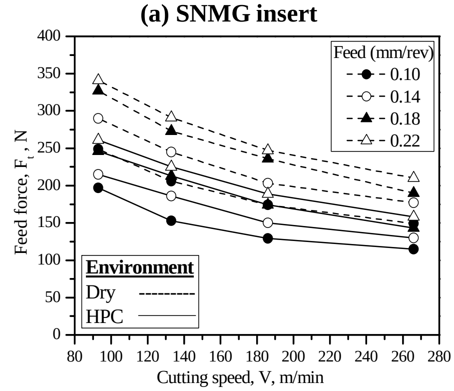
This improvement can be reasonably attributed to reduction in the cutting temperature particularly near the main cutting edge where seizure of chips and formation or tendency of formation of built-up edge is more predominant. Favorable change in the chip-tool interaction and retention of cutting edge sharpness due to reduction of cutting zone temperature seemed to be the main reason behind reduction of cutting forces by the high pressure coolant jet.

Fig.9 and Fig.10 representing the feed force acquired during machining the steels under aforesaid process parameter and conditions. It is evident from Fig.9 and Fig.10 that F_t decreased sizeably due to application of high-pressure coolant more or less at all the V-f combinations. This improvement can be reasonably attributed to reduction in the cutting temperature particularly near the main cutting edge where seizure of chips and formation or tendency of formation of built-up edge is more predominant. In this respect, the high-pressure coolant jet impinged along the rake surface seems to be more effective in cooling the neighbourhood of the main cutting edge.

Fig.9 and Fig.10 are clearly showing that F_t has also uniformly decreased with the increase in cutting speed more or less under all machining trial undertaken as usual due to favourable change in the chip-tool interaction. In machining ductile metals like steels by carbide tools, which are not chemically inert like ceramics, the chip material under elevated temperature and high pressure sticks in their layer on the tool surface by adhesion and diffusion and often resulting in gradual piling of the strain hardened layers forming built-up edge near the cutting edge. After growing to certain size, the built-up edge gets separated from the tool by the increased transverse force. Both the formation and frequent separation of built-up edge are detrimental because it not only raises and fluctuates the cutting force but also impairs the finished surface and reduces tool life.

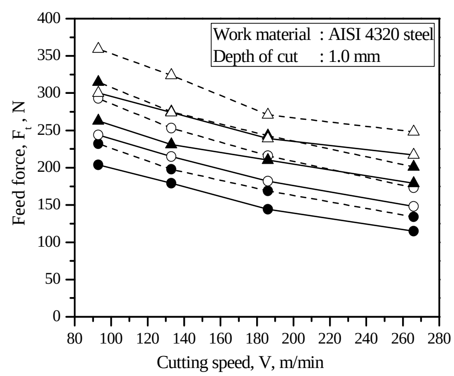


(a) SNMG insert

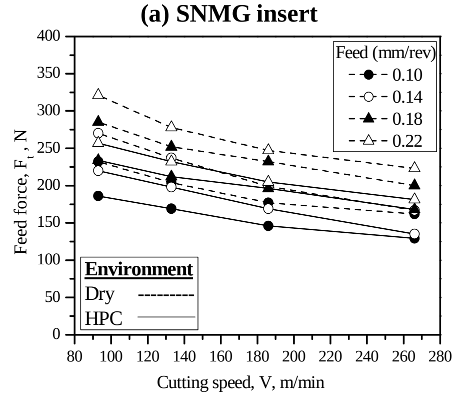


(b) SNMM insert

Fig 9. Variation in Feed force (F_t) in turning AISI 1060 steel



(a) SNMG insert



(b) SNMM insert

Fig 10. Variation in Feed force (F_t) in turning AISI 4320 steel

4. CONCLUSIONS

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

i. The cutting performance of High pressure coolant jet assisted machining is better than that of dry machining with uncoated carbide cutting tools.
ii. High pressure coolant provides the benefits mainly by substantial reducing the cutting temperature and chip-tool and/or work-tool interface friction which improves the chip-tool interaction and maintains sharpness of the cutting edges.
iii. Due to HPC cooling, the form and color of the steel chips became favorable for more effective cooling and improvements in nature of interaction at the chip-tool interface.
iv. High-pressure coolant provides reduction in the cutting forces. Lower cutting forces were recorded when machining at high-pressure coolant supply due to improved cooling and lubrication (low frictional forces) at the chip-tool interface.

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