# PERFORMANCE OF COATED CARBIDE TOOLS FOR HIGH SPEED MACHINING OF HARDENED STEEL UNDER HIGH PRESSURE COOLANT CONDITION

By

**Samrat Kumar Dey**

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# Declaration

I do hereby declare that this thesis work has been done by me and neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Samrat Kumar Dey

Samrat Kumar Dey

# Table of Contents

# List of Tables

# List of Figures

# List of Symbols

| | | |
|---|---|---|
| HPC | : | High Pressure Coolant |
| $a_1$ | : | Uncut chip thickness |
| $a_2$ | : | Chip thickness |
| BUE | : | Built-Up Edge |
| MRR | : | Material Removal Rate |
| $F_f$ | : | Feed force |
| $P_{XY}$ | : | Resultant force of $P_X$ and $P_Y$ |
| $P_Y$ | : | Radial force |
| $F_c$ | : | Main cutting force |
| R | : | Nose radius of the turning tool |
| $R_a$ | : | Surface roughness |
| SEM | : | Scanning Electronic Micrograph |
| f | : | Feed rate |
| θ | : | Average chip-tool interface temperature |
| t | : | Depth of cut |
| $V_B$ | : | Average principal flank wear |
| V | : | Cutting speed |
| $V_f$ | : | Chip velocity |
| $V_M$ | : | Maximum flank wear |
| $V_N$ | : | Flank notch wear |
| $V_S$ | : | Average auxiliary flank wear |
| $V_{SM}$ | : | Maximum auxiliary flank wear |
| β | : | Shear plane angle |
| γ | : | Equivalent or effective rake angle |
| $r_c$ | : | Chip thickness ratio ($a_2/a_1$) |
| φ | : | Principal cutting edge angle |

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Author

# Abstract

A difficult-to-cut material like hardened steel is used predominantly in the automotive and bearing industries due to its exceptional corrosion and thermal resistance and high shear strength. Abrasive machining processes such as grinding have typically been required to machine hardened steels, but advances in machine tools and cutting materials have allowed hard turning on modern lathes to become a realistic replacement for many grinding applications. Despite so many advantages, implementation of hard turning remains relatively low, primarily due to concerns about the quality of hard turned surfaces and a lack of understanding about the wear behavior of cutting tools. In general, the most important point in machining processes is the productivity, achieved by cutting the highest amount of material in the shortest possible time using tools with the longest lifetime. Combining all the parameters involved in the machining process to maximize productivity is, nevertheless, a very complex task and becomes much more difficult when working at high speed machining in hardened steels. To address this concern, this research investigated the effects of changing process conditions on wear behavior when turning hardened medium carbon steel (56 HRC) with coated carbide cutting tools.

The aim of this research is to investigate the influence of feed rate and cutting speed on the wear behavior of both SNMG and SNMM coated carbide inserts under high pressure coolant condition. Investigation on the effect of high pressure coolant on the machined chip, cutting temperature, cutting forces and product quality is the prime intention of this research.

To become a realistic replacement for grinding operation, surface roughness produced by hard turning must be comparable to grinding process if hard turned surfaces are to be accepted. Steady and progressive surface roughnesses with dimensional deviation have been investigated in this research work. The results indicate that proper selection of machining condition and high pressure cooling system yields acceptable dimensional accuracy and surface quality. It also allows adequate tool life by keeping the cutting zone temperature and cutting forces at lower levels.

# Chapter-1



# Introduction

## 1.1 Introduction

Manufacturers generally attempt to produce a product within the shortest possible time keeping the cost of the product at a minimum level without affecting the quality of the product as well. As, environmental regulations are being emerged and imposed, the manufacturers are put to re-fabricate their manufacturing processes and reduce or eliminate harmful chemicals, dusts and effluents associated with machining that can deteriorate the environment. The harmful waste present in machining includes cutting fluid, chip and worn out cutting tool.

We measure the performance and service life of an engineering component based on its dimensional and form accuracy and surface quality. After bulk material removal by machining we have to perform grinding as a finishing operation to attain the desired accuracy and surface integrity. The ever increasing demand for higher productivity, product quality and low production cost in manufacturing by machining and grinding, particularly to meet the challenges thrown by liberalization and global cost competitiveness, insists high material removal rate and high stability and long life of the cutting tools.

In practice, high production machining with high cutting velocity, feed and depth of cut is intrinsically associated with the generation of huge amount of heat that ultimately consequences high cutting temperature at the cutting zone. This high cutting temperature not only reduces dimensional accuracy and tool life but also adulterates the surface integrity of the product. Greater energy consumption leads to more severe thermal effects, eventually making the metal cutting process more and more incompetent in terms of tool life, dimensional accuracy and material removal rate. Elevated tool temperatures have negative impact on tool life. The chip-tool interface temperature plays a vital role in the thermal distortion and dimensional accuracy the machined part and in the tool life as well. It also weakens the surface integrity of the product by inducing residual stresses in the surface and subsurface micro-cracks in addition to rapid oxidation and corrosion. Tool becomes softer and wears more hastily by abrasion as temperature is increased. In many cases, constituents of the tool may diffuse into the chip or react chemically with the work piece or cutting fluid. So, our efforts should be focused on reducing the cutting zone temperature as far as possible.

When carbide tools were introduced with other new methods of machining, the efficiency of the metal cutting operations improved to a certain extent under normal cutting conditions. Presently the high temperature problems are tried to be eliminated by reducing heat generation and removing the generated heat from the cutting zone by using the combination of optimum machining parameters along with the work and tool material and application of effective cutting fluid. The foremost process parameters in this case are the cutting speed, feed rate and depth of cut. Some recent techniques have enabled partial control of the machining temperature by using heat resistant tools like coated carbides, PCD, CBN, PCBN etc. However, diamond and CBN tools are very expensive and the practices in the industry are still not wide spread. Machining productivity can be significantly improved by employing the right combination of cutting tools, cutting conditions and machine tool that prop up high speed machining without compromising the integrity and tolerance of the machined components.

Over a long period the manufacturers have been trying to reduce cutting temperature by applying water soluble cutting fluid from overhead position. This type of cutting fluid not only cools the tool and job but also provides lubrication and handles the chip to clean the cutting zone and protects the nascent finished surface from contamination by the gases(such as; oxygen) present in the atmosphere. But these conventional types of coolants and the methods of their application surely have some limitations.

With the increase in cutting velocity and feed it becomes almost impossible for the cutting fluid to enter into the chip-tool interface to cool and lubricate the interface due to bulk plastic contact of the chip with the tool rake surface. Besides, often in high speed machining the cutting fluid may cause premature failure of the cutting tool by fracturing due to close curling of the chips and thermal shocks. This is for why the application of water based cutting fluids is generally avoided in machining steels by brittle type cutting tools like carbides and ceramics. The more severe apprehensions associated with the use of cutting fluid, particularly oil-based type, are the pollution of the working environment, water pollution, soil contamination and possible damage of the machine tool slide ways by corrosion.

In conventional cooling system, the cutting zone is often flooded with coolant without considering the requirements of the specific process. Scientific investigations and industrial applications have indeed shown that the type of coolant and its supply influence the quality of product and tool life to a great extent. But in some cases, application of cutting fluids is considered undesirable, especially in machining some alloys and heat treated materials.

The manufacturers in modern industries are, therefore, searching for possible means of dry, and pollution free machining. In order to control high cutting temperature in high speed machining, some alternative methods has been reported. Typically the high cutting temperature is controlled by profuse cooling [1-3]. But such profuse cooling with conventional cutting fluids is not able to solve these problems fully even when employed in the form of jet or mist. With the advent of some modern machining process and harder materials and for demand of precision machining, the control of machining temperature by more effective and efficient cooling has become extremely essential. Cutting forces and temperature is reduced while machining steel with tribologically modified carbide inserts. Coating technology improves dry lubrication under normal cutting conditions. Near dry machining technologies or minimum quantity lubrication (MQL), which uses the fine spray of cooling medium, are being perused as alternatives for conventional coolants. Cryogenic machining with liquid nitrogen and machining with minimum quantity lubrication (MQL) has improved machinability of steel to a certain extent under normal cutting conditions. It has also been reported that though the machining of steel with liquid nitrogen improves the machinability index; it is not used in industrial practices due to high cost of liquid nitrogen and sharp increment of notch wear under nitrogen rich atmosphere.

High Pressure Coolant delivery is an emerging technology that uses up to 3000 psi (205 bars) to deliver a high velocity jet of coolant to the cutting zone. The combination of fluid volume and high velocity provides a major improvement to the machining process over the traditional flooded delivery. Long stringy chips are broken up and rapidly flushed from the cutting edge so that they are not cut again by the tool, providing longer tool life and a better finish. Heat is reduced at the tool that significantly extends its life. Greater lubricity of the coolant is achieved by the high velocity jet between the chip and the cutting tool. Productivity and quality are maximized and coolant life is extended. The high pressure and high volume delivery of clean coolant to the cutting surface permit increased tool life and higher rotational speeds with reduced cycle time.

Under these considerations, the concept of high-pressure coolant presents itself as a possible solution for high speed machining in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, if the high pressure cooling parameters can be strategically tuned. Mazurkiewicz et al. [4] reported that a coolant applied at the cutting zone through a high-pressure jet nozzle could reduce the contact length and coefficient of friction at chip-tool interface and thus could reduce cutting forces and increase tool life to some extent. It has been reported that the cooling and lubrication is improved in high speed machining of difficult-to-machine materials by the use of high-pressurized coolant/lubricant jet [2]. High-pressure coolant injection technique not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid by 50% [2, 5].

The overall success of implementing this technology in the realm of metal removal industries therefore depends on increased research activities providing credible data for sound understanding of high-pressure coolant supplies at the chip-tool interface and integrity of machined components. In this regard, the present research work is carried out to experimentally investigate the role of high-pressure coolant on chip morphology, average chip-tool interface temperature, cutting force, feed force, tool wear, dimensional deviation and surface finish in turning hardened medium carbon steel, at different cutting velocity and feed combinations by coated carbide insert under completely dry and high-pressure coolant conditions and to find out the advantages of high-pressure coolant machining over dry cutting. So, the aim of the high-pressure cooling system is to improve the quality of the surface machined (roughness and accuracy) and to prolong the tool life under high speed machining as well.

## 1.2 Literature Review

### 1.2.1 Introduction

Hard turning differs from conventional turning of softer materials in several key ways. Because the material is harder, specific cutting forces are larger than in conventional turning, and thus the engagement between cutting tools and the workpiece must be limited. At the small cutting depths required, cutting takes place on the nose radius of cutting tools, and the tools are typically prepared with chamfered or honed edges to provide a stronger edge geometry that is less prone to premature fracture. Edge preparation is critical for ceramic cutting tools, which are required because they maintain adequate hardness even at the elevated temperatures that are developed when machining hardened steels. Cutting on a chamfered or honed edge equates to a large negative effective rake angle, while neutral or positive rake angles are typical in conventional machining. The large negative rake angles yield increased cutting forces compared to machining with positive rake tools, and also induce larger compressive loads on the machined surface. Higher temperatures are also generated in the cutting zone, and because cutting is typically done without coolant, hard turned surfaces can exhibit thermal damage in the form of micro structural changes and tensile residual stresses.

### 1.2.2 Research on Hard Turning

As large cutting force is associated with hard turning, rigid and precise machine tools are prime prerequisites to expel any vibration or chatter. In juxtaposition with the invention and development of new cutting tool materials and the rigid machine tools hard turning have become a practicable process. Tonshoff et al. [6] found that the large negative rake angles (from the edge chamfer) on tools used for hard machining yield large dynamic thrust forces that require adequate machine rigidity, spindle power, damping characteristics, and accuracy of motion along the axes of the machine. Bosssom [7] found that tools with chamfered edges produced cutting forces twice as large as non-chamfered tools. Chryssolouris [8] showed that when machining in a poor stiffness setup, tools failed quickly due to edge fracture. These needs have led to recent machine tool designs that improve stiffness and damping by several methods. New machines have incorporated polymer composite materials in the machine base, reduced the number of joints in the machine, and developed improved slide ways such as hydrostatic designs [9, 10]. Advances in the control capabilities have also improved the accuracy of the machines.

It would be ideal to eliminate all machining operations, including both hard turning and grinding, because they are wasteful processes that are not particularly efficient. However, many parts specifications necessitate that finish machining be done after heat treatment. Historically this has been done by grinding, and hard turning must be capable of producing similar geometric precision and quality surfaces. Several studies have investigated the capability of the process to compete with grinding, and most have concluded that at proper conditions with a good machine, hard turning can produce dimensional accuracy and surface finishes acceptable for most applications. Matsumoto et al. [11] were able to hard turn parts with surface finish ranging from 0.045-0.197 µm, and surface waviness from 0.775-1.26 µm. They had determined that requirements for a ball bearing surface were less than 0.2 µm for $R_a$ surface finish and less than 1.5 µm for waviness. Similar results were found by Jochmann and Wirtz [12], who produced consistent peak-to-valley finishes below 1.0 µm, roundness below 0.2 µm, and cylindricity below 1.0 µm. Abrao and Aspinwall [13] were able to produce a surface finish with roughness value $R_a$ as low as 0.14 µm

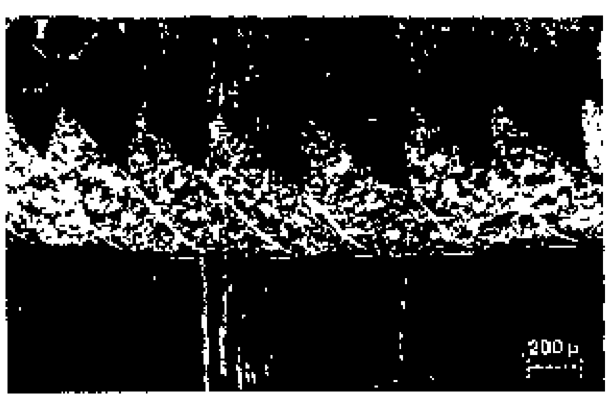


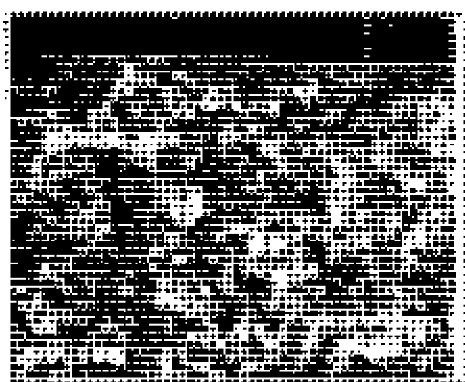

**Fig. 1.1** Saw-toothed chip produced by hard turning [14]

A significant amount of research in hard turning has focused on understanding chip formation. The mechanics of chip formation in hard turning are very unlike chip formation in softer steels, where continuous chips have typically been observed. This type of chip formation was the basis of early machining models as shown by Merchant [14] and Lee [15]. However, many machining operations produce cyclic chips that can be described as the wavy chip, the catastrophic shear chip, the segmental chip, and the discontinuous chip [16]. In hard turning, periodic sew-toothed chips have been observed by many researchers, as seen in Figure 1.1. Two separate explanations of the mechanism that causes this type of chip formation have developed.

The first theory suggests that chip segmentation is initiated by shear fracture, caused by a compressive stress induced by the cutting tool that exceeds the critical shear stress of the material at the free surface of the workpiece [17, 18]. The crack creeps toward the cutting edge until the compressive strength is sufficient to stop crack propagation and cause plastic deformation of the remaining portion of the chip segment along the fracture line. As the tool continues to move, the chip segment is pushed out along the fracture line, and a new chip segment forms as the compressive stress builds and a new shear fracture initiates ahead of the cutting edge.

A second theory describes the chip segmentation mechanism as catastrophic strain localization [19, 20]. Strain localization occurs when thermal softening behavior dominates over the effects of strain rate hardening in the shear zone. This behavior has been observed in many materials with poor thermal properties, such as titanium and nickel alloys. These materials' ability to deform plastically can vary with temperature due to a possible phase transformation and the resulting changes in crystal structure [16]. The conditions for strain localization are typically met when the strain rate exceeds a critical value. This critical strain rate is a material property, and can be exceeded with increasing cutting velocity. Evidence of this theory is the onset of chip segmentation above a critical cutting velocity [21].

If hard turning is to replace any grinding operation, it must be capable of producing surfaces of acceptable quality. This includes both the surface topography (surface finish) and surface integrity, which is achieved when "the surface of a component meets the demands of a specific stress system and environment" [22]. Field et al. [23] defined an "extended surface integrity data set" which includes: surface finish, microstructure, microhardness, fatigue resistance, residual stress state, and frictional characteristics.



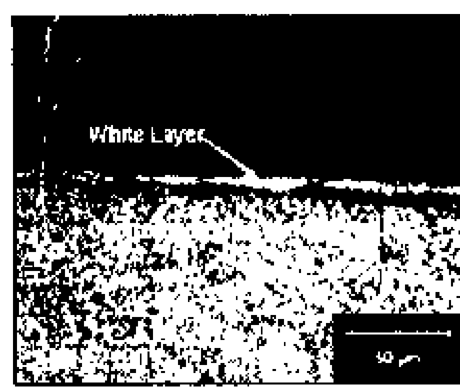



**Fig. 1.2:** Typical white layers [24]

There are two major types of surface damage that can be caused by hard turning. The first is white layer, which has generally been assumed to result from temperatures generated at the workpiece surface that exceed the austenitizing temperature of the material, followed by rapid cooling. The second type of damage is the formation of undesirable residual stress profiles at, and just below, the workpiece surface. Mechanical loading, plastic flow, and phase transformation can affect residual stresses, but negative effects are primarily due to the elevated temperatures during machining. Thus, the two types of damage (white layer and tensile residual stress) are related and have generally been investigated together. Typical white layers from machining hardened steels are shown in Figure 1.2. Notice that even when white layers exist, the thickness is very small. Abrao and Aspinwall [25] reported that at a range of test conditions, the thickness of the transformed layer was below 3 μm.

It is generally believed that generation of white layer requires both excessive heat at the workpiece surface and subsequent rapid cooling. Heat generation is attributed to large amounts of energy generated in the shear region during chip formation and to the frictional energy between the tool flank and workpiece surface. However, experimental results disagree about the source of rapid cooling. Tonshoff et al. [26, 27] performed hard turning experiments with and without coolant and found the white layer magnitude was identical, indicating that workpiece self-cooling, and not coolant, must be responsible for quenching of the workpiece surface. This argument is reasonable because the heat-affected zone is small in hard turning, and because the cutting velocities are large enough that the contact time between the tool and workpiece is minimal. Therefore, it is possible that the bulk workpiece material acts as a heat sink and draws heat from the surface to create a self-cooling effect. However, Konig et al. [28] found that cutting with a worn tool produced white layer, but that similar cutting conditions with the application of coolant resulted in undamaged surfaces.

Many researchers have paid considerable attention to the generation of white layer because it appears similar to thermal damage generated in grinding that is referred to as "grinding burn." To determine the structure of white layer, Tonshoff et al. [26] used an X-ray technique to determine the separate structures of the bulk workpiece material and the white layer region. The results showed that for 16 MnCr 5 steel hardened to 60-62 HRC, the bulk material was composed of approximately 75% martensite and 25% austenite. The white layer consisted of only 30% martensite and almost 70% austenite. However, inspection of chemical concentrations when machining ASTM 5115 showed no difference between the surface layer and bulk [26]. Apparently, the crystallographic structure may change, but there is not sufficient time for diffusion.

Griffiths [29] reported three situations where white layers have been generated: surfaces subjected to significant rubbing and wear (railroad tracks as an example), surfaces that see similar conditions resulting from pin-on-disk testing, and surfaces that undergo certain machining processes. Brinskmeier and Brockhoff [30] presented evidence that in addition to machining conditions, material properties affect white layer generation. They attributed formation of all white layers to heating and quenching of the material, and concluded that chemical composition of the material affects the transformation. Griffiths [29] did not agree that all white layers are caused by a transformation, and suggested that other causes may be surface reactions with the environment and plastic flow that causes grain refinement. Several publications have proposed that white layers may have increased hardness relative to the bulk material [30-32]. Others have reported nearly identical hardness in the white layers compared with the bulk material [33].

To discuss the effects of hard turning on residual stresses, the surface influences of hard turning compared to grinding should be mentioned. Compared to grinding, the force components are large, particularly the thrust force, which is generally larger than the cutting force in hard turning. If the tool loading is thought of as a Hertzian contact, the maximum compressive stress induced in the workpiece occurs at a depth approximately

0.7 times the contact area of the tool. Because the contact area is larger than grinding (a single grit) and load is increased, larger residual compressive stresses that penetrate deeper below the workpiece surface result in hard turned components. This was verified by Brinksmeier et al. **[34]** and Konig et al. **[35]**. As expected, the magnitude and depth of residual stresses are a function of tool geometry and process conditions **[11, 31, 34 and 36]**.

Unlike residual tensile stress, reasonable levels of compressive stress are desirable. Based on the residual stress caused by mechanical loading only, hard turned surfaces should exhibit increased fatigue life compared to ground surfaces. However, the undesirable tensile stresses generated by heat are superimposed on the compressive stress **[27, 35]**. As tool flank wear increases, so does the frictional energy between the tool flank and workpiece, as well as the depth of the compressive stress induced by mechanical loading. Thus, increased tool wear results in larger tensile stresses near the surface, which is then followed by steep stress gradients with a larger compressive stress further below the surface. The stress pattern with less overall change was generated by a tool with very little flank wear compared to the other stress pattern, which was generated with a significantly worn tool.

In addition to tool wear, tool edge geometry has an effect on the residual stress profiles that are generated. Kishawy and Elbestawi **[37]** investigated the effect of the edge preparation in combination with cutting speed on the residual stresses of hardened D2 tool steel. Thiele et al. **[38]** reported the effects of edge geometry, feed, and workpiece material hardness on subsurface deformation and residual stresses when finish machining hardened AISI 52100 steel.

While much attention has been paid to the influence of hard turning on surface integrity, surprisingly little has been done to understand the effects of resultant surface integrity on performance (wear resistance, strength, fatigue resistance, etc.). Significant concerns exist about white layer and tensile residual stresses on the workpiece surface, but most research has disputed these concerns about hard turned surface quality. Griffiths and Furze [39] showed that white layers reduced wear when running block-on-ring tests on EN24T (similar to AISI 4340). Tonshoff and Brinksmeier [40] attempted to use micro-hardness and residual stresses to identify mechanical and thermal influences on the workpiece and relate this to functional behavior. Matsumoto et al. [41] fly cut AISI 4340 at 58 HRC and found that hard machined fatigue samples exhibited slightly increased endurance limits compared to ground samples. Rotating bending tests showed a 7% decrease in fatigue limit with increased tool wear [26]. The results also indicated that hard turned surfaces always exhibited comparable fatigue strength to ground surfaces. Abrao and Aspinwall [13] performed axial fatigue tests on hard turned bars, and found that bars turned with PCBN tools performed better than bars machined with alumina tools and also better than ground surfaces. Matsumoto et al. [42] showed similar results, indicating that hard turned and superfinished components had comparable or improved fatigue life. Smith [43] found improved wear resistance and axial fatigue life on hard turned surfaces, even with white layers.

Even if the issues of machine tool design, dimensional accuracy, and surface integrity can be addressed satisfactorily, tool wear remains a major obstacle to further implementation of hard turning. Most research in the area of tool wear has focused on the influence of tool material properties, workpiece material properties, and cutting conditions on wear behavior, although some studies have also reported the effects of wear on surface integrity.

Resistance to tool wear is related to CBN content, grain size, binder material, tool geometry, cutting edge geometry (sharp, honed, or chamfered), workpiece properties, and cutting conditions. The effects of tool wear include: reduced tool life, increased surface roughness, increased cutting forces; more tensile residual surface stresses, and increased white layer thickness. While tool wear and tool life ultimately dictate whether or not hard turning can produce acceptable surfaces over the life of a tool, and whether or not it can be justified economically compared to grinding, research in the area of tool wear seems to have take a back seat to studies of chip formation and surface integrity. This seems unfortunate because the research has shown that acceptable surfaces can be produced at proper conditions, so for many applications uncertainty about wear behavior is all that has limited hard turning.

Tool material properties and workpiece properties obviously affect the wear behavior of tools. Several efforts have focused on tool composition, with the goal of determining optimal mixtures for the composite tools used in hard turning. Bossom [7] showed that low CBN content tools (<70% CBN) produced better tool life and surfaces than high CBN content tools (>90%). Similar results have been cited by many others [42]. Takatsu et al. [44] performed tests on JIS SUJ2 bearing steel hardened to 62 HRC with tools that were identical other than CBN content. They found that flank wear and crater wear were both minimized at a CBN percentage of 55%. This confirms that lower CBN content tools perform better than high CBN content tools, but no consistent explanation for the improved performance has been presented.

Workpiece material properties also affect the wear behavior of PCBN tools in hard machining. Luo et al. [45] machined AISI 4340 steel at hardness ranging from 35-55 HRC, and found that hardness affected cutting forces and tool life. Both cutting forces and tool life were optimal (low forces, long life) at a workpiece hardness of 50 HRC. Matsumoto and Narutaki [46] found adhesion of iron on the tool face when turning hardened steel with a high CBN content tool, and proposed that this adhered layer contributed to decreased tool life. However, they also found that adhesion of MnS on the tool face when machining a carburized bearing steel created a lubricating layer that reduced tool/chip friction and increased tool life. Barry and Byrne [47] found a 400% difference in the wear rate of nominally similar 4340 steels with only slight differences in the workpiece inclusion content and size.

It seems that no cohesive body of knowledge has developed to explain the interactions between the cutting tool and workpiece that lead to tool wear. Surely research will continue in this area until wear phenomena are better understood. In the meantime, it is also important to understand the effect of tool wear on the hard turning process, and more specifically, on the quality of machined surfaces. Since much attention has been paid to surface integrity, the general influence of tool wear on white layer generation and residual stresses is better known that the mechanisms for tool wear itself. In general, CBN tools form scars on both the flank and rake surfaces of the cutting tool. Historically, flank wear has been studied more than crater wear because it is easier to measure and because it is believed to relate more directly to surface finish and surface integrity [25]. Increasing flank wear tends to increase the friction between the tool and workpiece, and the additional heating that results from friction was shown to cause white layer formation by Konig et al.

[35]. They also reported that the thermal effects from increased friction lead to more tensile residual stresses at the workpiece surface, but more compressive subsurface stress profiles. Chou and Barash [48] suggested that flank wear is the main contributor to white layer formation. Chou and Evans [49] showed that surface roughness and cutting forces increased significantly with flank wear when turning M50 steel. They found similar results for M50 formed by powder metallurgy [50] and Sista et al. [51] showed similar results when hard turning M2 tool steel.

Because tool wear affects cutting forces, cutting temperatures, resultant surface quality, and tool life, it is important to quantify this behavior and relate it to changing process conditions. A summary of the literature indicates that tool wear tends to increase workpiece temperatures, increase cutting forces (especially the thrust force), cause more tensile residual stresses, generate larger white layers, and diminish surface finish. However, most work has been qualitative in nature. Research that investigated wear of different grades of tool materials on various workpiece materials has not produced quantitative descriptions of wear modes. Research focused on the effects of wear on temperatures, forces, and surface quality has not sufficiently described the condition of the cutting tool, because the effect of the crater scar on the cutting process has been neglected. Surprisingly, the effects of process conditions (speeds, feeds, and depth of cuts) on wear behavior are relatively scarce in the literature. Thus, this research aims to describe in a quantitative way the influence of cutting conditions on the chip formation mechanism, wear behavior of carbide tool and relate the wear behavior to changes in cutting temperatures and resultant surface quality.

Machinability of materials usually judged mainly in respect of chip morphology, chip tool interaction, cutting temperature, cutting forces, dimensional accuracy, surface integrity and wear and life of cutting tool with using cutting fluid and without using cutting fluid. Heat generation and high cutting temperature is inherent characteristics of machining due to shearing of work material, friction between the flowing chips and rake face of the tool as well as friction of auxiliary flank with finished surface. At such elevated temperature the cutting tool if not enough hot hard may loose their form or 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, though in different degree, with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material. Usually water soluble cconventional cutting fluid is applied to control such elevated cutting temperature but it is ineffective in high speed machining and also is a major source of environmental pollution in the machining industries. Research has also been initiated on control such pollution by neat and clean machining like Cryogenic cooling, MQL cooling and high-pressure coolant (HPC) machining and their technological effects particularly in temperature intensive machining and grinding. A brief review of some of the interesting and important contributions in the closely related areas is presented in this section.

The high specific energy required in machining under high cutting velocity and unfavorable condition of machining results in very high temperature which reduces the dimensional accuracy and tool life by plastic deformation and rapid wear of the cutting points [52-54]. On the other hand, such high temperature impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, surface and sub-surface cracks [53].

The mechanisms of material deformation, friction and material removal lead to the initiation of machined components, where the temperature of the rake and flank is the most important factor to affect the chip formation, tool wear, cutting forces and surface integrity [5, 55]. At elevated temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increased cutting forces and premature tool failure [56].

According to Muller and Blumke [57], high speed machining for a given material can be defined as that speed above which shear-localization develops completely in the primary shear zone. Ekinovic et al. [58] showed that when hardened steel is machined, high speed machining conditions appeared at cutting speed above 150 m/min. Their conclusion was drawn on the basis of evaluation on chip shape collected during machining.

Ng et al. [59] proposed that there is a peak cutting temperature at an intermediate cutting speed and when cutting speed is increased from this point, there is a reduction in temperature. Since this claim most of the literature has concluded that there is no corresponding reduction in temperature at higher cutting speeds. Conversely, Vernon and Ozel [60] stated that the limit of cutting speed is a function of the cutting tools used. Ekinovic et al. [61] suggested that temperature is increased with cutting speed up to maximum which is equal to the melting point of the work piece. No temperature reduction occurred at higher cutting speeds. But there is no fixed limit to the cutting speed when machining aluminum alloy because the melting point of this alloys (up to 600°C) is lower than the temperature at which cemented carbide and ceramic tool materials begin to lose their strength and wear rapidly.

Cutting chips becomes blue in color due to intensive high temperature during machining. With the increase in cutting speed, feed, depth of cut and hardness of the work material the chips turns to gradual deep blue. Kosa and Ney [62] suggested that in machining ductile metals, the heat and temperature developed due to plastic deformation and rubbing of the chips with tool, may cause continuous built-up of welded debris which affects machining operation. Austenitic stainless steels are generally considered difficult-to-machine because of high work-hardening rate, toughness and ductility. Therefore, tools will be subjected to high frictional heat, and chips will have a tendency to stick and cause severe built-up edge formation. It was observed [63] that, in machining ductile metals, producing long chips, the chip-tool contact length have a direct influence on the cutting temperature and thermo-chemical wear of cutting tools. The cutting temperature becomes the maximum on the rake face of the tool at a certain distance from the cutting edge where cratering occurs. Such high rake face temperature can also raise the temperature at the flank of the tool. Komanduri and Schroeder [64] reported that machining Inconel with hot-pressed ceramic and cubic boron nitride cutting tool produces different types of longitudinal chips. At lower speed (<30 m/min) the chips are mechanically continuous although highly coiled. With increased speed (up to about 91.5 m/min), shear localization is initiated. The chips formed are comprised of many segments strongly joined together forming a continuous tight coil. With a further increase in speed, the extent of contact between the segments decreases. At about 152.5 m/min, short chips with only a few segments joined together are produced, and from this speed onward, the chip segments are completely isolated. Pashby et al. [65] proposed that the cutting speed at which a change in chip form occurs varied from tool material to tool material. Kitagawa et al. [66] conducted experiments with ceramic tool under flood cooling condition and concluded that with increase in cutting speed, serrations in the chip become obvious and the chip thickness decreases.

Vleugels [67] observed that the contact length between the tool and chip has a direct influence on the cutting temperatures and the amount of heat energy that is dissipated in the tool which enhances thermally activated chemical wear. Toropov and Ko [68] also reported that, in machining ductile metals, the chip contact length plays significant role on the chip and tool temperature which becomes maximum almost at the centre of the chip-tool contact surface where crater wear begins and grooves intensively.

Generally, shear angle decreases with increase in cutting velocity and a high shear angle improves the machinability of steel. Masatoshi Hirao et al. [69] concluded that molybdenum and vanadium mixed nitriding steel produces long cutting chips at low cutting velocity but the cutting tool is sometimes broken by long continuous chips which affects shear angle. Duan and Wang [70] suggested that an increase of work material hardness increases the shear angle, the temperature and the yield strength but reduces the average stress ratio on the primary deformation zone. Sutter [71] reported that continuous chip forms during machining material having good thermal property and low hardness, whereas ribbon like chip or a segmental (or shear localized) chip forms during machining material having poor thermal property and high hardness.

Strafford and Audy [72] investigated the relationship between hardness and machining forces during turning of AISI 4340 steel with mixed alumina tools. The results suggest that an increase in hardness leads to an increase in the machining forces. Tool geometry is another important factor affecting machining forces, especially the feed (axial) and thrust (radial) force components [73]. The use of large nose radius together with low depths of cut leads to low true side cutting edge angle values, thus resulting in high thrust forces [58]. Liu et al. [75] observed that the cutting temperature is optimum when the work piece material hardness is HRC 50. With further increase in the work piece hardness, the cutting temperature shows a descending tendency. Liu et al. [74] also suggests that, under different cutting parameters, the role of cutting force changes with work piece hardness. The main cutting force features an increasing tendency with the increase of the work piece hardness.

According to Trent [75], the cutting tool generally undergoes both flank wear and crater wear during machining. Flank wear generally causes an increase in the cutting forces, dimensional inaccuracy and vibration. Crater wear takes place on the rake face of the tool where the chip slides over the tool surface. Reed and Clark [76] reported that the hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate. Moreover, thermal stresses in the tool increase with the temperature resulting in more cracks in the tool and premature failure of the tool. The amount of energy dissipated through the rake face of the tool raises the temperature at the flanks of the tool [77]. Wang et al. [78] reported that the normal turning chips often have considerable strength and cause crater wear, crack development or other kinds of surface damage on the rake face of the tool. Liao and Shiue [79] reported that built-up edge (BUE) is formed with chipping of the cutting edge during machining Inconel with carbide. They also observed Ni and Fe diffusion into the cutting tool. This diffusion of the work elements into the cutting tool may be explained by the very high cutting temperature during the experiments.

Kitagawa et al. [66] investigated tool wear and cutting tool temperature by means of turning experiment in the presence of 10% water base coolant. Temperature rose monotonically, up to about 1200° C, with increasing cutting speed. They confirmed that notch wear VN were the major types of wear observed. However taking into account the decreasing of notch wear at higher cutting speed, they estimated that the wear characteristics observed cannot be exclaimed by temperature alone and the wear is rather developed by an abrasive process than a thermally activated adhesion mechanism.

Rahman et al. [80] discussed the machinability of Inconel 718 subjected to various machining parameters including tool geometry, cutting speed and feed rate on flank wear of the coated carbide inserts, work piece surface roughness and cutting force components as the performance indicators for tool life. They observed that tool life increases with the increase in side cutting edge angle for the inserts and the heat generated during the cutting process is distributed over a greater length of cutting edge. This improves the heat removal from the cutting edge, distributes the cutting forces over a larger portion of the cutting edge, reduces tool notching and substantially improves tool life.

Most of the major parameters including the choice of tool and coating materials, tool geometry, machining method, cutting speed, feed rate, depth of cut, lubrication, must be controlled in order to achieve adequate tool lives and surface integrity of the machined surface [81, 82]. A crater is usually formed at some distance from the cutting edge and it is most frequently observed when cutting steels and other high-melting-point metals at relatively high cutting speeds [83]. This crater gradually becomes deeper with time and may lead to the breakage of the cutting edge, rendering the tool useless.

Luo et al. [45] reported that when turning AISI 4340 steel using mixed alumina and PCBN tools the flank wear is reduced as work material hardness increased up to a critical value. A further increase in the work piece hardness accelerates the tool wear rate. The reduction in tool wear up to critical is attributed to the elevation of the cutting temperature, which reduces the shear strength of the work material; however, this effect is not observed when the hardness exceeded critical value. The material transfer leads to the formation of a crater on the tool rake face and consequently reduces the tool mechanical resistance and its efficiency. Diffusion phenomena were first reported by Molinari and Nouari [84] who showed that at conventional speed, tool wear is mainly due to abrasion and adhesion, but is dominated by diffusion process at higher speeds.

Severe flank wear and notching at the tool nose and/or the depth of cut line are the dominant failure modes when machining nickel-based alloys with carbide tools [78, 85, 86]. The recommended cutting speeds range is from 10 to 30 m/min when machining nickel-based alloys with cemented carbide tools [87]. Cemented carbide tools cannot be used to machine nickel-based alloys at high speed since they cannot withstand the conditions of extreme high temperature and stress in the cutting zone. Rapid increase in notching occurs on carbide tools at higher cutting speed. This usually leads to the premature fracture of the entire insert edge [88]. Flank wear generally causes an increase in the cutting force and the interfacial temperature, leading normally to dimensional inaccuracy in the work pieces machined and to vibration which makes the cutting operation less efficient [89]. Large nose radius and cutting edge angle values may improve the surface finish of the machined part provided tool vibration can be avoided [90].

### 1.2.3 Controlling of Cutting Temperature

Research that has been carried out in the past focused on the temperature and its distribution in the cutting zone because it is believed that it has a direct impact on tool life [91]. Due to such high temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increased 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, micro-cracks and structural changes. Cutting zone temperature can be controlled by

i. proper selection of machining parameters
ii. Using conventional coolant
iii. Using modified coated tool applying multilayer coating for dry lubrication
iv. using heat and wear resistance cutting tools
v. using proper type of coolant and their effective application (Cryogenic machining, MQL cooling and high pressure coolant jet assisted machining).

The machining temperature can be reduced to some extent by improving the machinability characteristics of the work material metallurgically, optimizing the tool geometry and by proper selection of the process parameters [92, 93, 94]. But for higher productivity in manufacturing by machining to meet the global cost competitiveness, insists high material removal rate as well as high process parameters.

Generally, suitable cutting fluid is employed to reduce cutting temperature through cooling and lubrication at the cutting zone. The cutting fluids are believed to reduce cutting temperature either by removing heat as a coolant or reducing the heat generation as a lubricant. In addition, the cutting fluid has a practical function as a chip-handling medium [95]. But it has been reported that lubrication is effective at low speeds when it is accomplished by diffusion through the work piece and by forming solid boundary layers from the extreme pressure additives, but at high speeds no sufficient lubrication effect is evident [96]. The primary function of cutting fluids is to reduce this cutting temperature and increase tool life [97]. The ineffectiveness of lubrication of the cutting fluid at high speed machining is attributed to the inability of the cutting fluid to reach the actual cutting zone and particularly at the chip-tool interface due to bulk or plastic contact at high cutting speed [98-101].

The high cutting temperature is controlled by profuse cooling [1-3]. But such profuse cooling with conventional cutting fluids is not able to solve these problems fully even when employed in the form of jet or mist. Cutting fluids also help in machining of ductile materials by reducing or preventing formation of a built-up edge (BUE), which degrades the surface finish [86].

The effect of the heat generated at the primary shear zone is less significant for its lesser intensity and distance from the rake surface. However, the heat generated at the chip-tool interface is of much greater significance, particularly under high cutting speed conditions where the heat source is a thin flow-zone seized to the tool [76, 102, 103]. The coolant cannot act directly on this thin zone but only externally cools the chip, work piece and the tool, which are accessible to the coolant. Removal of heat by conduction through the chip and the work piece is likely to have relatively little effect on the temperature at the chip-tool and work-tool interface. The cooling and lubricating affects by cutting fluid influence each other and diminish with increase in cutting velocity [67]. Since the cutting fluid does not enter the chip-tool interface during high speed machining, the cutting fluid action is limited to bulk heat removal only.

A cutting fluid may impart two more actions, namely the mechanical strength reducing action and the electro-chemical action. The mechanical strength reducing action seemed to be negligible when steel jobs are machined at moderate cutting speeds with carbide tools [1]. The influence of the electric current flowing through the cutting zone on the rate of tool wear is also well known [104]. However, most commercial cutting fluids are non electro-conductive, and as such the situation with respect to current flow is not vary significantly from the dry cutting case. The electrochemical action is treated as a corrosion phenomenon in respect of tool wear.

The application of abundant cutting fluid, however, increases the cutting process costs and in hardened steel cutting, does not allow the work piece soften, which is good for the process [105]. Ekinovic et al. [59] suggested that, the use of abundant cutting fluid (wet condition) has the advantages of providing chip transportation, reducing friction and cooling the work piece. For example if cutting fluid is not used in machining of both aluminum alloys and soft steels, the wear caused by attrition is unacceptable.

Seah et al. [106] also reported that at the first stage of machining (first 40 seconds or so), tool wear is faster in wet cutting than in dry cutting. Later on, the wear rate is stabilized and is somewhat the same for both dry and wet cutting. Minimum volume of oil technique may represent a compromise between the advantages and disadvantages of completely dry cutting and cutting with abundant soluble oil [107, 108]. The application of cutting fluid may not always reduce the cutting tool wear as is commonly believed. Rather some conditions like machining steels by carbide tools, the use of coolant may increase tool wear. It has been experienced that there was more tool wear when cutting with coolant than cutting dry in case of machining AISI 1040 and AISI 4340 steels by carbide cutting tool [101].

Apart from these cost aspects, cutting fluids represents a serious problem to the preservation of the environment and health. About 80 percent of all occupational diseases are caused by skin contact with fluids [109, 110]. Cutting fluids are the important causes of occupational contact dermatitis, which may involve either irritant or allergic mechanisms. Water mixed fluids generally determine irritant contact dermatitis and allergic contact dermatitis when they are in touch with workers skin. These fluids often contain sulphur (S), phosphorus (P), chlorine (Cl) or other extreme-pressure additives to improve the lubricating performance. These chemicals present health hazards. Furthermore, the cost of treating the waste liquid is high and the treatment itself is a source of air pollution. The major problems that arise due to use of cutting fluids are [111]:

i. At high cutting temperature the cutting fluids breakdown into its harmful constituents that cause air pollution and create breathing problems to nearby people.

ii. Biological hazards to the operators from the bacterial growth in the cutting fluids if it comes in physical contact to them

iii. Mechanical hazard of the machine parts due to contamination of the parts with the fluid.

iv. Water pollution and soil contamination are caused if the spent cutting fluids mix with them during disposal

Like other manufacturing activities, machining also leads to environmental pollution mainly because of the use of cutting fluids [112, 113].

With the advent of some modern machining process and harder materials and for demand for precision machining, the control of machining temperature by more effective and efficient cooling has become extremely essential. Some recent techniques have enabled partial control of the machining temperature and eliminated pollution by using heat resistance tools like coated carbides, CBN etc under dry condition. The thermal deterioration of the cutting tools can be reduced by using CBN tools [114]. If properly manufactured, selected and used, CBN tool provides much less cutting forces, temperature and hence less tensile residual stresses [115]. However, CBN tools are very expensive. Recent studies have reported that CBN tools can be used for machining high temperature super alloys, especially titanium alloys, at higher cutting speeds despite the high reactivity of titanium-alloys with the tool materials in addition to their relatively high cost [116]. Owing to their high hardness and high melting point, CBN tools can withstand the heat and pressure developed during cutting without compromising surface integrity of the machined component because of their ability to maintain a sharp cutting edge for longer periods [117].

The contact surface of turning inserts by deposition of a soft bearing material was modified by EDM [118]. Although the modified inserts offered reduced cutting force, their beneficial effect on surface finish was marginal. At higher cutting velocities, the brought on layers are fast depleted with cutting time and do not contribute to wear resistance of the tool, especially at the flanks. The machining of hardened steel is usually done using dry cutting, because the increase of the temperature makes chip deformation and shearing of the hardened material easier. Nevertheless high temperatures cause an inconvenience such as work piece dilation, which affects dimensional and geometric accuracy and runs the risk of surface integrity damage. On the other hand, the complete absence of lubrication harms chip transportation and causes increases of tool-chip and tool-work piece friction, which generate the increase of abrasive wear and attrition [105].

Thoors and Chandrasekaran [119] observed that $CO_2$ snow could function as a good coolant under certain circumstances, which are very much related to the tool-work combination and the actual mode of feeding the coolant to the cutting zone. Machining temperature can be controlled by the use of $CO_2$ snow as the coolant in machining [120]. This is feasible if $CO_2$ in liquid form under pressure (60 bars) is fed to the cutting zone and diffused through a capillary jet. This results in a change of state and the formation of $CO_2$ snow (endothermic reaction resulting in a temperature of -79$^0$C). But under intense temperature $CO_2$ produces harmful CO gas.

Cryogenic machining with liquid nitrogen has improved machinability of steel to a certain extent under normal cutting conditions [121]. Chilling the cutting tool by liquid nitrogen jets enhances tool hardness and life, dimensional accuracy and improves surface roughness. Cooling the chip makes it brittle and aids easy removal. Because nitrogen is an abundant atmospheric constituent and the quantities used are small. So, there is neither unfavorable environmental and health impact nor any coolant disposal cost and the chips can be readily recycled [98, 122, 123]. Their results indicate substantial benefit of cryogenic cooling on cutting force, tool life, dimensional accuracy and surface roughness due to mainly reduction of cutting zone temperature and favorable changes in the chip-tool interaction.

Dhar and Kamruzzaman [124] investigated the role of cryogenic cooling by liquid nitrogen jet on chip formation, grinding zone temperature and surface roughness in grinding alloy steels. Their experimental results indicate significant reduction in grinding temperature on application of cryogen, which enables favorable chip formation. Though cryogenic grinding provides relatively more surface roughness for less plastic deformation and rubbing, shearing and fracturing modes of chip formation and retention of the grit's sharpness, it provides environment friendliness and improves the grindability characteristics.

Dhar and Kamruzzaman [125] observed substantial benefit of cryogenic cooling on tool life, surface finish and dimensional deviation. This may be attributed to mainly reduction in cutting zone temperature and favorable change in the chip-tool interaction. Further it was evident that machining with soluble oil cooling failed to provide any significant improvement in tool life, rather surface finish deteriorated.

It has also been reported that the machining of steel with liquid nitrogen improves the machinability index in respect of lowering cutting force as well as energy consumption due to decrease in chip reduction coefficient, increasing tool life by retaining sharpness of the cutting tool for a long time preventing formation of built up edge, increase product quality by decreasing surface roughness and thermal stress [98, 99, 126-127] but cryogenic machining is costly due to high cost of liquid nitrogen. Also accelerated notch wear on the principal flank of the carbide insert was observed at nitrogen rich atmosphere of cryogenic machining.

Machado and Wallbank [129] conducted experiments on turning medium carbon steel (AISI 1040) using a venturi to mix compressed air with small quantities of liquid lubricant, water or soluble oil with a mean flow rate of 3 and 5 ml/min. The mixture was directed onto the rake face of a carbide tool against the chip flow direction. The application of a mixture of air and soluble oil was able to reduce the consumption of cutting fluid, but it promoted a mist in the environment with problems of odors, bacteria and fungi growth of the overhead flooding system. Minimal quantity lubrication [130, 131] is a recent technique introduced in machining to obtain safe, environmental and economic benefits, reducing the use of coolant lubricant fluids in metal cutting. Attanasio et al. [132] reported that when MQL is applied to the tool rake, tool life is generally no different from dry conditions, but MQL applied to the tool flank can increase tool life. Lubricating the flank surface of a tip by the MQL technique reduces the tool wear and increases the tool life. Traces of lubricant compounds have been found on the worn surfaces only when MQL has been applied on the flank surface. Though MQL gives some advantages during the turning operation, it presents some limits due to the difficulty of lubricant reaching the cutting surface.

Dhar et al. [133-136] suggested that the use of minimum quantity lubrication leads to reduced chip reduction coefficient, lower cutting temperature and lower dimensional deviation. Dhar et al. [134, 137] also suggested that MQL reduced the cutting temperature; such reduction has been more effective for those tool-work combinations and cutting conditions, which provided higher value of chip reduction coefficient, ζ for adverse chip-tool interaction causing large friction and built-up edge formation at the chip-tool interface. 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 MQL. Dimensional accuracy also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of MQL.

Machining of alloys at high speed conditions can be achieved by a combination of the appropriate tool material, machining technique and the choice of a suitable cooling technology [138]. High pressure assisted cooling is one of the preferred technologies, currently, under exploitation especially in the aerospace and power plant industries for machining exotic materials. The credibility of high-pressure coolant assisted machining had been thoroughly investigated over the years [4, 139-143]. The system not only provides adequate cooling at the tool-workpiece interface but also provides an effective removal (flushing) of chips form the cutting area. The coolant jet under such high pressure is capable of creating a hydraulic wedge between the tool and workpiece, penetrating the interface deeply with a speed exceeding that necessary even for very high speed machining. This phenomenon also changes the chip flow condition [144]. 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 **[2, 145, and 146]**. This is attributed to a coolant wedge, which forms between the chip and tool forcing the chip to bend upwards giving it a desirable up curl required for segmentation. There is a drastic reduction in the cutting forces required to remove material from the work piece with the application of high-pressure coolant jet.

### 1.2.4 Effects of High-Pressure Coolant

Nagpal and Sharma **[147]** proposed that tool-chip interface temperature initially decreases with an increase in jet pressure, up to critical pressure, above which it rise to a relatively constant value for pressures in excess of the critical pressure.

Mazurkiewicz et al. **[4]** reported that a coolant applied at the cutting zone through a high-pressure jet nozzle can reduce the contact length and coefficient of friction at chip-tool interface and thus can reduce cutting forces and increase tool life to some extent. In machining ductile metals even with cutting fluid, the increase in cutting velocity reduces the ductility of the work material and causes production of long continuous chips, which raises the cutting temperature further **[148]**. In general, the attempts to apply pressurized cutting fluid can be classified into three groups, such as:

i. Coolant/lubricant jet injected into tool-chip interface through an external nozzle **[4]**

ii. Jet delivered into the clearance between flank and machined surface, and

iii. Jet injected directly through the tool rake face into tool-chip interface **[2, 4]**.

Kovaccevic et al. [144] suggested that the application of high-pressure water jet through the tool rake face, friction is reduced at the tool-chip interface due to formation of a cushion layer, which prevents intimate contact at the tool-chip interface, consequently leading to bending and self-breakage of chips. Whereas in the case of high-pressure water jet through an external nozzle, tool-chip contact area is reduced due to the breakage of the chip by the impinging jet. The enhance effectiveness of the coolant/lubrication by applying the cutting fluid at high pressures in the form of a narrow jet, leads to a reduction in the quantity of the cutting fluid being used, reducing the amount of disposal which is a primary concern of Environmental Protection Authorities.

Cozzens et al. [149] conducted an experimental investigation on single point boring aiming to study the role of cutting fluid, tool and workpiece material, tool geometry and cutting conditions on machinability. The results indicated that the cutting fluid conditions have no significant effect on surface texture, forces and built-up edge. Since boring is a high-speed operation and lubrication is ineffective, no effect was seen on the forces. However, the cutting fluid was found to have a significant effect on surface integrity.

Ezugwu et al. [139] observed that 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. Chip segmentation is considerably enhanced, as the chip curl radius is reduced significantly, due to targeted maximum coolant pressure/force on to the chip which aids the chip shearing process and consequently lowering cutting forces. Coolant is one of the most influential factors affecting tool performance when machining nickel-based alloys [139, 150]. The use of a high-pressure coolant supply when machining nickel-based (Inconel 901) super alloy with cemented carbide tools gives higher tool lives than when machining with the conventional coolant supply [139]. The use of a high-pressure coolant supply results in a significant reduction in the tool-chip contact length, and hence in the contact area, which in turn decreases the compressive stress at the tool edge with little change in the cutting forces. This prevents the formation of notching, thus leading to a higher tool life.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life is obtained by proper cutting fluid [151]. However, surface finish does not improve significantly. Wearing of cutting tools not only causes loss of the cutting edges or tips of the inserts but loss of the entire insert after wear of all the corners. It was reported that coolant injection offers better cutting performance in terms of surface finish, tool force and tool wear when compared to flood cooling [3]. The chip curl radius also depends on the coolant pressure and the flow rate. Therefore at a given power, smaller chip curl radius can be achieved at a lower coolant pressure with a high coolant flow rate [145]. From an environmental perspective, therefore, the significant waste is not the portion of the tool worn away by the tool-work contact, but the remaining portion of the tool that is disposed after its useful life [152]. Cutting tools operate within a safety temperature zone with minimal tool wear when machining at the critical coolant pressure as thermal stresses are kept to a minimum, thereby prolonging tool life [153].

Ezugwu and Bonney [88] reported that machining Inconel-718 with coated carbide inserts under high-pressure coolant supplies improve tool life by up to 7 folds, especially at high speed conditions. Tool life tends to improve with increasing coolant pressure. There is also evidence that once a critical pressure has been reached any further increase, in coolant pressure may only result to a marginal increase in tool life. Lower cutting forces [142, 143] are recorded with increasing coolant supply pressure when machining Inconel 718 with SiC whisker reinforced alumina ceramic tool. The reduction in cutting forces observed is also partly due to the chip segmentation when machining with high-pressure coolant supplies. Higher forces [142, 143] are recorded when machining with conventional coolant flow where continuous type chips are generated.

Chip segmentation is another advantage of employing the high-pressure cooling technique. Because the tool contact time is shorter, the tool is less susceptible to dissolution wear caused by chemical reaction with newly generated chips [154]. A more recent study of the effect of high-pressure coolant flow in face milling of Ti-base Ti-6Al-4V alloy with cemented carbide tools reported a 2.5 times increase in tool life than when machining with conventional coolant flow [155]. Studies have shown that it is possible to increase cutting speed by over 67 and 150% when machining titanium alloys with carbides under high coolant pressures of 15 and 30 MPa, respectively, compared to conventional coolant supply [117].

### 1.2.5 Summary of the Review

The literature review on hard turning and machinability of hardened steels highlights the vast potential of the control of machining temperature and its detrimental effects. It is obvious that the machining temperature holds a vital influence on chip formation, cutting forces, tool wear and surface quality. All these responses are very important in deciding the overall performance of the tool and the cooling system applied.

At an elevated temperature the cutting tools may undergo plastic deformation and attain rapid tool wear because of adhesive, abrasive, chemical and diffusion wear at the flanks and the crater. The dimensional accuracy and surface integrity of the work piece also deteriorate due to high temperature. The conventional cutting fluids are not that effective in high speed machining particularly in continuous cutting of materials like hardened steels. Furthermore, the conventional cutting fluids are not environment friendly. The disposal of the cutting fluids often leads to local water pollution and soil contamination. Recycling and reuse of conventional cutting fluids are further problematic.

From all these investigations, it is evident that applying cutting fluid in the form of a jet at higher pressure into the cutting zone is more beneficial than conventional cooling techniques. A high-pressure fluid 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. In practice, at low pressure 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 are limited to stationary single edge cutting tool operations. However there is a great crave for improving machining performance by perking up cooling methods in the case of turning, drilling and milling especially while machining difficult to machine materials.

HPC jet cooling is a promising technology in high speed machining, which economically addresses the current processes, environmental and health concerns. In this unique process cutting oil is impinged through a nozzle precisely at the narrow cutting zone. The success of implementing this technology across the metal removal industries is therefore depends 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 growing demands for high MRR, precision and effective machining of exotic materials is restrained mainly by the high cutting temperature. It is revealed from the abovementioned literature survey that the cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy, can be substantially controlled by high-pressure coolant jet. Thorough investigation is essential to explore the potential benefits of high-pressure coolant jet machining in such cases. But enough work has not been done systematically yet in this direction.

## 1.3 Objectives of the Present Investigation

The present work studies some aspects on the turning process applied on hardened steel using multilayer coated carbide inserts at high cutting speeds under high pressure coolant condition. The influence of cutting parameters (cutting velocity, feed rate, and depth of cut) on chip-tool interface temperature, tool wear, cutting forces and surface roughness will be analyzed. The current literature review reports many studies using PCBN tools on hardened steels but it is also important to know the results when using coated carbide tools, mainly for economic reasons. The objectives of the present investigation, keeping in view the overall improvement in productivity and quality in machining hardened steel using multilayer coated carbide inserts under high pressure coolant condition are

Systematic experimental study on the effects of high pressure coolant on the machinability characteristics of hardened steel using multilayer coated carbide insert at high cutting speeds in terms of :

i. chip morphology i.e. chip shape, chip color, chip reduction coefficient and mode of chip formation.
ii. average chip-tool interface temperature and work-tool temperature
iii. cutting forces i.e. main cutting force and feed force
iv. tool wear (average principal flank wear, maximum principal flank wear, notch wear, average auxiliary flank wear and maximum auxiliary flank wear).
v. surface integrity along with surface finish and
vi. product quality (dimensional deviation)

The outcome of the thesis work improves machinability of hardened steel using coated carbide inserts by reducing cutting zone temperature and cutting forces enabling favorable chip formation and chip-tool interaction. It also provides reduction in tool wear, which will enhance the tool life, dimensional accuracy and surface finish.

## 1.4 Scope of the Thesis

One of the possible and emerging technologies to overcome the aforementioned problems associated with conventional cooling system on the on the machining industries is the application of high-pressure coolant (HPC). For any machining operation, the tool life achieved, material removal rate (MRR), components of forces and power consumption, quality of the surface generated and surface integrity of the machined component as well as the shape of the chips can all be used to measure machinability. Considering all these, the present research work has been carried out to explore the role of high-pressure coolant (HPC) on major machinability characteristics in turning hardened medium carbon steel by coated carbide inserts under different machining conditions.

**Chapter 1** offers the current status of hard turning using expensive ceramic tools and aims the possibilities of using the relatively cheap coated carbide tools assisted by high pressure coolant jet. This chapter discusses the problems of hard turning using PCD, CBN and PCBN tools. The controlling of cutting temperature has been given the utmost priority here. The methods adopted by the researchers for controlling the tool-chip interface temperature are conferred in Chapter 1. It also presents the general necessities associated with machining industries, function of cutting tools, techno-environmental and socio-economical problems related with the high cutting temperature and the practice of conventional cooling methods and the expected role of high-pressure coolant. Investigation and findings of previous works and objective of the present work are also presented in this chapter.

**Chapter 2** deals with the heat treatment mechanism of medium carbon steel. It begins with the hurdles dealt with regarding the selection, sizing, shaping of the work material and ends with the detailed description of correct heat treatment process to obtain the required hardness.

**Chapter 3** presents the description of high-pressure coolant system for the present work to enable proper cooling of the cutting zone. Calibration of tool-work thermocouple comprising of job material and coated insert is also presented in the chapter. Chapter 3 also offers a glimpse of the procedure and conditions of the machining experiments carried out and the experimental results on the effects of HPC in comparison with dry machining on chip morphology, average chip-tool interface temperature, cutting forces, tool wear, surface roughness and dimensional deviation in turning hardened medium carbon steel under different cutting conditions.

**Chapter 4** contains the detailed discussion on the experimental results and possible interpretations on the results obtained. Finally, a summary of major contributions and future work is given in chapter 5 and references are provided at the end.

# Chapter-2

# Material Preparation

## 2.1 Introduction

According to the definitions of hard turning, it is obligatory to use material with hardness over 50 HRC for the research. Due to monetary constraints, it was not affordable to buy material with such hardness from the store rather I had to develop the material myself. Numerous attempts were made with several types of materials and heat treatment procedures to achieve the target. The materials were first checked under Optical Emission Spectrometer to find the carbon content. Then they were quenched and tempered and tested in the hardness testing machine. After so many iterations the medium carbon steel served the purpose.

But there was a problem with the distribution of hardness within the material. The core of the material didn't become as hard as the surface. This was due to the uneven quenching of the material. The outer surface dissipates heat more rapidly than the core which results in a gradual decrease of the hardness towards the core. To eliminate this problem, hollow cylindrical shaped material was used for the heat treatment. It facilitated the cooling from both outer and inner surface of the material and the hardness distribution after the heat treatment became uniform.

## 2.2 Preparing the Material

The material used in the thesis was medium carbon steel (85-90 HRB) with approximately 0.445% carbon content. It was a long hollow cylinder which had been sliced in small pieces with the help of band saw to fit into the electric furnace. The length of the pieces was 260 mm with external and internal diameters of 100 mm and 30 mm respectively.

To make provision for pulling the red hot metal pieces from furnace, hook had to be facilitated. A 120 mm long solid shaft of medium carbon steel with external diameter same as the internal diameter of hollow pieces had been inserted into the hollow piece. The joint was secured by welding. Using drilling and boring tools a through hole of diameter 25.4 mm was made in the solid part. This was done so that hot water vapor can easily come out when it would be quenched in brine solution. Another through hole of diameter 12 mm was made in the solid part in radial direction. A triangular hook of mild steel was attached to the work piece through the radial hole so that the work-piece can be pulled out from the furnace with the help of a tong as shown in Fig.2.1. A test sample made from the same material (25mm×15mm×10mm) was also prepared for the hardness test.

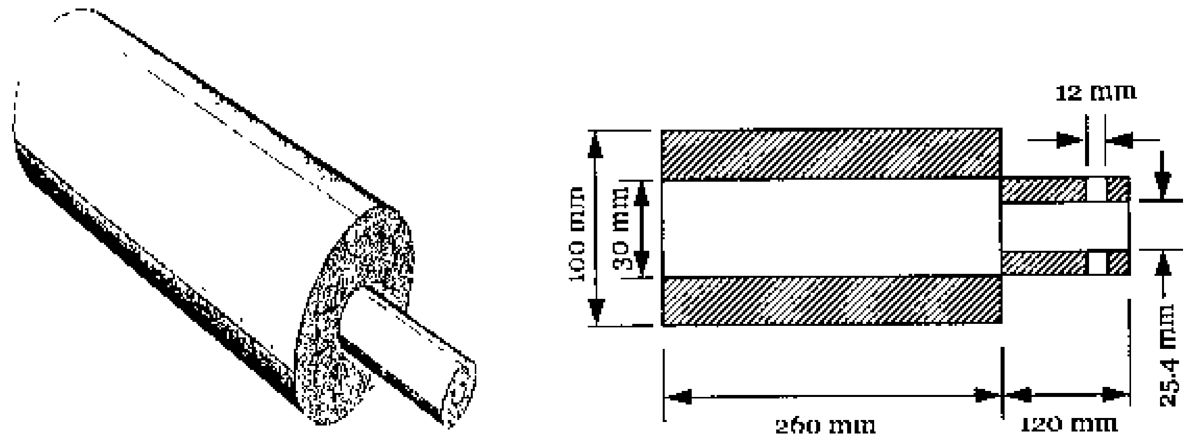



**Fig. 2.1** Work material specimen for hardening

## 2.3 The Heat Treatment Process

Electric furnace of high heating element (RG-3000C, 240 V, 32 amps) was used for heat treatment. Before loading the work piece and the test sample, the furnace had to be made oxygen free to avoid oxidation because a scale is formed on the surface of the work material during hardening. In this circumstance, two ceramic pipes of internal diameters of 3 mm and 4.5 mm were connected with the furnace inlet and outlet respectively. The other end of the ceramic pipe with 3 mm internal diameter was connected to an argon gas cylinder with the help of a hose pipe. The door of the electric furnace was sealed and isolated from the atmosphere by an asbestos sheet. Argon gas was then passed (7 liters/min and 130 bars) through the furnace chamber to drive out air to make an inert environment in the furnace chamber. After 2 minutes, turn on the furnace with 5 amperes current rating with 5.5 liters/min of argon gas supply at a pressure of 130 bars. It took three hours to raise the temperature to 900°C and soaked the work material at that temperature for one and half hour in the heating chamber.

## 2.1 Quenching of the Material

A quench tank having capacity 140 liters was used for quenching the work material. The quench tank should be large enough to hold the part being treated and should have adequate circulation and temperature control. The temperature of the brine solution should not exceed 40°C. The brine solution was prepared by mixing 10 kg of ice and sodium chloride with 120 liters of water. This mixture reduces the absorption of atmospheric gases that, in turn reduces the amount of bubbles. As a result, brine wets the metal surface and cools it more rapidly than water. In addition to rapid and uniform cooling, the brine removes a large percentage of any scale that may be present.

The work piece as well as test sample was pulled quickly but carefully out from the furnace using a tong and was immersed vertically into the brine solution. The solution is stirred vigorously for about 10 minutes for uniform cooling and was continued until the specimen is cool enough. Heat transfer is not so fast through the steam layer. On the other hand the very act of transforming the water into steam means the water has to take in enormous amounts of energy to transform the water from liquid state to gaseous state (steam). Moving the part and re-circulating the water aids in getting the best quench. The test sample was also quenched in the same solution following same manner.

## 2.5 The Tempering Process

Quenched carbon steels always required to temper because of steels are often more harder than needed and too brittle for most practical uses. Also, several internal stresses like residual stresses are set up during the rapid cooling from the hardening temperature. As a result, to relieve the internal stresses and reduce brittleness, tempering was done. It was done by heating the workpiece as well as test sample to a specific temperature (160 $^0$C), holding it at that temperature for one hour, and then cooling it, usually instill air. The resultant strength, hardness, and ductility depend on the temperature to which the specimen is heated during the tempering process. The purpose of tempering was also to produce definite physical properties within the specimen.The sample was cleaned and ground a flat surface of 0.015 inches deep along the face of the sample. Hardness of the sample was measured on the C scale of Rock-well hardness tester. The hardness of the sample before heat treatment was 163 HRB and after heat treatment it became around 56 HRC. The hardness distribution within the sample is shown below.

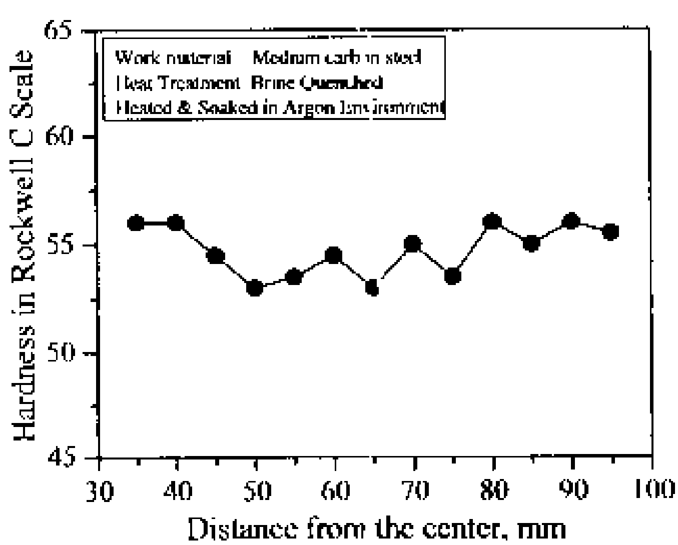



**Fig. 2.2** Hardness distribution curve of sample

# Chapter-3

# Experimental Investigations

## 3.1 High-Pressure Coolant System

The high cutting temperature generated during machining not only reduces tool life but also impairs the product quality. The temperature becomes more intensive when cutting velocity and feed are increased for higher MRR and the work materials are relatively difficult to machine for their high strength, hardenability and lesser thermal conductivity. Cutting fluids are widely used to reduce the cutting temperature. But the major problems associated with the use of conventional methods and type of cutting fluids, which are mostly oil based, are:

i. ineffectiveness in desired cooling and lubrication
ii. health hazards due to generation of obnoxious gases and bacterial growth
iii. inconvenience due to uncleanliness of the working zone
iv. corrosion and contamination of the lubricating system of the machine tools
v. need of storage, additional floor space, pumping system, recycling and disposal
vi. environmental pollution and contamination of soil and water

In this regard, it has already been observed through previous research that proper application of high-pressure coolant may play vital role in providing not only environment friendliness but also some techno-economical benefits.

For achieving substantial technological and economical benefits in addition to environment friendliness, the high-pressure coolant system needs to be properly designed considering the following important factors:

i. effective cooling by enabling high-pressure coolant jet reaches as close to the actual hot zones as possible
ii. avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes
iii. minimum consumption of coolant by pin-pointed impingement and only during chip formation
iv. control of pressure and flow rate of coolant according to need

The cutting fluid needs to be drawn at high pressure from the coolant tank and impinged at high speed through the nozzle. Considering the conditions required for the present research work and uninterrupted supply of coolant at pressure around 100 bar over a reasonably long cut, a coolant tank of large capacity (200 liter) has been used **[156-159]**. The photographic view of the coolant tank along with motor-pump assembly, flow control valve, relief valve and directional control valve is shown in Fig.3.1.

The coolant is contained in the coolant tank and a pump is used to ensure desired high driving pressure during the high withdrawal periods. This is accomplished by controlling relief valve through flow control valve that creates a high pressure. When the flow control valve is open, coolant taken from the tank at normal pressure is pressurized at a required pressure by controlling relief valve. A relief valve installed in the discharge line with a return line back to the supply tank is to provide complete protection against an unexpected over pressure situation. The flow control valve is pressure and temperature compensating type valve and maintains a constant flow rate independent of change in system pressure (load) and temperature (viscosity of the fluid). The valve with an integral check valve allows a controlled flow and reverses free flow. The high-pressure coolant is impinged through a nozzle at the chip-tool interface. A direction control valve is used to control the flow direction of the jet during machining.

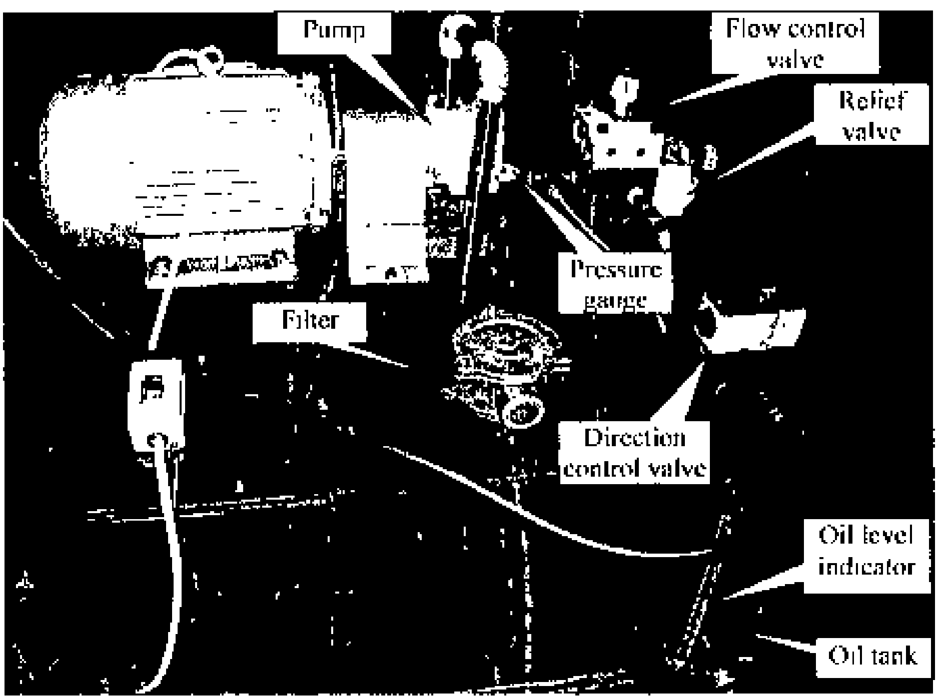



**Fig. 3.1** Photographic view of high-pressure coolant system [157]

The purpose of a nozzle is to direct cutting fluid to the optimal position to achieve maximum fluid flow at the chip-tool interface. The nozzle also fulfills the purpose of increasing the fluid velocity by contracting the cross-sectional area of the jet stream. A well designed turbulent flow nozzle converts more of the pressure energy in the flow into kinetic energy than does a laminar flow nozzle. A laminar flow nozzle however has the benefit that the jet stream maintains its coherency for a longer period meaning that turbulent flow nozzles must be positioned as close to the chip-tool contact as possible.

The nozzle has been designed and fabricated so that the nozzle spray pattern, covering area and coolant flow rate can be controlled. The nozzle developed and used and its setting along the tool holder are schematically shown in Fig.3.2. The nozzle tip of 0.50 mm bore diameter was fixed to the tool post and is connected with direction control valve through hydraulic pipe to supply coolant in the form of jet to the cutting zone. A flow control valve is used to control the flow of coolant as required. The jet should impinge at the cutting zone in liquid state only. The expected result of this arrangement is effective cooling with economical coolant dispensing. It is important to properly position coolant delivery nozzle to achieve the following:

i. getting the fluid to the tool/workpiece interface
ii. minimizing mist and odor problems
iii. controlling thermal shock. The tool will be alternately heated and cooled, if the fluid stream does not continually reach the tool
iv. keeping the workpiece constantly in the fluid's flow and
v. moving the chips/ swarf out of the cutting zone. This is one of the most important functions of the fluid, and may require positioning one or more fluid lines just to move chips out of the cutting zone

Nozzle is placed 15.0 mm away 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 without avoiding of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes.

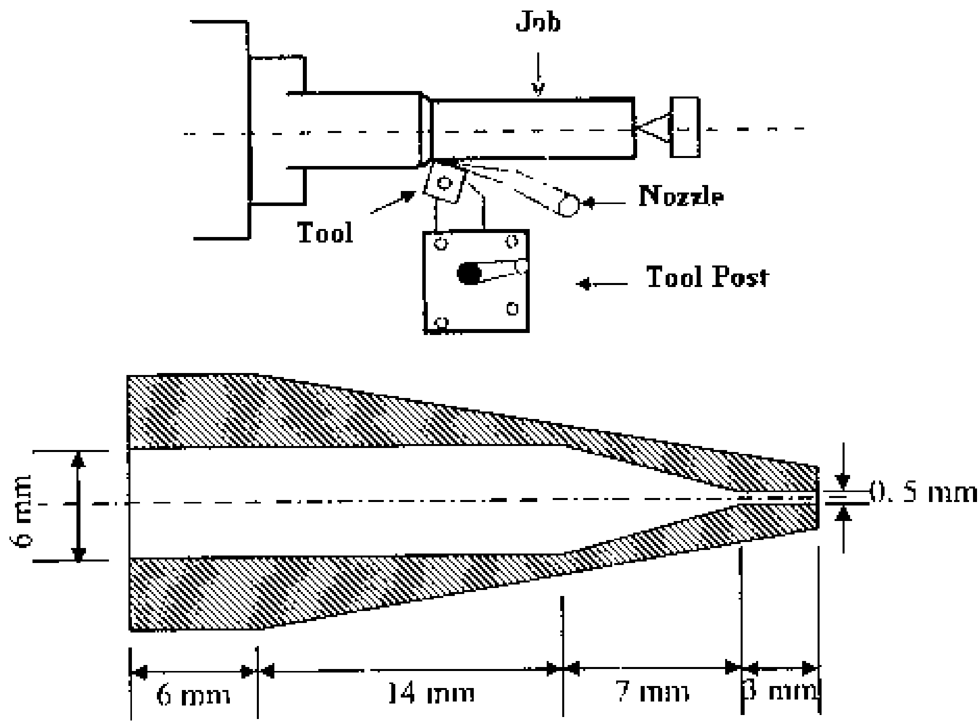



**Fig. 3.2** Schematic view of the nozzle used for coolant delivery at the cutting zone [158]

## 3.2 Experimental Procedure and Conditions

The concept of high-pressure coolant presents itself as a possible solution for high speed machining in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, provided that the high-pressure cooling parameters can be strategically tuned. It has the benefits of a powerful stream that can reach the cutting area, it provides strong chip removal, and in some cases enough pressure to deburr. High-pressure coolant injection technique not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid. The aim of the present work is primarily to explore and evaluate the role of high-pressure coolant on machinability characteristics of hardened medium carbon steel mainly in terms of cutting temperature and chip-forms, which govern productivity, product quality and overall economy.

The machining was carried out on lathe, which has a 7.5 kW main spindle power and a maximum spindle speed of 700 rpm. The photographic view of the experimental set-up is shown in Fig.3.3. The work material was medium carbon steel, hardened to nominal values of 56 HRC. Initially, a solid bar stock was hardened to 56 HRC; but it was found that the hardness decreased gradually towards the center of the stock. Thus it was decided to machine a hardened hollow stock, which allowed a heat treatment that provides consistent hardness of 56±2 HRC.

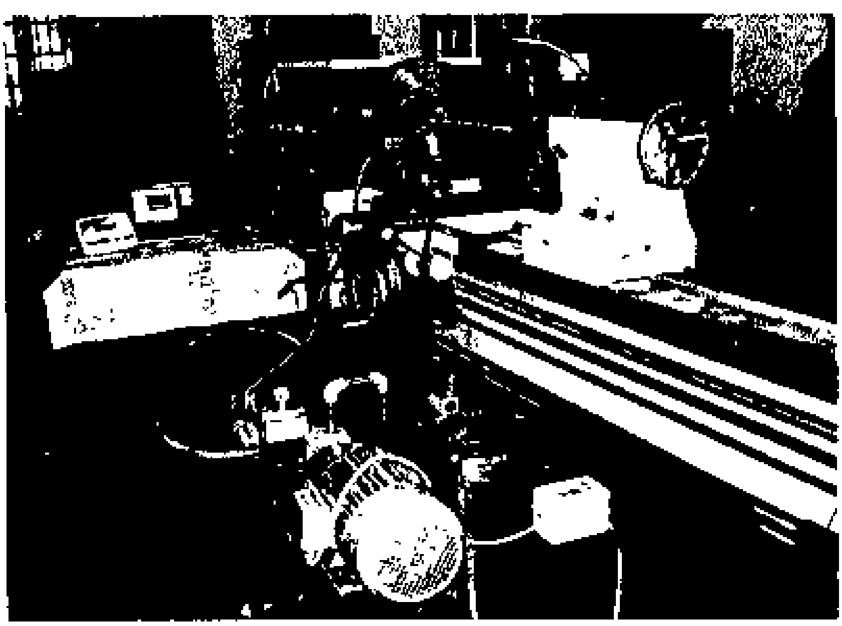


**Fig. 3.3** Photographic view of experimental set-up

The positioning of the nozzle tip with respect to the cutting insert has been set after a number of trials. The final arrangement made and used has been shown in Fig.3.4. The high pressure coolant jet is directed along the auxiliary cutting edge at an angle 30° to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges.

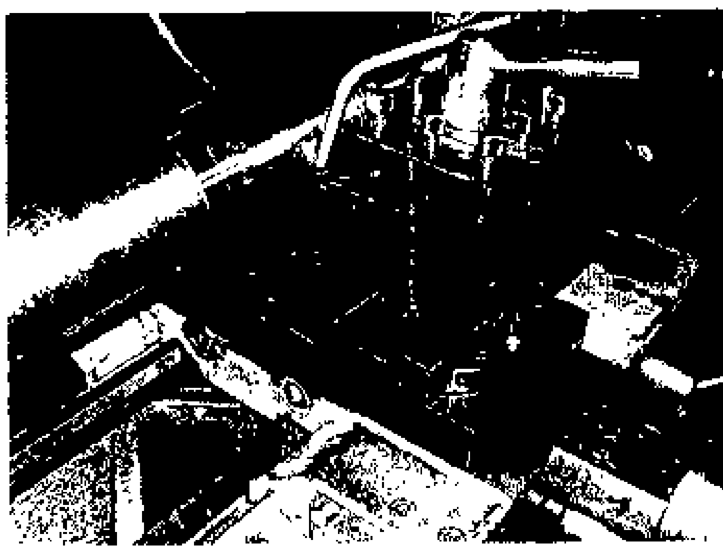
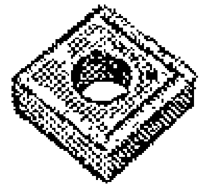
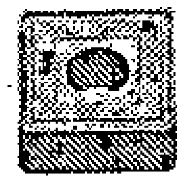


**Fig. 3.4** Photographic view of high-pressure coolant delivery nozzle

The cutting tool used was uncoated carbide insert (ISO specification: SNMG 120408 and SNMM 120408, Widia). The tool holder provided negative 6° side and back rake angles and 6° side cutting-edge and end cutting-edge angles. The ranges of the cutting velocity (V) and feed rate (f) were selected based on the tool manufacturer's recommendation and industrial practices. Keeping in view less significant role of depth of cut (d) 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 mm, which would adequately serve the present purpose. The conditions under which the machining tests have been carried out are briefly given in Table-3.1.

Table 3.1 Experimental conditions

| | |
|---|---|
| **Machine tool** | : Lathe Machine(China), 7.5 kW |
| **Work materials** | : Hardened medium carbon steel |
| Hardness (HRC) | : 56 |
| Size | : External dia.=100, internal dia.=30mm and length=260 mm |
| **Cutting tool** | :   |
| | SNMG TN 4000, Widia    SNMM TN 2000, Widia |
| Coating | : TiCN, WC, Co |
| Geometry | : -6°,-6°,6°,6°,15°,75°,0.8 mm |
| **Tool holder** | : PSBNR 2525 M12 (ISO specification), Widia |
| **Process parameters** | |
| Cutting velocity, V | : 83, 119, 166 and 237 m/min |
| Feed rate, f | : 0.12, 0.14 and 0.16 mm/rev |
| Depth of cut, d | : 1.0 mm |
| **High pressure coolant** | : 70 bar, Coolant: 6.0 l/min through external nozzle |
| Coolant type | : VG-68 (ISO grade) |
| **Environment** | : Dry and High pressure coolant (HPC) condition |

For the improvement of cutting performance, the knowledge of temperature at the chip-tool interface with good accuracy is essential. Several experimental and analytical techniques have been developed for the measurement of temperatures generated in cutting zone. The average chip-tool interface cutting temperature was measured under both dry and high-pressure coolant conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. Fig.3.5 shows the calibration curve obtained for the tool-work pair with carbide as the tool material and the hardened medium carbon steel undertaken as the work material. In the present case, almost linear relationships between the temperature and emf have been obtained with correlation coefficients of 0.994.

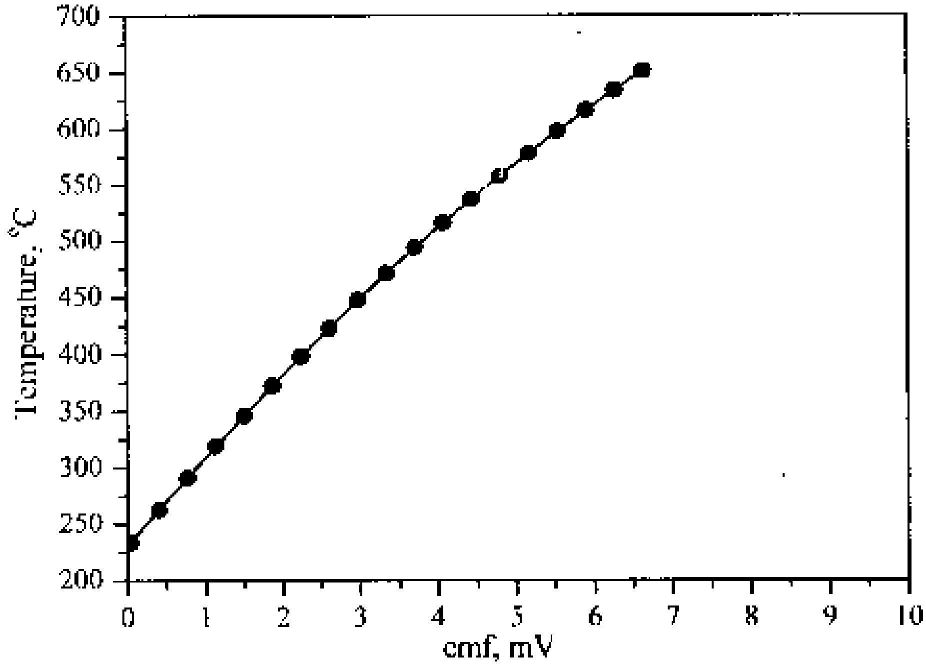



**Fig. 3.5** Tool-work thermocouple calibration curve

The form, colour and thickness of the chips directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples were collected during both short run and long run machining for all the V-f combinations under both dry and high-pressure coolant conditions. The form and colour of all those chips were noted down. The thicknesses of the chips were repeatedly measured by a slide calliper to determine the value of chip thickness ratio, $r_c$ (ratio of chip thickness before and after cut) which is an important index of machinability. The average cutting temperature was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration.

The cutting force components, $F_c$ (main cutting force) and $F_f$ (feed force) were monitored by a sensitive but robust 3-D dynamometer (KISTLER) and stored in a PC through a data acquisition system.

The life of the tools, which ultimately fail by systematic gradual wear, is generally assessed at least for R&D work, by the average value of the principal flank wear (VB), which aggravates cutting forces and temperature and may induce vibration with the progress of machining. The pattern and extent of wear (VS) of the auxiliary flank affects surface finish and dimensional accuracy of the machined parts. Growth of tool wear is sizeably influenced by the temperature and nature of interactions of the tool-work interfaces which again depend upon the machining conditions for given tool-work pairs.

During machining under each condition, the cutting insert was withdrawn at regular intervals and then the salient features like, VB, VS etc. were measured under a optical microscope (Carl Zeiss, Germany) fitted with a precision micrometer. At the end of machining and attaining sufficient wear the pattern and extent of wear of each tool was examined under Scanning Electron Microscope (Philips XL 30, Japan) and the photographs are taken for onward comparative study.

After machining the different steel rods by the different inserts, at different V-f combinations under both dry and high-pressure coolant conditions, the surface finish and dimensional deviation on diameter in axial direction of the machined jobs were measured respectively by a Talysurf (Surtronic 3+, Rank Taylor Hobson Limited) and by a digital dial gauge which was firmly fitted on the saddle and travelled slowly parallel to the job axis.

## 3.3 Experimental Results

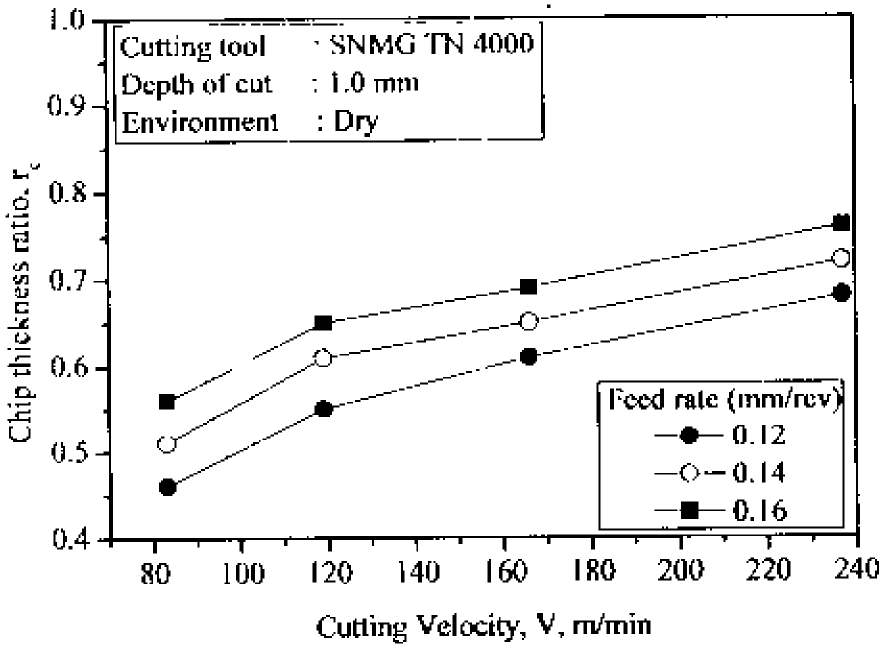
### 3.3.1 Machining Chips

The chip samples collected while turning the hardened medium carbon steel by the insert of configuration SNMG and SNMM at different V-f combinations under both dry and high-pressure coolant conditions have been visually examined and categorized as per ISO standard 3685 [66] with respect to their shape and color. The results of such categorization of the chips produced at different V-f combinations and environments have been shown in Table 3.2.

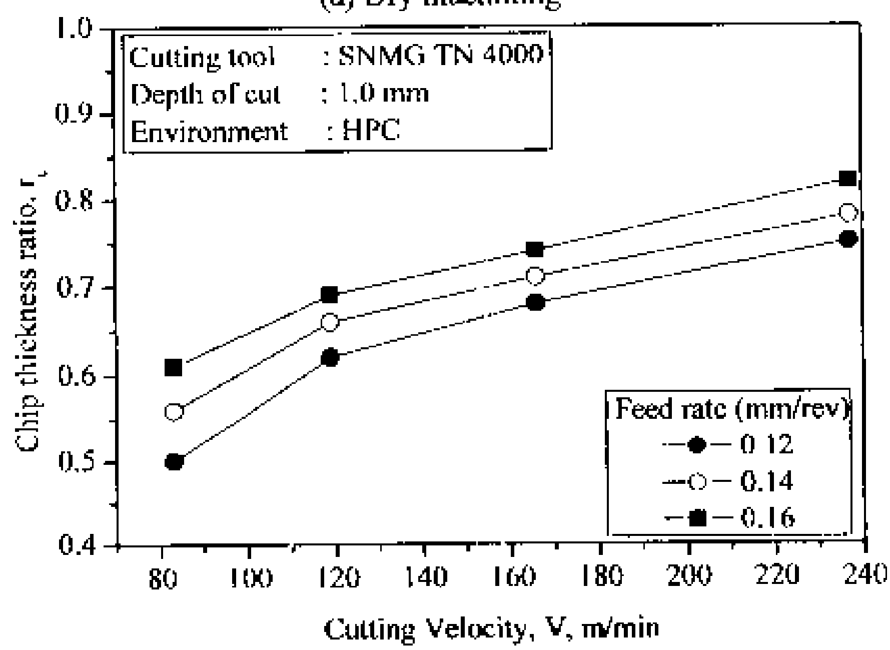
**Table 3.2** Shape and color of chips produced during machining

| f (mm/rev) | V (m/min) | Insert | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SNMG 120408 | | | | SNMM 120408 | | | |
| | | Dry | | HPC | | Dry | | HPC | |
| | | shape | color | shape | color | shape | color | shape | color |
| 0.12 | 83 | snarled ribbon | bluish | short washer | metallic | snarled ribbon | blue | short washer | metallic |
| | 119 | snarled tubular | bluish | loose arc | metallic | snarled ribbon | blue | short washer | metallic |
| | 166 | snarled tubular | blue | loose arc | metallic | snarled ribbon | blue | loose arc | metallic |
| | 237 | snarled ribbon | blue | loose arc | metallic | short washer | blue | loose arc | metallic |
| 0.16 | 83 | snarled tubular | bluish | short washer | metallic | snarled ribbon | blue | short washer | metallic |
| | 119 | snarled ribbon | bluish | loose arc | metallic | snarled ribbon | blue | loose arc | metallic |
| | 166 | snarled ribbon | blue | loose arc | metallic | short washer | blue | loose arc | bluish |
| | 237 | long washer | blue | loose arc | bluish | short washer | blue | loose arc | bluish |
| 0.18 | 83 | snarled ribbon | bluish | loose arc | metallic | snarled ribbon | blue | loose arc | metallic |
| | 119 | snarled tubular | blue | loose arc | metallic | snarled ribbon | blue | loose arc | metallic |
| | 166 | snarled ribbon | blue | loose arc | bluish | short washer | blue | loose arc | bluish |
| | 237 | long washer | blue | loose arc | bluish | loose arc | blue | loose arc | blue |

The variation in value of chip thickness ratio ($r_c$) with change in tool configuration, cutting speeds and feeds as well as machining environment evaluated for hardened medium carbon steel have been plotted and shown in Fig.3.7 and Fig.3.8 respectively.

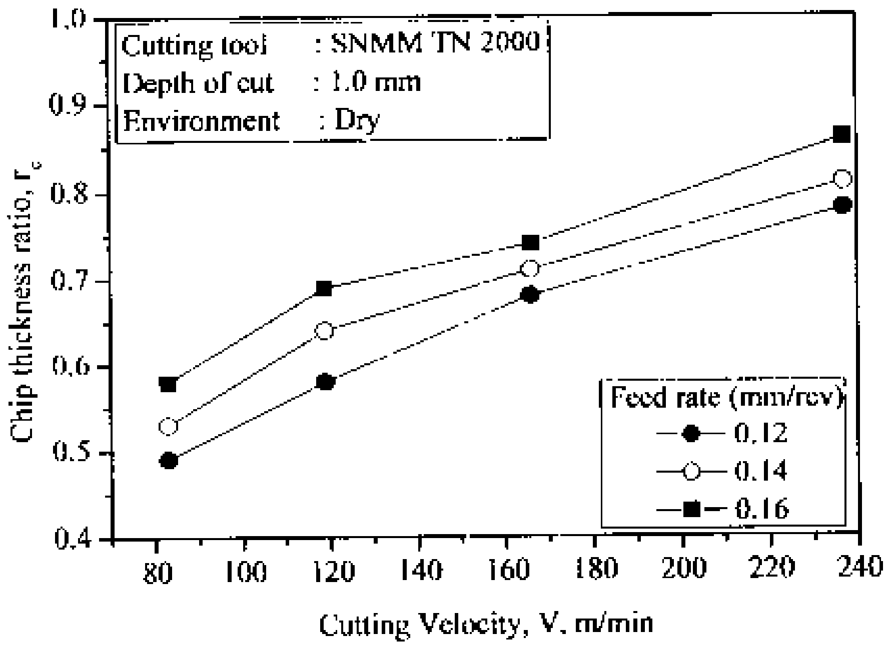



(a) Dry machining

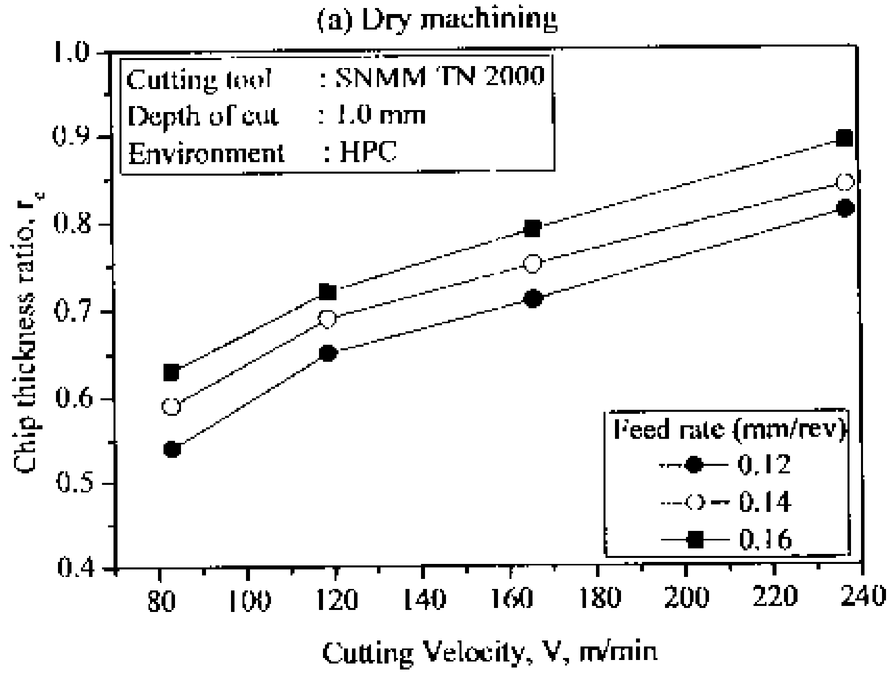



(b) HPC machining

**Fig.3.6** Variation in chip thickness ratio ($r_c$) with that of V and f in hard turning by SNMG insert under (a) dry and (b) HPC conditions.




(a) Dry machining



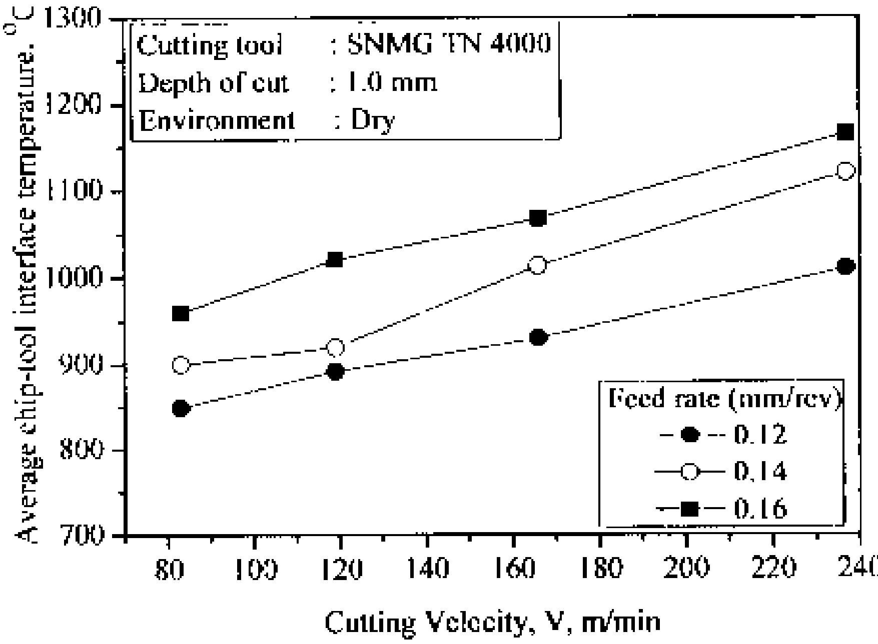

(b) HPC machining

**Fig. 3.7** Variation in chip thickness ratio ($r_c$) with that of V and f in hard turning by SNMM insert under (a) dry and (b) HPC conditions.

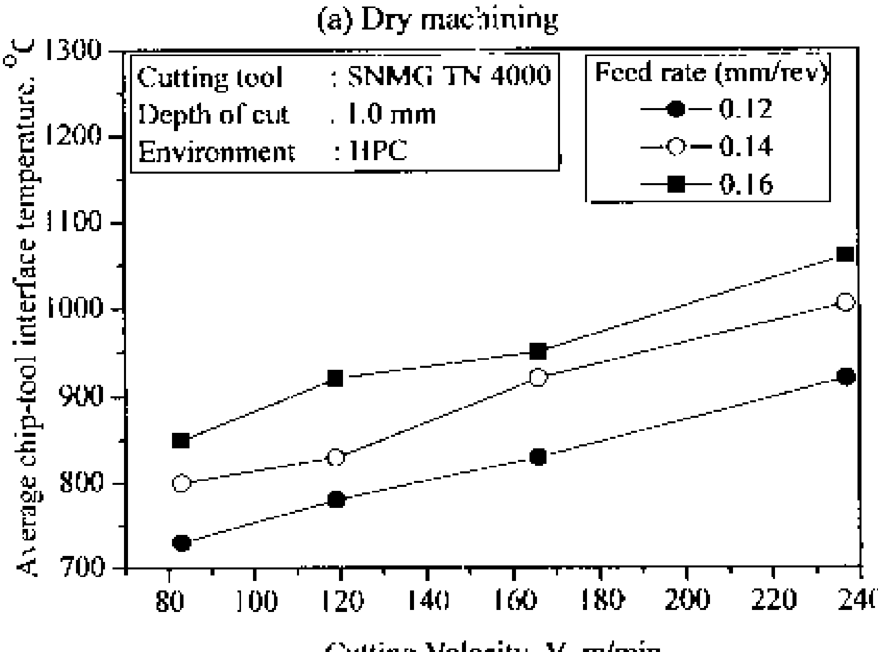
### 3.3.2 Cutting Temperature

High production machining associated with high velocity and feed rate inherently generates high heat as well as high cutting zone temperature. The cutting temperature if not controlled properly, cutting tools undergo severe flank wear and notch wear, lose sharpness of the cutting edge by either wearing or become blunt by welded built-up edge and weaken the product quality. 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 as well as with the increase in hardness and strength of the work material. Therefore, attempts are made to reduce this detrimental cutting temperature.

In the Present work, the average cutting temperature was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. The evaluated role of high-pressure coolant on average chip-tool interface temperature in turning hardened medium carbon steel by two types of inserts at different V–f combinations in compare to dry condition have been shown in Fig.3.9 and Fig.3.10 respectively.

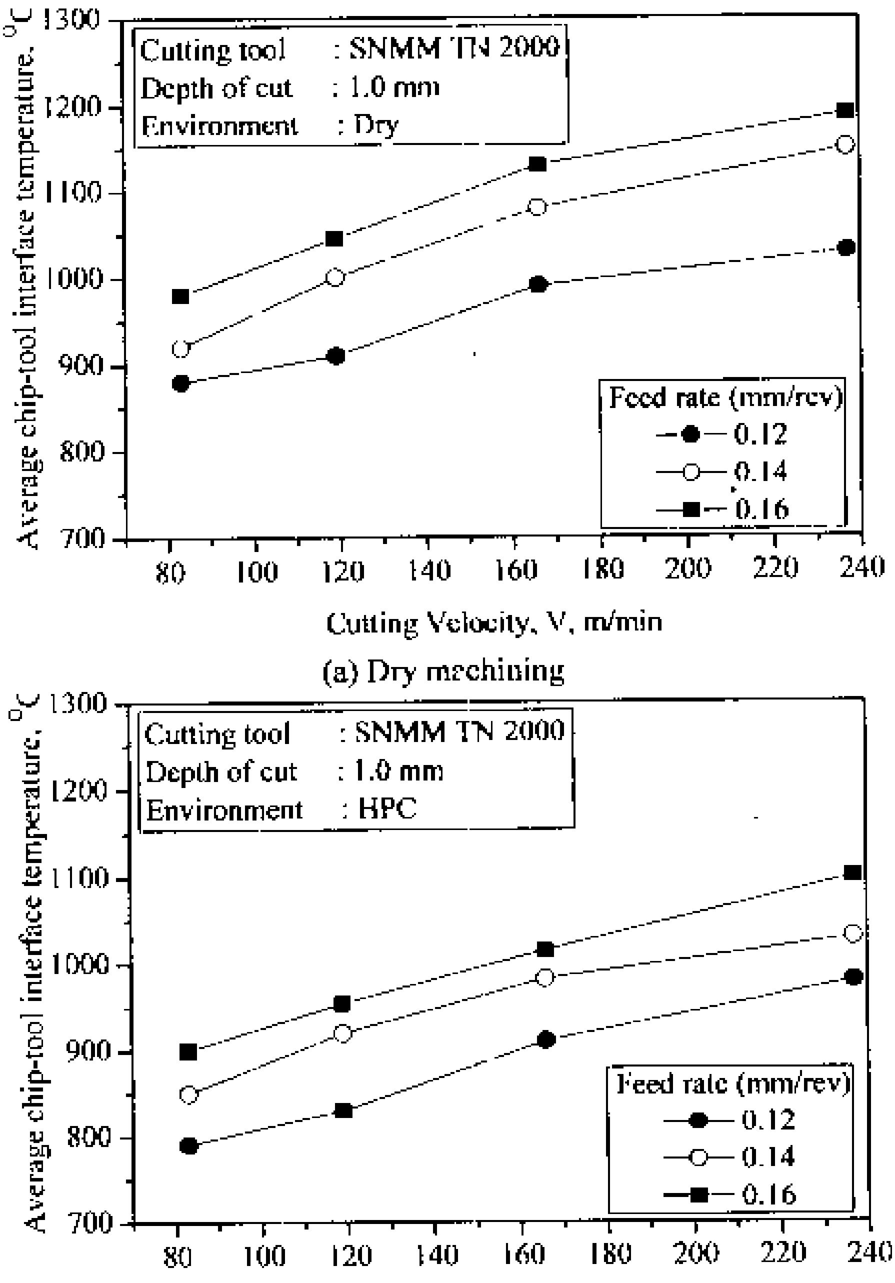



(a) Dry machining




(b) HPC machining

**Fig. 3.8** Variation in average chip-tool interface temperature with that of V and f in hard turning by SNMG insert under (a) dry and (b) HPC conditions.




(a) Dry machining



(b) HPC machining

**Fig. 3.9** Variation in average chip-tool interface temperature with that of V and f in hard turning by SNMM insert under (a) dry and (b) HPC conditions.

### 3.3.3 Cutting Forces

Cutting forces are generally resolved into components in mutual perpendicular directions for convenience of measurement, analysis, estimation of power consumption and for design of Machine-Fixture-Tool-Work systems. In turning by single point tools like inserts, the single cutting force generated is resolved into three components namely; tangential force or main cutting force, $F_c$, axial force or feed force, $F_t$ and transverse force, $F_r$ as has been indicated in Fig.3.11. Each of those interrelated forces has got specific significance.

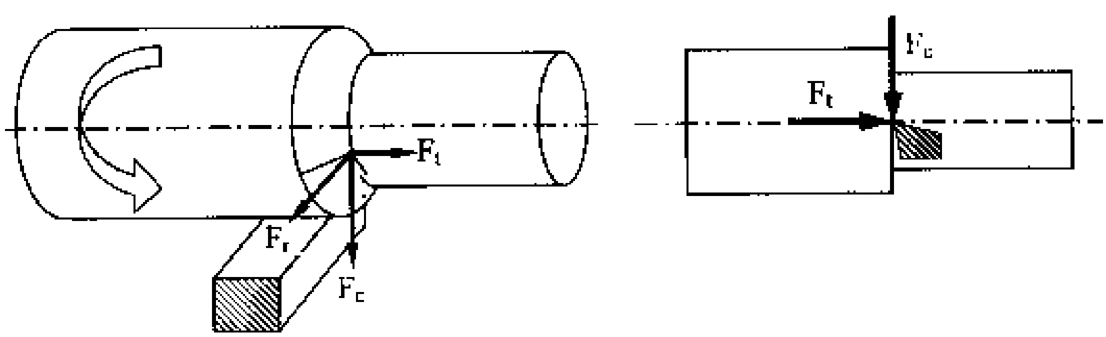
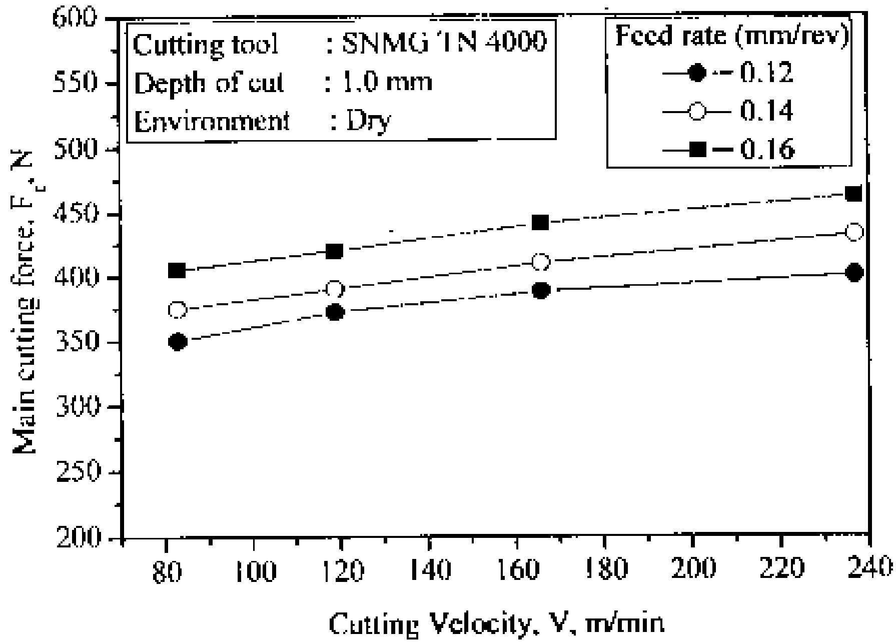
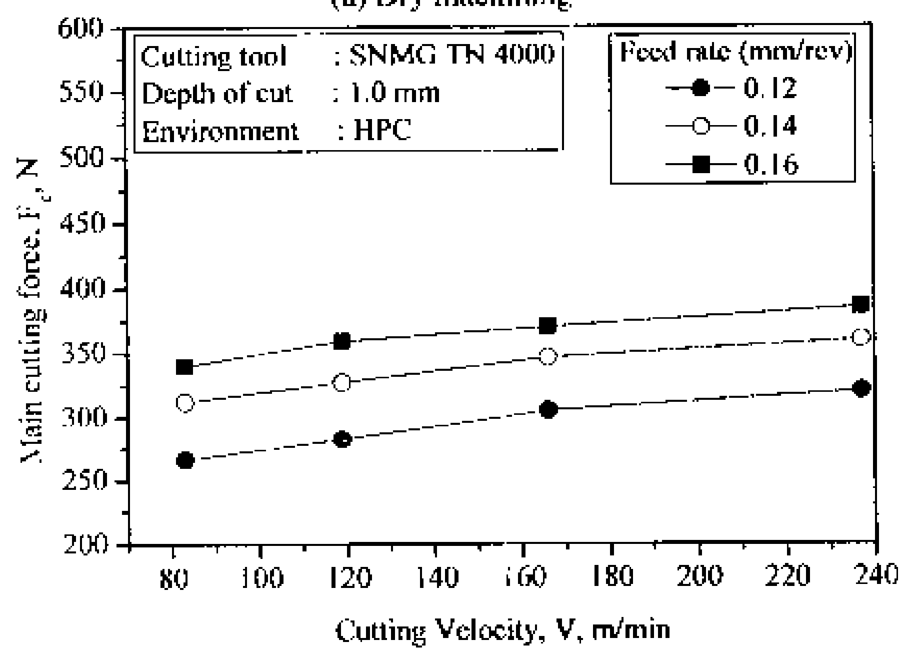



**Fig. 3.10** Component of cutting forces acting on the tool

In the present work, the magnitudes of $F_c$ and $F_t$ have been monitored by dynamometer for all the combinations of tool configurations, cutting velocities, feeds and environments undertaken. The effect of high-pressure coolant on $F_c$ that have been observed while turning hardened medium carbon steel by the carbide inserts (SNMG and SNMM) under different V and f have been graphically shown in Fig.3.11 and Fig.3.12. The effects of high-pressure coolant jet on the axial force or feed force, $F_t$ recorded under different machining conditions have been shown in Fig.3.13 and Fig.3.14.

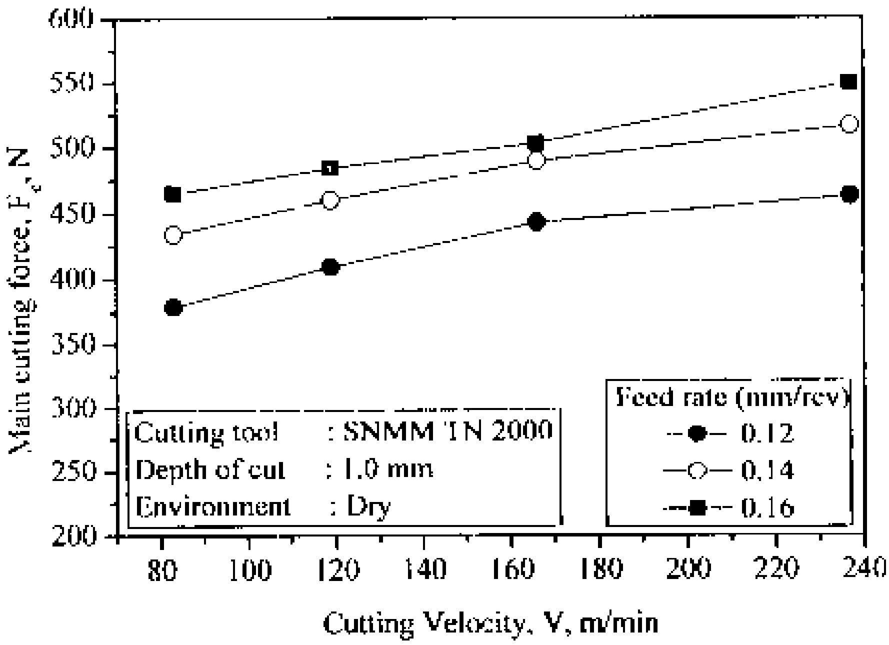



(a) Dry machining

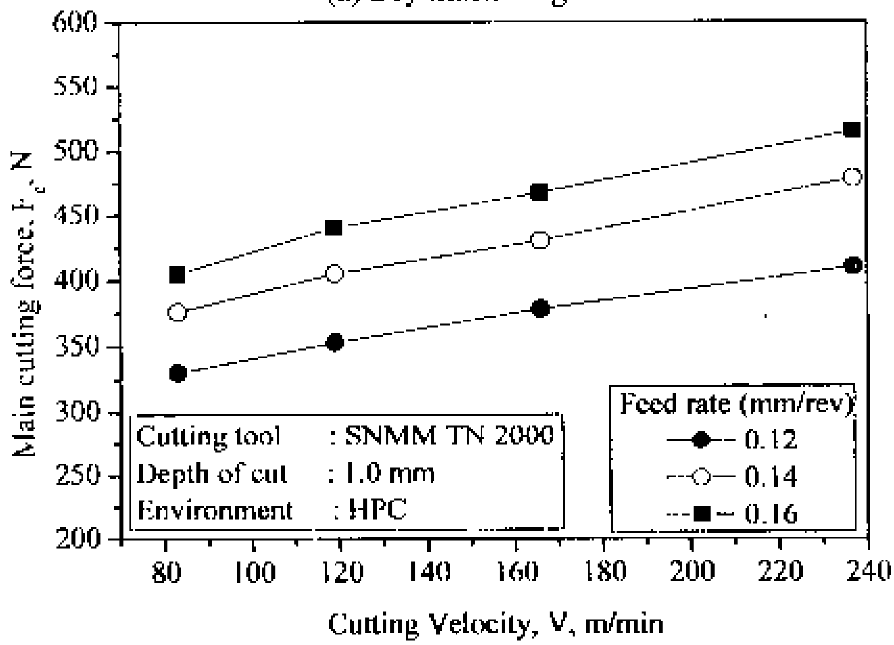



(b) HPC machining

**Fig. 3.11** Variation in main cutting force ($F_c$) with that of V and f in hard turning by SNMG insert under (a) dry and (b) HPC conditions.

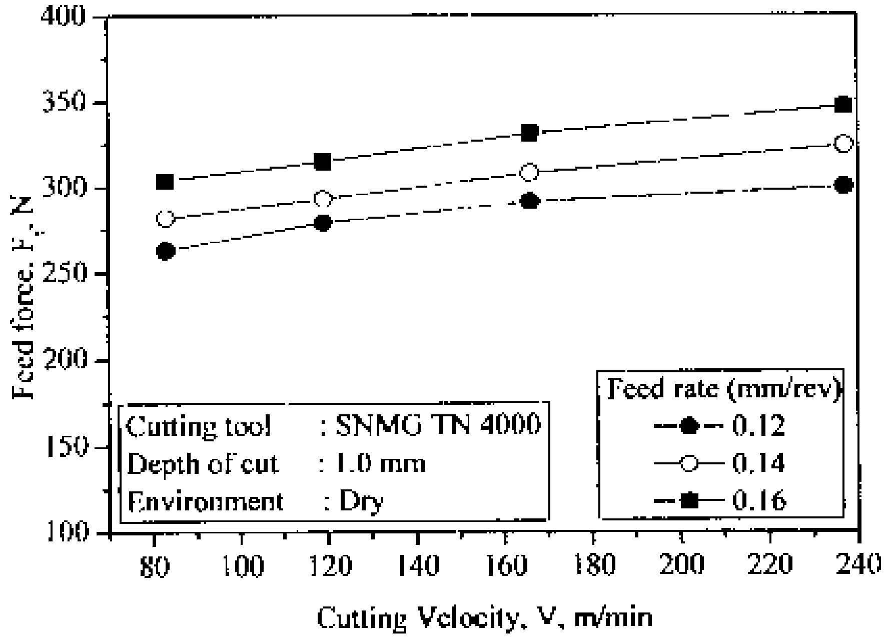



(a) Dry machining

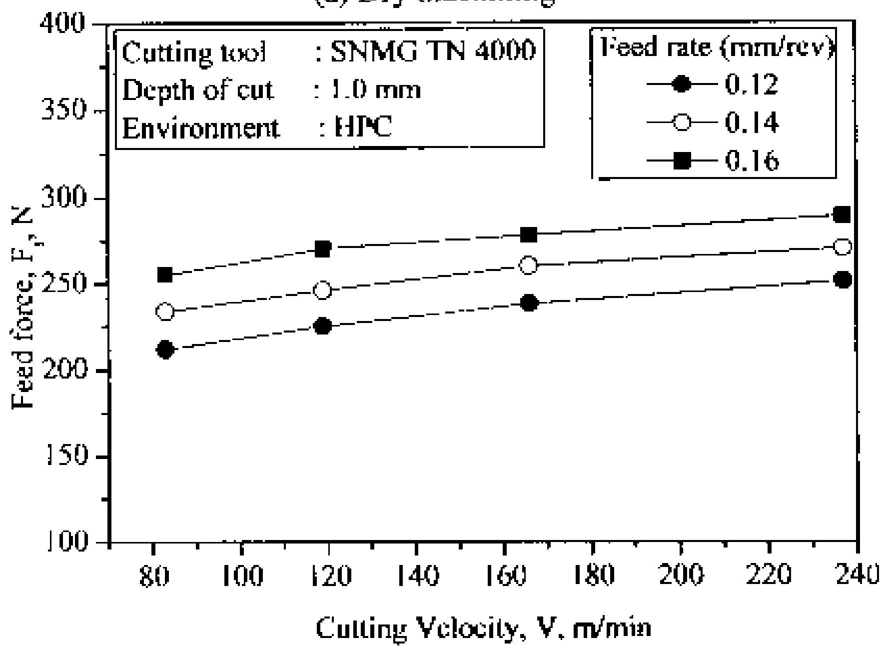



(b) HPC machining

**Fig. 3.12** Variation in main cutting force ($F_c$) with that of V and f in hard turning by SNMM insert under (a) dry and (b) HPC conditions.

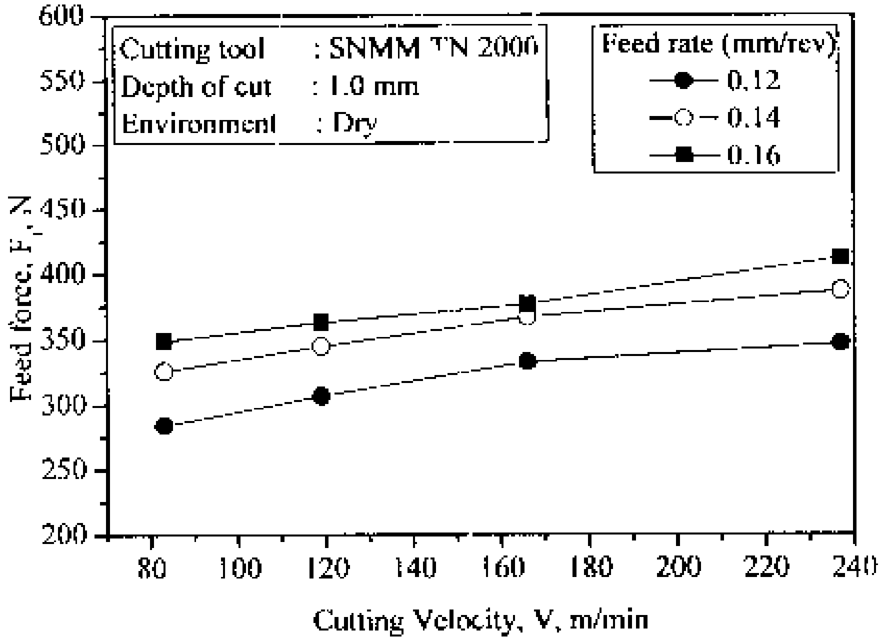



(a) Dry machining

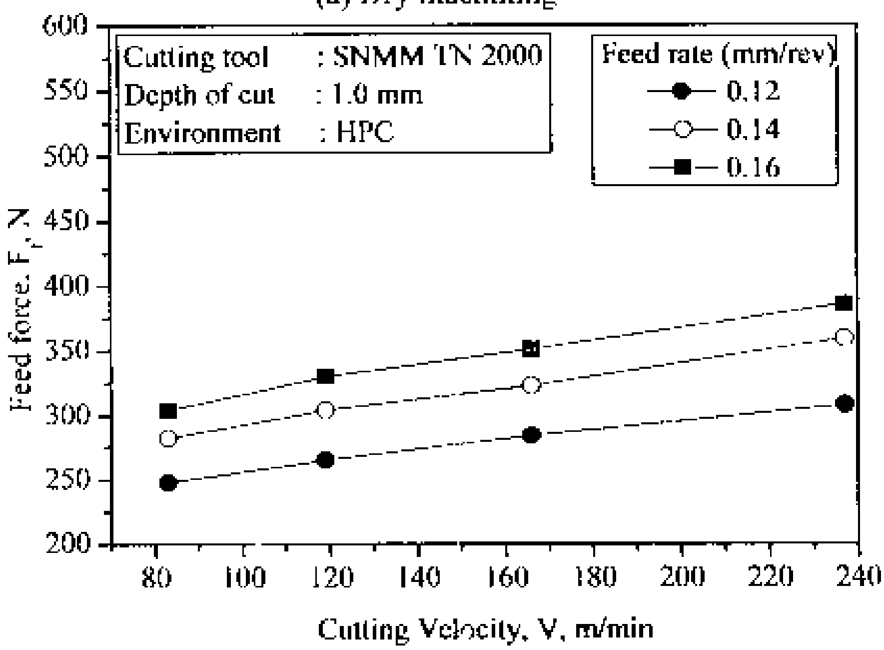



(b) HPC machining

**Fig. 3.13** Variation in feed force ($F_f$) with that of V and f in hard turning by SNMG insert under (a) dry and (b) HPC conditions.




(a) Dry machining




(b) HPC machining

**Fig. 3.14** Variation in feed force ($F_f$) with that of V and f in hard turning by SNMM insert under (a) dry and (b) HPC conditions.

### 3.3.4 Cutting Tool Wear and Condition

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

Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature and/or dynamic loading at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness. However, in the present investigations with the tools 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 inserts is schematically shown in Fig.3.15. The major features that characterize flank wear and crater wear are also indicated in that figure.

The growth of flank wear, $V_B$ with progress of machining recorded while turning hardened medium carbon steel by the SNMG and SNMM type inserts under dry and high-pressure coolant conditions have been shown in Fig.3.16. The auxiliary flank wear which affects dimensional accuracy and surface finish have also been recorded at regular intervals of machining under all the conditions undertaken. The growth of average auxiliary flank wear, $V_S$ with time of machining of hardened medium carbon steel under dry and high-pressure coolant conditions have been shown in Fig.3.17.

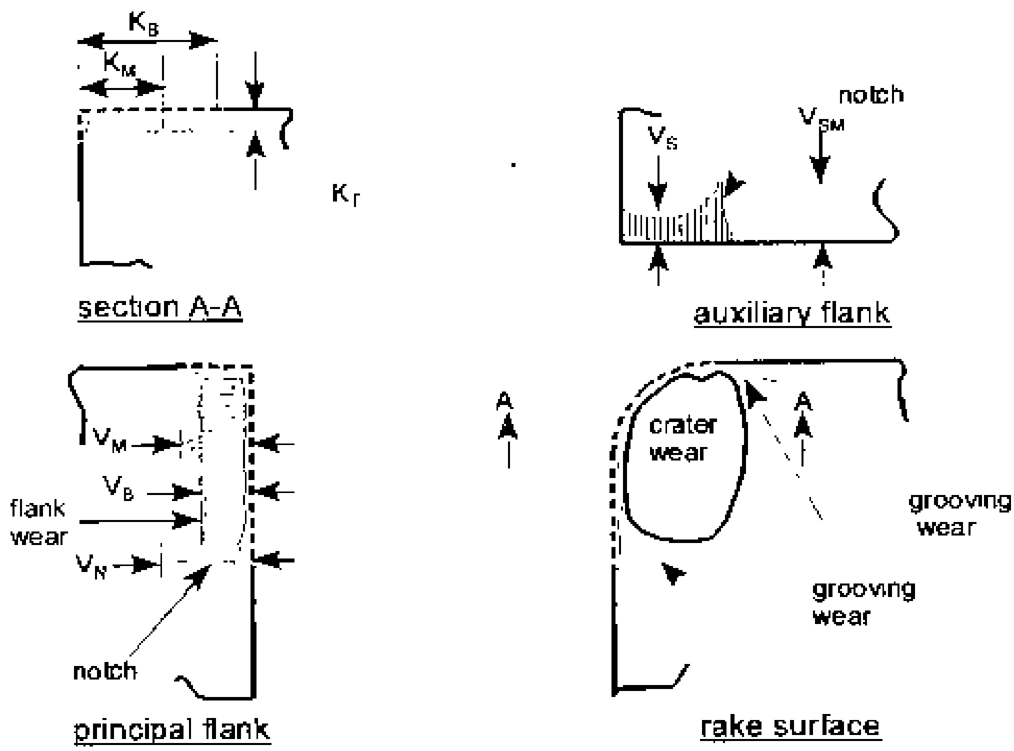
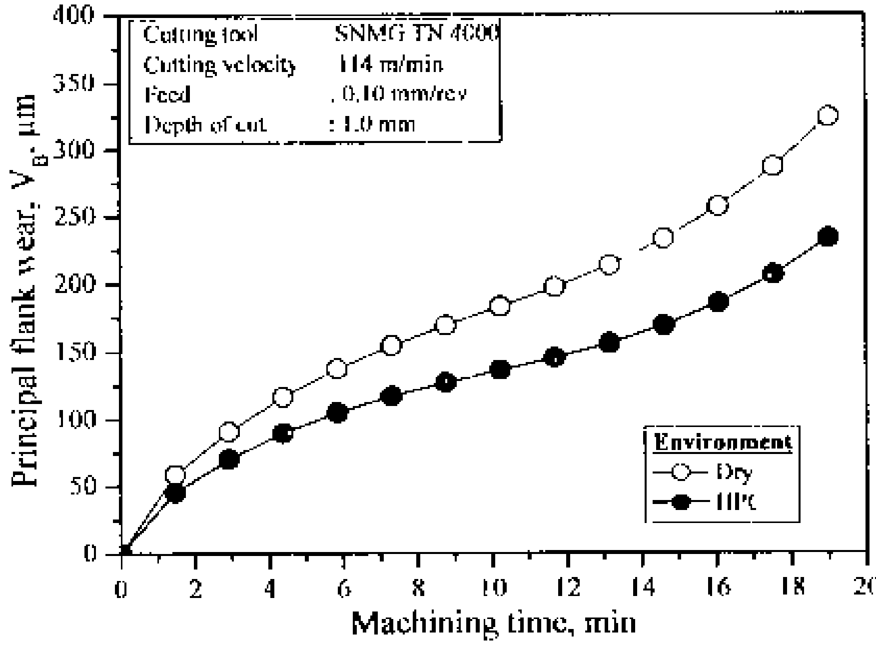
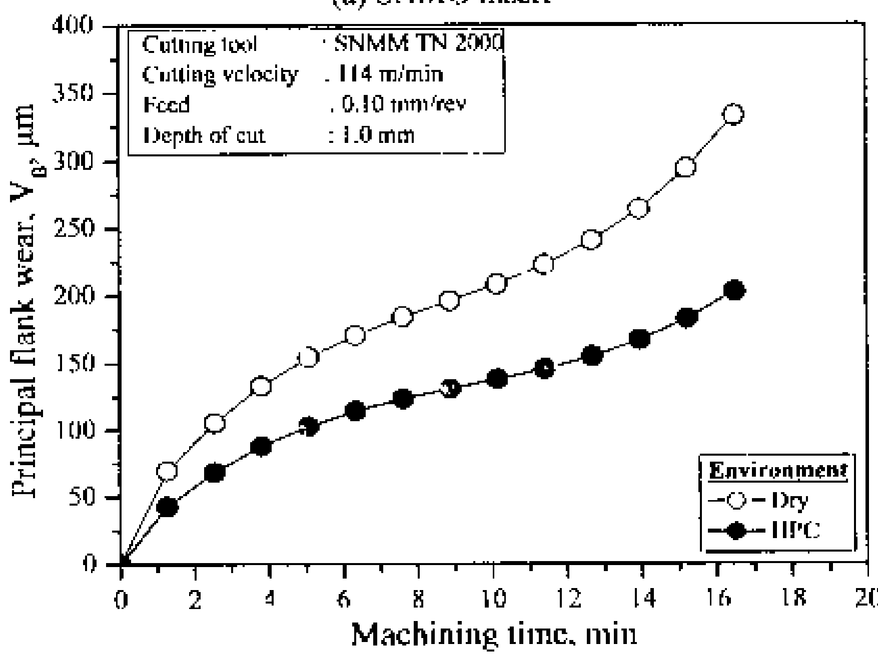



**Fig.3.15** Schematic view of general pattern of wear [98]

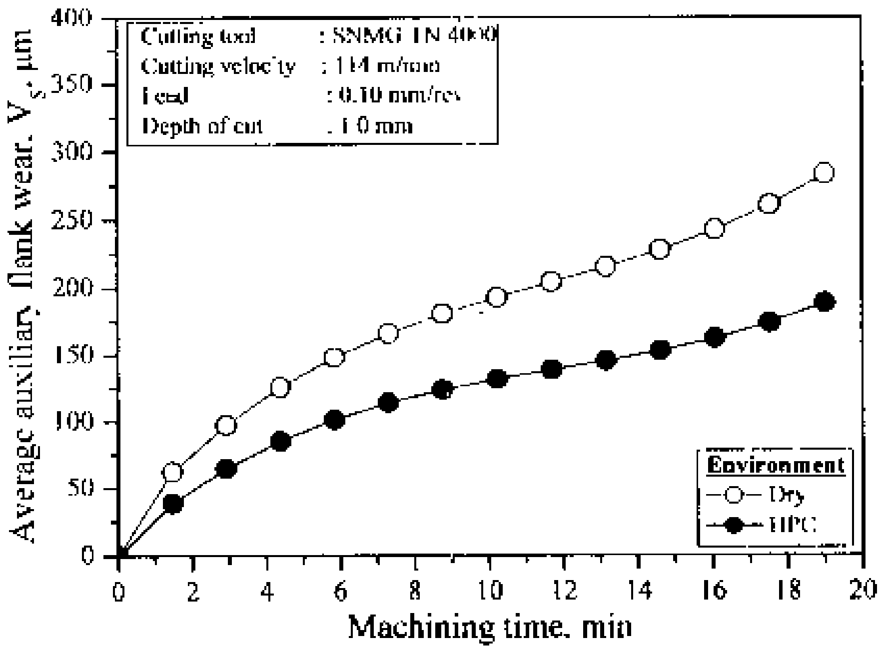



(a) SNMG insert

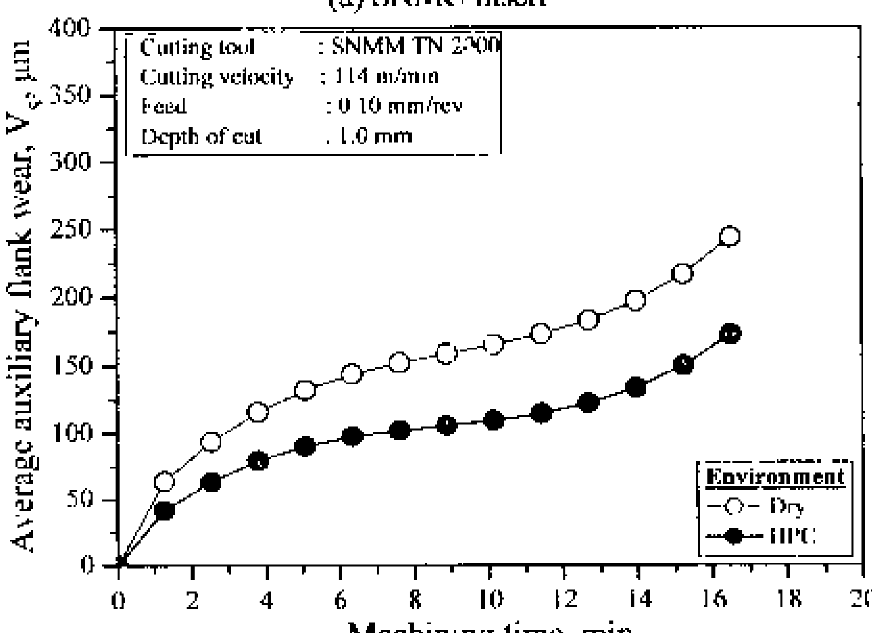



(b) SNMM insert

**Fig. 3.16** Growth of average principal flank wear ($V_B$) with time recorded during turning hardened medium carbon steel by (a) SNMG and (b) SNMM insert under dry and HPC conditions.



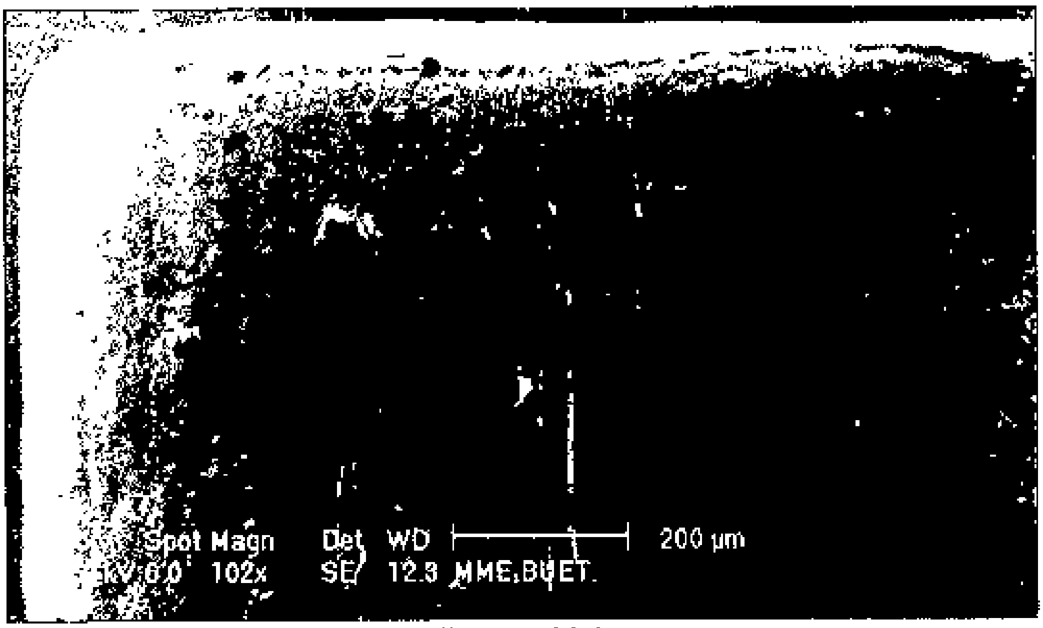

(a) SNMG insert



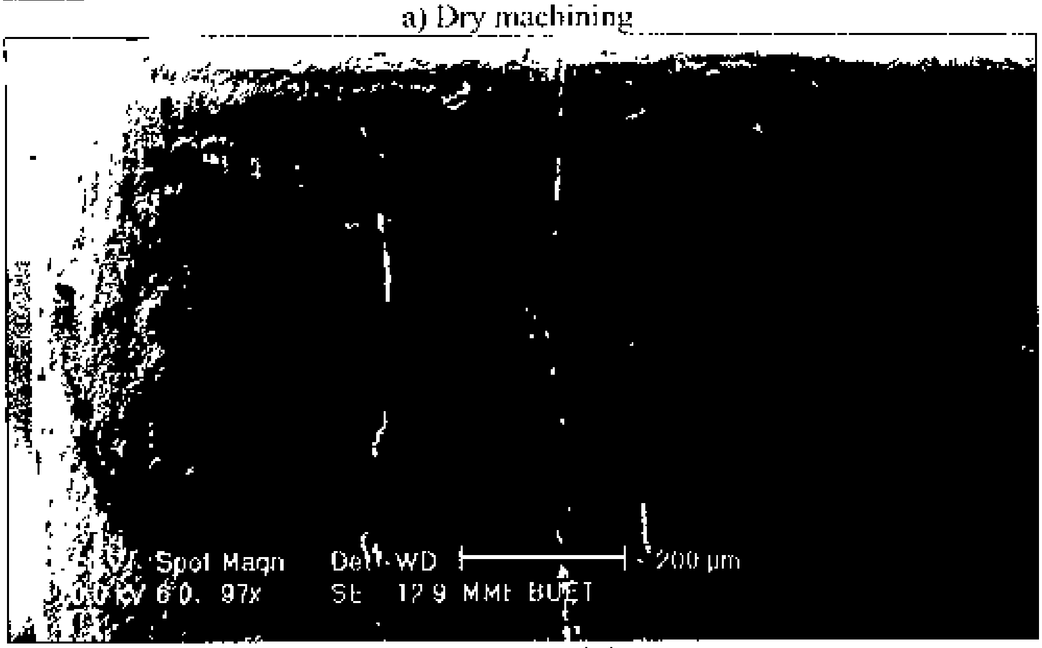

(b) SNMM insert

**Fig. 3.17** Growth of average auxiliary flank wear ($V_S$) with time recorded during turning hardened medium carbon steel by (a) SNMG and (b) SNMM insert under dry and HPC conditions.

The pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining the different steels over reasonably long period have been observed under Scanning Electron Microscope (SEM) to see the actual effects of different environments on wear of the carbide inserts of present two configurations. The SEM views of the worn out SNMG inserts and SNMM inserts after about 19 minutes and 16.5 minutes of machining under dry and high-pressure coolant conditions have been shown in Fig.3.18, Fig.3.19, Fig.3.20 and Fig.3.21 respectively.

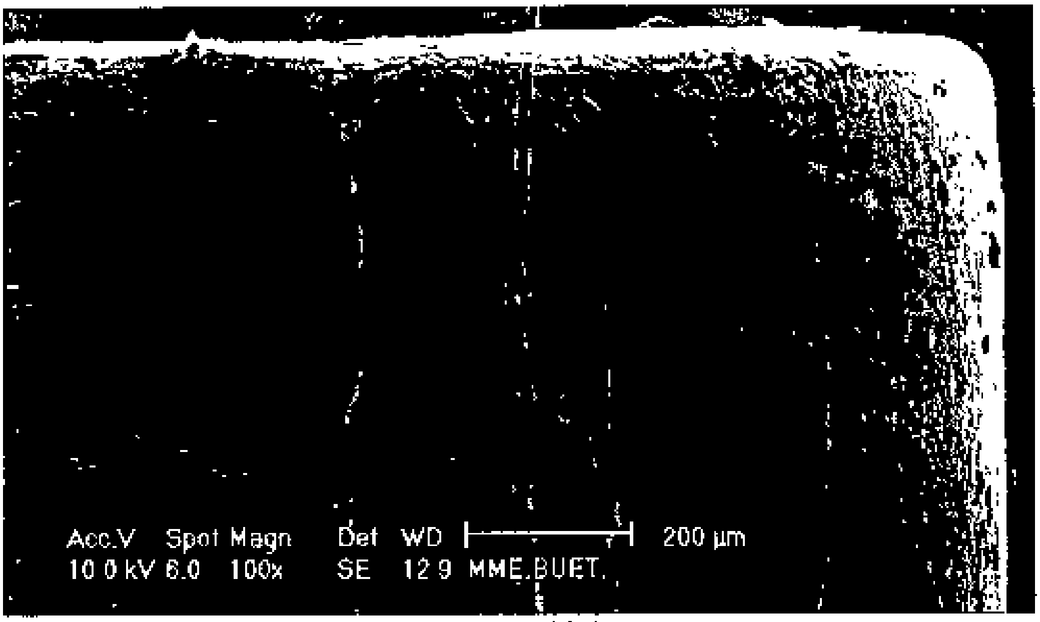



a) Dry machining

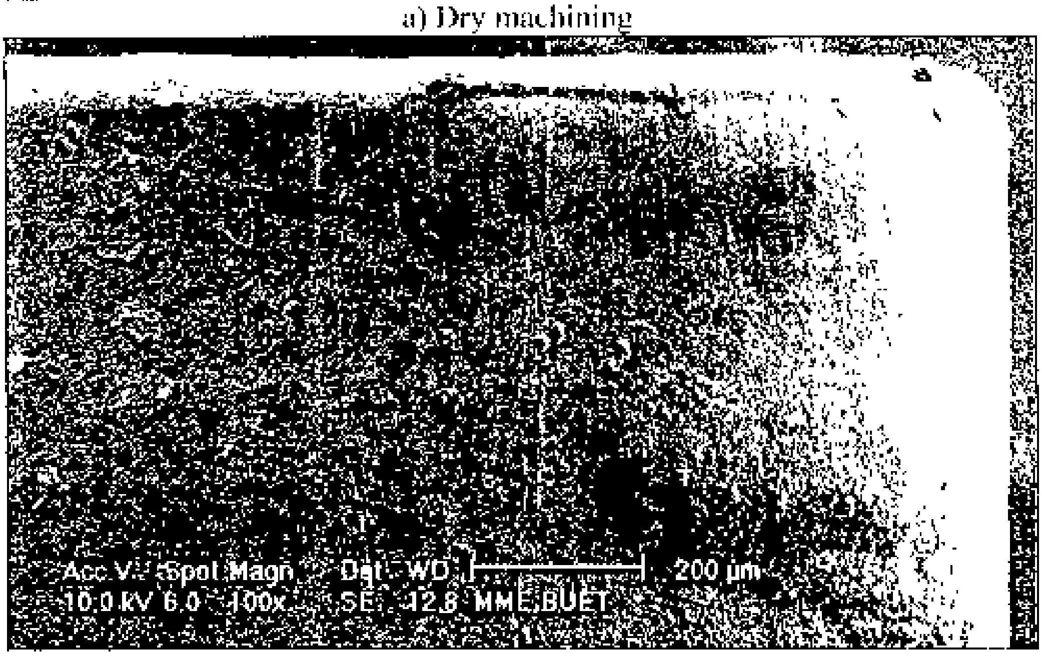



(b) HPC machining

**Fig.3.18** Scanning electronic micrograph (SEM) of principal flank of worn out tip of SNMG insert after machining under (a) dry and (b) HPC conditions.

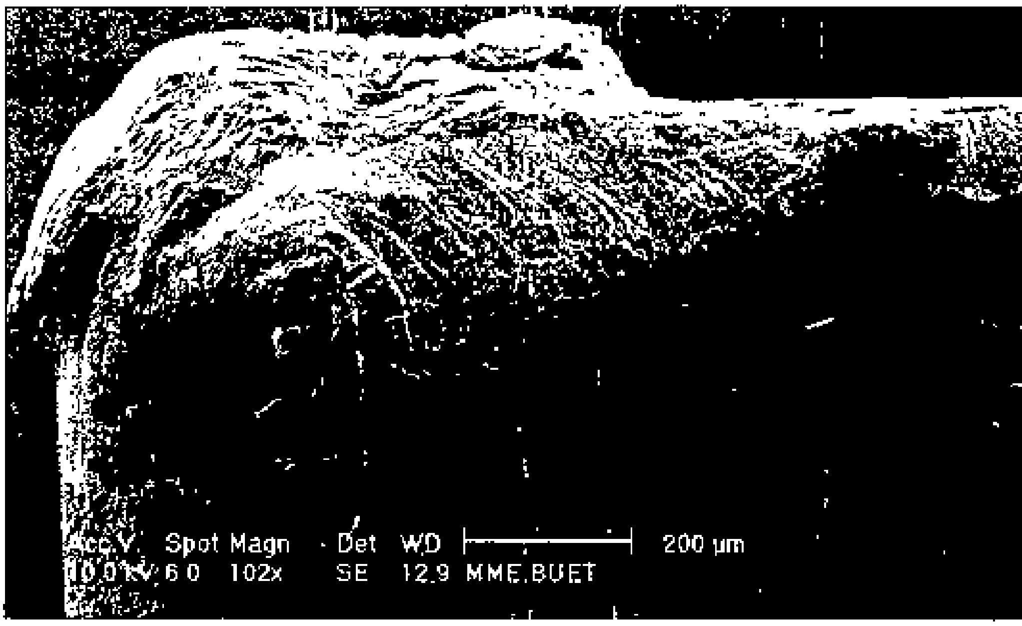



a) Dry machining

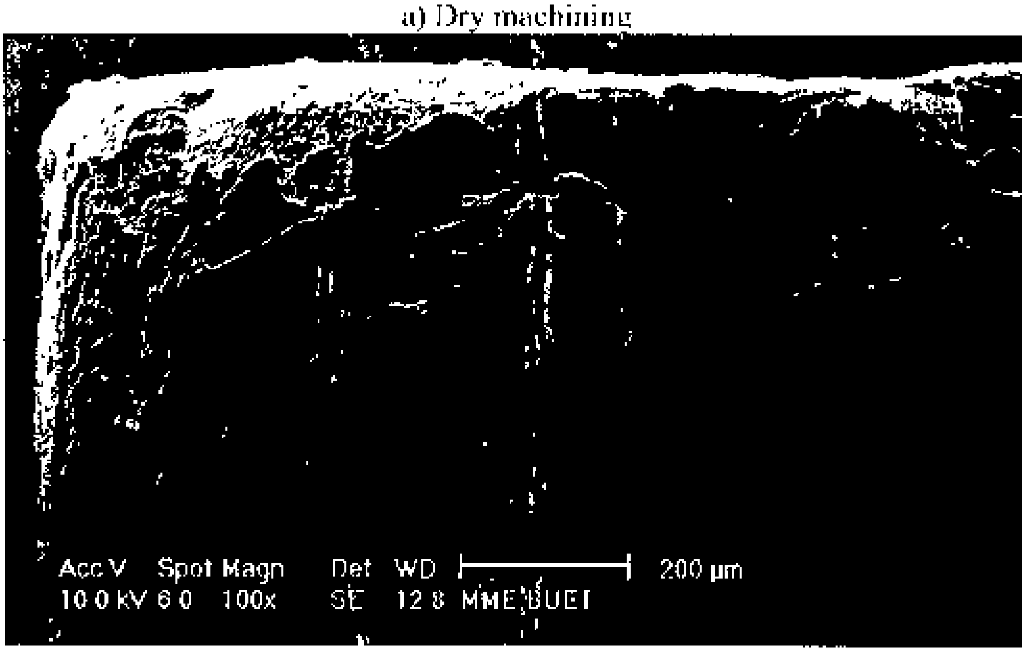



(b) HPC machining

**Fig. 3.19** Scanning electronic micrograph (SEM) of auxiliary flank of worn out tip of SNMG insert after machining under (a) dry and (b) HPC conditions.

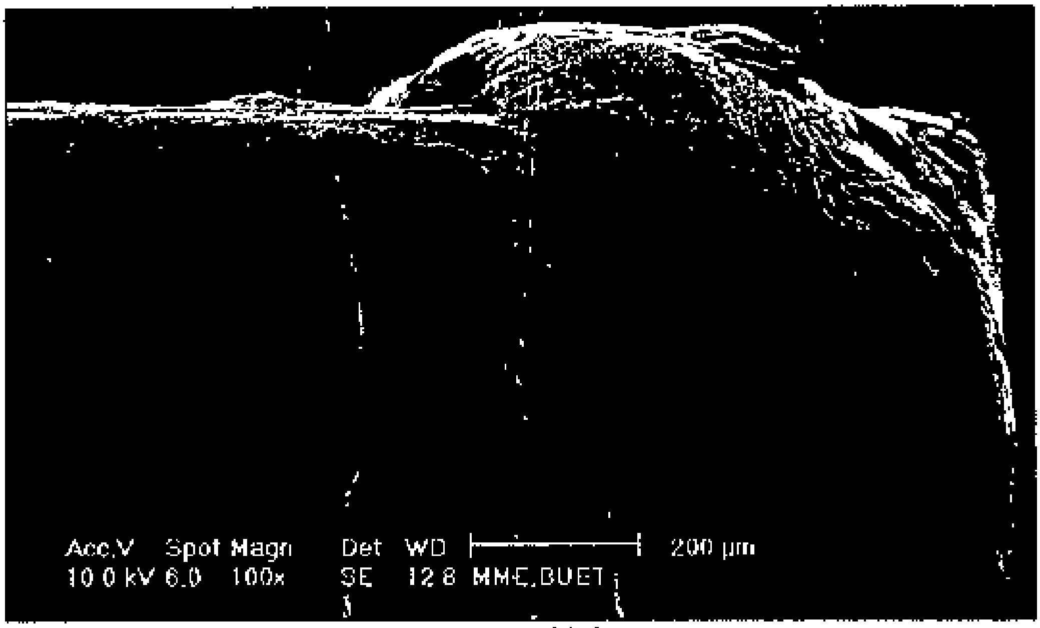



a) Dry machining

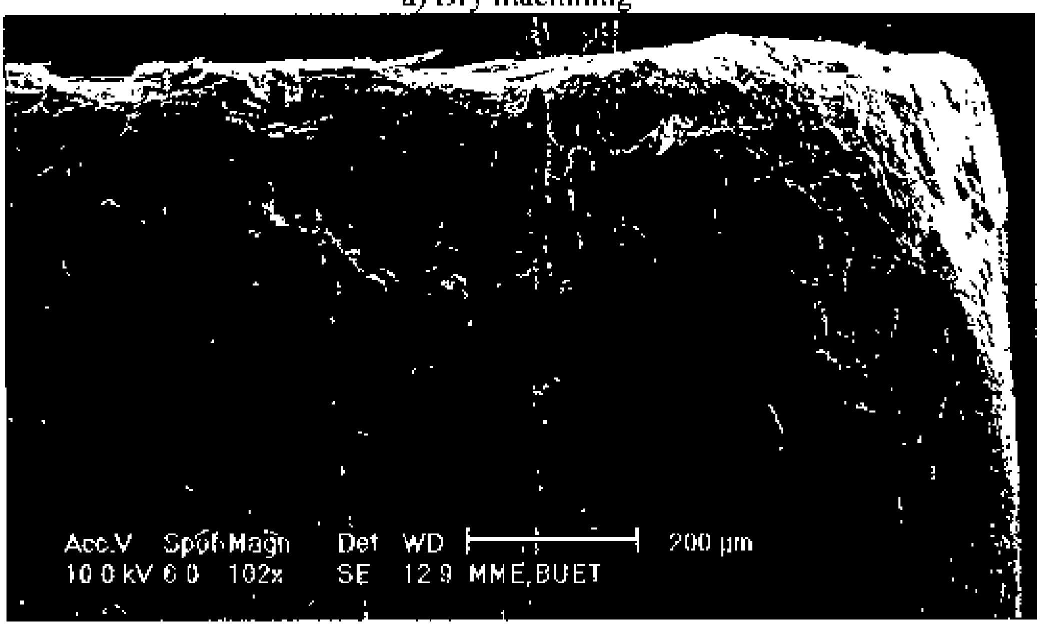



(b) HPC machining

**Fig. 3.20** Scanning electronic micrograph (SEM) of principal flank of worn out tip of SNMM insert after machining under (a) dry and (b) HPC conditions.




a) Dry machining




(b) HPC machining

**Fig. 3.21** Scanning electronic micrograph (SEM) of auxiliary flank of worn out tip of SNMM insert after machining under (a) dry and (b) HPC conditions.

### 3.3.5 Product Quality

The performance and service life of any machined part are governed largely by quality of that product, which for a given material is generally assessed by dimensional and form accuracy and surface integrity of the product in respect of surface roughness, oxidation, corrosion, residual stresses and surface and subsurface microcracks. In the present work, only surface roughness and dimensional deviation on diameter have been investigated to evaluate the relative role of high-pressure coolant on those two major aspects.

Surface roughness is an important index of machinability which is substantially influenced by the machining environment for given tool-work pair and speed-feed conditions. Surface roughness has been measured at two stages; first, after a few seconds of machining with the sharp tool while recording the cutting forces and second, with the progress of machining while monitoring growth of tool wear with machining time.

The surface roughness attained after 45 seconds of machining of the hardened steel by the sharp (a) SNMG and (b) SNMM inserts at various V-f combinations under dry and high-pressure coolant conditions are shown in Fig.3.22 and Fig.3.23. The variation in surface roughness observed with progress of machining of the hardened steel by the two types of inserts at a particular set of V, f and d under dry and high-pressure coolant conditions have been in shown in Fig.3.24.

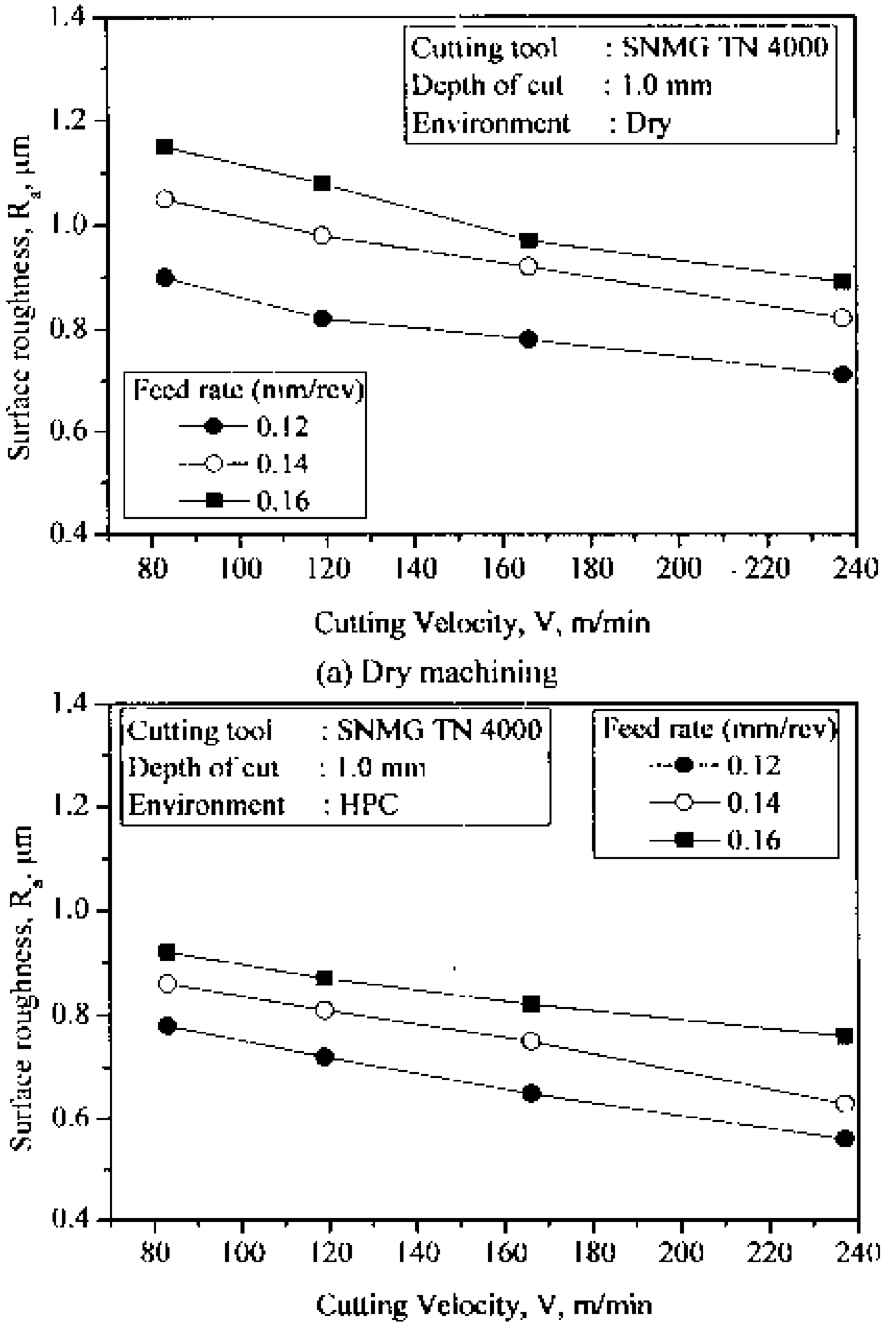
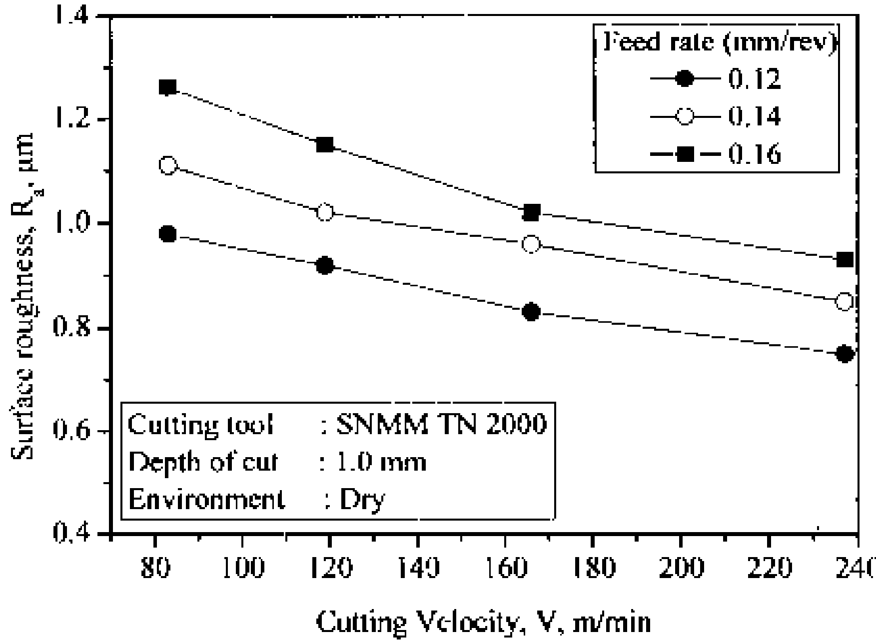
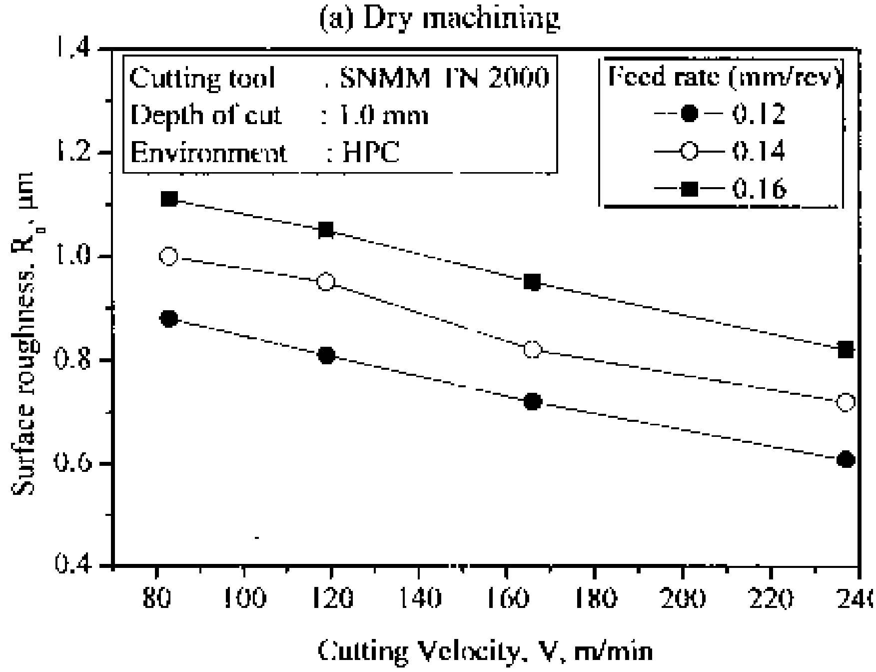



**Fig. 3.22** Variation in surface roughness ($R_a$) with that of V and f in turning hardened medium carbon steel by SNMG insert under (a) dry and (b) HPC conditions.

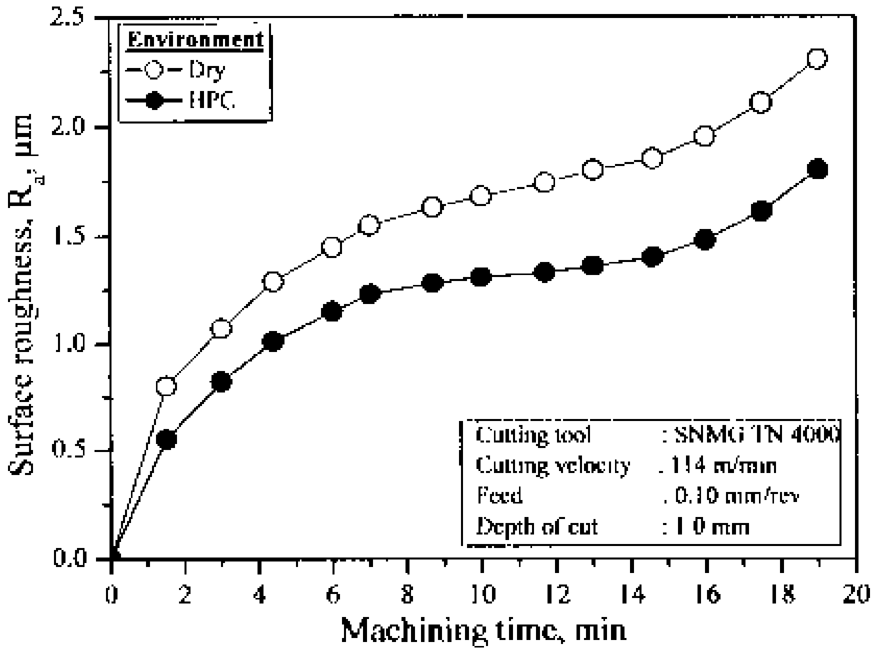



(a) Dry machining

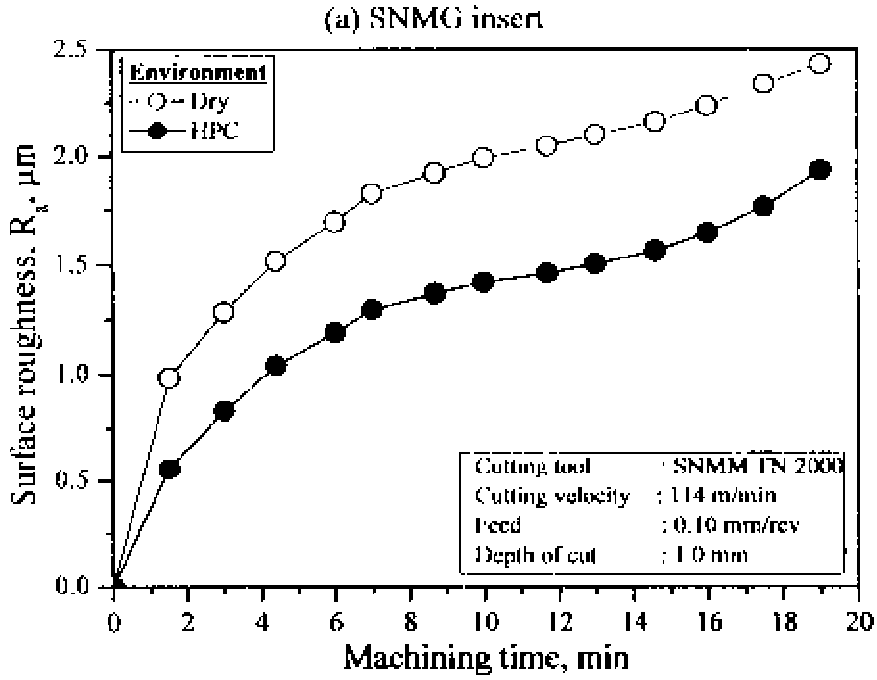



(b) HPC machining

**Fig. 3.23** Variation in surface roughness ($R_a$) with that of V and f in turning hardened medium carbon steel by SNMM insert under (a) dry and (b) HPC conditions.




(a) SNMG insert




(b) SNMM insert

**Fig. 3.24** Surface roughness ($R_a$) developed with progress of machining of the hardened medium carbon steel by (a) SNMG and (b) SNMM insert under dry and HPC conditions.

During straight turning in a centre lathe, the diameter of the machined part is generally found to

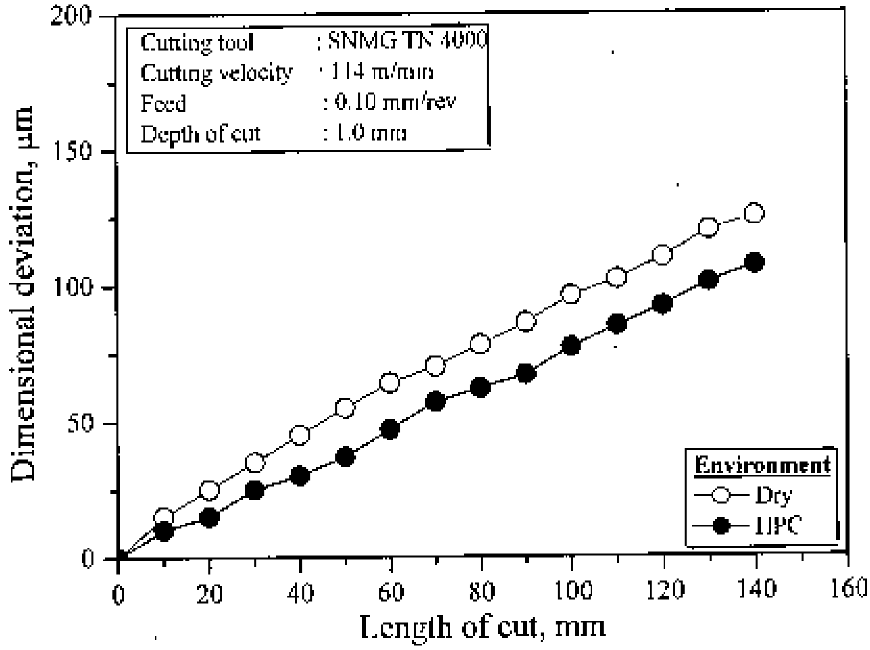
i. increase along length of cut due to gradual wear of the tool tip

ii. decrease due to thermal expansion and subsequent cooling of the job if the job temperature rises significantly during machining

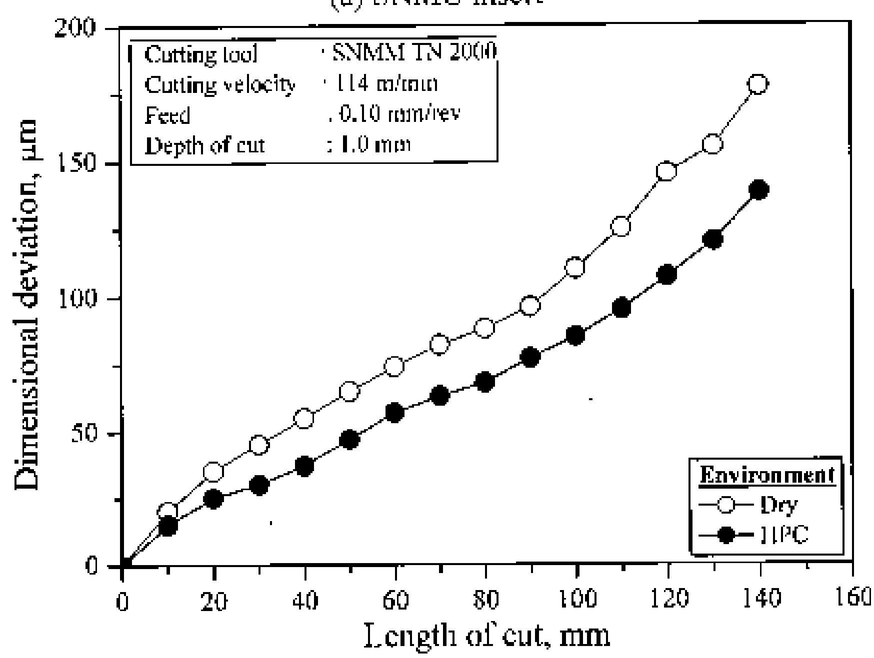
iii. increase due to system compliance of the machine-fixture-tool-work (M-F-T-W) system under the action of the cutting forces

The order of dimensional deviations possible due to thermal expansion of the job even under dry machining and due to compliance of the M-F-T-W system were calculated for the steel specimens being machined under the present conditions and the values appeared to be extremely small (less than 1 μm) compared to that possible due to wear of the tool tips. Therefore, in the present study, the dimensional deviations are considered to be mainly due to wear of the tool tips. The variation in diameter of the job was precisely measured along its axis after one full pass of the machining over 260 mm length with full depth, at reasonably high feed and cutting velocity suitable for the tool-work combination. This has been done for all the tool-work-environment combinations undertaken keeping the initial diameter and length of the steel rods same and uniform as far as possible.

The gradual increase in dimensional deviations on diameter observed along the length of cut on the steel rod after one full pass of machining at cutting velocity of 114 m/min,1.0 mm depth of cut and 0.1 mm/rev feed under dry and high-pressure coolant conditions have been shown in Fig.3.25.




(a) SNMG insert




(b) SNMM insert

**Fig. 3.25** Dimensional deviation observed after one full pass turning of hardened medium carbon steel by (a) SNMG and (b) SNMM insert under dry and HPC conditions.

# Chapter-4

# Discussion on Experimental Results

## 4.1 Chip

Machining chips inherently tells us the interaction characteristics at chip-tool interface. To asses the performance of the machining, it is always a good move to inspect the machining chips. In our research work, we inspected the color and shape of the chips and measured the chip thickness ratio ($r_c$) which is the ratio of the uncut chip thickness to that of machined chip. Chip properties largely depend on the hardness of the work material, tool geometry-especially the rake angle and the cutting parameters i.e. cutting speed, feed rate and depth of cut. They are also somewhat dependant on the cutting environment and the nature of the chip-tool interaction.

Table 3.2 presents the shape and color of machined chips under both dry and HPC conditions for SNMG and SNMM inserts. From the table we can see that the color of the chips are ranging from light to deep blue under dry condition for both the inserts. The blue color indicates the generation of high heat at the chip-tool interface. At lower speed and feed, the energy consumption is relatively lower, but at high speed and feed, high energy is consumed, friction between tool and work material increases and high temperature is reached which causes the color of the machining chips become deep blue. On the other hand, the color of the chip is metallic under high pressure coolant condition for both

SNMG and SNMM inserts. The high pressure coolant jet lifted the chip upward, created a wedge effect, and reached at the interface that ultimately reduced the temperature at the cutting zone.

Now, if we compare the result between the SNMG and the SNMM insert, we find that the SNMG insert was the one which showed better result under high pressure coolant condition. The effect of high pressure coolant jet was more significant for the groove type SNMG insert. This better result can be accredited to effectively larger positive rake of the tool and enhanced cooling by the coolant jets impending along the groove parallel to the cutting edges.

The chip thickness ratio ($r_c$) is another important index of chip formation and specific energy consumption for a given tool-work combination. It is calculated from the following equation,

$$r_c = \frac{a_1}{a_2} = \frac{f \sin\varphi}{a_2} \quad \text{.........} [3.1]$$

where,

$a_1$ = Uncut chip thickness = f sinφ

$a_2$ = Chip thickness

φ = Principal cutting edge angle

f = Feed rate

In case of turning, the machined chip thickness is greater than the uncut chip thickness because during turning process, the chips are under compression from three sides. As a result, the chip thickness ratio shows a value smaller than 1. If the friction at chip-tool interface can be reduced, the compressive force on chips will be reduced also which will yield a higher value of chip thickness ratio.

All parameters in machining are directly or indirectly linked with the chip thickness ratio. If there is excessive heat generated at the cutting zone, there will be high friction between the tool and the work material. This frictional force will cause high energy consumption hence higher cutting force. These will lead to a low chip thickness ratio which is not desirable.

Fig. 3.6 and Fig. 3.7 show that the value of the chip thickness ratio ($r_c$) is smaller than 1.0 at every condition. As the cutting speed and feed rate increase, the value of the chip thickness ratio ($r_c$) decreases. This is due to the higher energy consumption associated with higher material removal rate. For all speed-feed combinations, the application of high pressure coolant shows higher values of feed rate as compared to dry cutting. The high pressure cooling jet, with both its lubricating and cooling effect, minimized the shrinkage of shear zone and plasticization and reduced the formation of built-up-edge.

The percentage increase in the chip thickness ratio ($r_c$) accomplished by applying the high pressure coolant jet for both SMNG and SNMM inserts under all speed-feed conditions is compiled in Table 4.1 for turning hardened medium carbon steel. The average value of the improvement in the value of chip thickness ratio ($r_c$) is shown in the last row.

Table 4.1 Percentage increase in chip thickness ratio ($r_c$) in turning hardened medium carbon steel

| Feed (mm/rev) | Cutting speed (m/min) | Insert SNMG Percentage increase in $r_c$ | Insert SNMM Percentage increase in $r_c$ |
|---|---|---|---|
| 0.12 | 83 | 9 | 10 |
| | 119 | 13 | 12 |
| | 166 | 11 | 4 |
| | 237 | 10 | 4 |
| 0.14 | 83 | 10 | 11 |
| | 119 | 8 | 8 |
| | 166 | 9 | 6 |
| | 237 | 8 | 4 |
| 0.16 | 83 | 9 | 9 |
| | 119 | 6 | 4 |
| | 166 | 7 | 7 |
| | 237 | 8 | 3 |
| | Average | 9 | 7 |

From Table 4.1 we get that the average percentage increase in the chip thickness ratio for the stated speed-feed condition is 9% under high pressure cooling condition for SNMG insert. The increment for SNMM insert is 7%. At lower speed-feed condition, the result is more satisfactory.

## 4.2 Average Chip-Tool Interface Temperature

Heat generation at the chip-tool interface is of prime concern in the machining process. The machining temperature at the cutting zone must be reduced to an optimum level. During machining, shearing of work material, friction between the flowing chips and rake face of the tool and friction of auxiliary flank with finished surface are the principal sources of heat generation. The magnitude of the cutting temperature increases with the increase of material removal rate i.e. with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by the ascend in temperature.

of cut, as a result, high production machining is constrained by the ascend in temperature. This problem increases further with the increase in strength and hardness of the work material.

High cutting temperature adversely affects, directly or indirectly, chip formation, cutting forces, tool life, dimensional accuracy and surface integrity nf the product. In order to cop with this problem, numerous attempts have been made to reduce this detrimental cutting temperature. It has been followed that in some cases, dry machining is preferable for hard and difficult-to-machine materials at low speeds. But at high speeds, cutting fluids can play a significant role. Application of conventional cutting fluids may cool the tool and the workpiece in bulk to some extents, but it can not cool and lubricate expectedly and effectively the chip-tool interface where the temperature is maximum. This is mostly because the flowing chips make mainly bulk cor tact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. This bulk contact does not allow the cutting fluid to penetrate into the chip-tool interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in cutting velocity when the chip-tool contact becomes almost fully plastic.

In this research work, a tool-work thermocouple was calibrated to determine the average chip-tool interface temperature and the values were plotted against different cutting speed under both dry and high pressure coolant condition for both coated SNMG and coated SNMM inserts. It was expected that the application of high pressure coolant jet would be much more effective at high speed-feed condition in reducing the average chip-tool interface temperature which plays an imperative role on productivity, dimensional accuracy, surface integrity and overall economy in turning hardened medium carbon steel.

In Fig. 3.8 and Fig. 3.9 the variation in average chip-tool interface temperature at different cutting speed and feed is shown. The variation was studied for both SNMG and SNMM inserts under dry and high pressure coolant condition. At high speed-feed condition, the MRR is high which requires high energy consumption. This high energy input helps the cutting zone temperature increase. This is why the controlling of temperature is more important in high speed machining.

Table 4.2 shows the range and average percentage reduction in chip-tool interface temperature (θ) in turning hardened medium carbon steel for different speed-feed conditions for both SNMG and SNMM inserts achieved by applying high pressure coolant jet. From Fig. 3.8 and Fig. 3.9 it is evident that with the increase in cutting velocity, the cooling effect gets more significant. The possible reason may be that high pressure coolant jet reached the chip-tool interface even at high speed-feed condition. The high velocity jet uplifted the chip creating a wedge effect and reached at the shear zone. There it performed both the cooling and lubricating effects and eventually reduced the temperature. This reduction in temperature is very much appreciable in retaining tool life and product quality. So, we can conclude that results of our research wok show that application of high pressure coolant contributes to a decrease in average chip-tool interface temperature by a momentous margin depending on the cutting parameters which is further demonstrated by the color of the machining chips.

Table 4.2 Percentage reduction in chip-tool interface temperature (θ) in turning hardened medium carbon steel

| Feed (mm/rev) | Cutting speed (m/min) | Insert | |
|---|---|---|---|
| | | SNMG | SNMM |
| | | Percentage reduction in θ | Percentage reduction in θ |
| 0.12 | 83 | 14 | 10 |
| | 119 | 13 | 9 |
| | 166 | 11 | 8 |
| | 237 | 9 | 5 |
| 0.14 | 83 | 11 | 8 |
| | 119 | 10 | 8 |
| | 166 | 9 | 9 |
| | 237 | 10 | 8 |
| 0.16 | 83 | 11 | 8 |
| | 119 | 10 | 9 |
| | 166 | 11 | 9 |
| | 237 | 9 | 8 |
| | Average | 11 | 8 |

## 4.3 Cutting Forces

The forces generated during the machining process have a significant effect on the quality of the part that can be machined. Excessive forces can lead to premature tool failure, tool vibration, high temperature generation, large tool deflections and significant mechanical loads on the workpiece surface. Large tool deflections can lead to form errors because the tool tip position deviates from the expected position. Large mechanical loads on the workpiece surface can affect the topography and integrity of a machined surface. For each of these reasons, it is important to understand how changing process conditions affect cutting forces. There have been so many experimental investigations in hard turning that have included cutting force data. Attempts have also been made to model cutting loads in machining through empirical, analytical, mechanistic, and numerical (finite element) techniques. These approaches have produced reasonable results for both expensive and inexpensive cutting tools (typically with an ideal geometry).

In hard turning, there are highly three-dimensional cutting geometry, large negative rake geometries, and a chip formation that typically has intermittent periods of high and low strain (chip segmentation). Each of these difficulties makes the force behavior in hard turning more complicated than conventional machining. The two components of cutting force (main cutting force and feed force) were recorded during machining under dry and high pressure coolant conditions for both SNMG and SNMM inserts at regular intervals. The force components were measured with a strain-gauge type force dynamometer and recorded with a PC-based data acquisition system, as detailed in chapter 1 and chapter 2.

Fig. 3.11 to Fig. 3.14 reveals that there is no significant increase of cutting forces with the increase of cutting speed although the energy input into the system and the strain stress were higher at high cutting speeds. This can be explained by increased heat generated at the shear zone that was sufficient to plasticize the workpiece material and hence reduce its strength.

Table 4.3 Percentage reduction in main cutting force ($F_c$) in turning hardened medium carbon steel

| Feed (mm/rev) | Cutting speed (m/min) | Insert | |
|---|---|---|---|
| | | **SNMG** | **SNMM** |
| | | **Percentage reduction in $F_c$** | **Percentage reduction in $F_c$** |
| 0.12 | 83 | 24 | 13 |
| | 119 | 24 | 14 |
| | 166 | 21 | 15 |
| | 237 | 20 | 11 |
| 0.14 | 83 | 17 | 13 |
| | 119 | 16 | 12 |
| | 166 | 16 | 12 |
| | 237 | 17 | 7 |
| 0.16 | 83 | 16 | 13 |
| | 119 | 15 | 9 |
| | 166 | 16 | 7 |
| | 237 | 17 | 6 |
| | Average | 18 | 11 |

From Fig. 3.11 to Fig. 3.14 we can see that the high pressure coolant jet has been successful in reducing the main cutting force and feed force. The reason behind this is mainly the reduction of friction accomplished by the lubricating effect of the coolant jet. The coolant jet, with its high pressure and velocity, was able to reach the tool tip where it performed its lubricating and cooling effects and minimized friction to a notable extent. Another reason acting behind these lowered cutting forces may be the reduction in chip load. The high velocity coolant jet impinged on the rake face uplifted the chip and reduced chip load which eventually helped the cutting forces fall down.

Table 4.3 and Table 4.4 shows the percentage reduction in main cutting force ($F_c$) feed force ($F_f$) in turning hardened medium carbon steel. For SNMG and SNMM inserts, the percentage reductions in main cutting force are 18% and 11% respectively and the percentage reductions in feed force are 17% and 11% respectively. The deep groove at the rake face in SNMG inserts facilitated the coolant jet to reach the tool tip more effortlessly than SNMM inserts. So, for SNMG inserts, the reduction in cutting forces is more significant than for SNMM inserts.

Table 4.4 Percentage reduction in feed force ($F_f$) in turning hardened medium carbon steel

| Feed (mm/rev) | Cutting speed (m/min) | Insert | |
|---|---|---|---|
| | | SNMG | SNMM |
| | | Percentage reduction in $F_t$ | Percentage reduction in $F_t$ |
| 0.12 | 83 | 19 | 13 |
| | 119 | 19 | 14 |
| | 166 | 18 | 15 |
| | 237 | 16 | 11 |
| 0.14 | 83 | 17 | 13 |
| | 119 | 16 | 12 |
| | 166 | 16 | 12 |
| | 237 | 17 | 7 |
| 0.16 | 83 | 16 | 13 |
| | 119 | 14 | 9 |
| | 166 | 16 | 7 |
| | 237 | 17 | 6 |
| | Average | 17 | 11 |

## 4.4 Tool Wear

At conventional speed, tool wear is mainly due to abrasion and adhesion, but is dominated by diffusion process at higher speeds. High pressure coolant directly reduces the diffusion process by decreasing the cutting zone temperature. As a result, a delayed progression of tool wear is followed under the high pressure coolant condition. The wear of cutting tools is generally quantitatively evaluated by the magnitudes of $V_B$, $V_S$, $V_M$, $V_{SM}$, $V_N$ etc. Among them, average principal flank wear, $V_B$ is considered to be the most significant parameter at least in research work. The earlier investigation carried out by the presearchers reveals that the application of conventional cutting fluid does not always help in reducing tool wear in machining steels by coasted or uncoated carbide inserts rather in some cases exacerbate wear.

Rise in cutting force and temperature is directly related with the growth of principal flank wear ($V_B$). So, the principal flank wear is the foremost concern among all the tool wears. The life of carbide tools, which usually fails by wearing, is assessed by the actual machining time after which the average value of its principal flank wear reaches a limiting value, like 300μm. so, decreasing the rate of growth of principal flank wear without sacrificing the MRR should be, therefore, our prime concern.

In order to measure the $V_B$ we used an optical microscope. The inserts were withdrawn at regular intervals to study the pattern and extent of wear on principal and auxiliary flank faces under both dry and high pressure coolant conditions. The gradual growth of principal flank wear ($V_B$) was observed during turning of hardened medium carbon steel by coated carbide inserts (SNMG and SNMM) at a cutting velocity of 114m/min, feed rate 0.14 and depth of cut 1.0mm under both dry and high pressure coolant conditions. This parameter combination is selected because from previous discussion it has been experienced that the performance of high pressure coolant is more effective in cutting velocity of 119m/min. feed rate 0.14 and depth of cut 0.8mm. It can be clearly observed that the principal flank wear ($V_D$) decreases significantly under high pressure coolant condition.

Fig.3.17 shows another tool wear criteria the average auxiliary flank wear ($V_S$) which governs the surface finish on the job as well as dimensional accuracy. If the average auxiliary flank wear ($V_S$) is high and irregular, the surface finish and dimensional accuracy will be interrupted. In Fig. 3.17 the growth of average auxiliary flank wear ($V_S$) has been depicted for both SNMG and SNMM inserts under dry and high pressure coolant conditions. This figure shows that there is a substantial improvement in reducing the average auxiliary flank wear ($V_S$) under high pressure coolant condition.

In high pressure cooling system, the coolant jet was pressurized about 70 bars. This high pressure carried the coolant jet into the plastic contact between tool tip and workpiece where it cooled the interface and lubricated properly. It also helped to reduce the heat generation caused by the friction between auxiliary flank face and finished surface by appropriate lubrication. Such improvement by high pressure coolant may also be attributed to retention of proper sharpness and hardness of the cutting edge by the steady and intensive cooling, protection from oxidation and corrosion and absence of built up edge formation which accelerates both crater wear and flank wear by flaking and chipping.

The auxiliary flank wear, which occurs due to rubbing of the tool tip against the finished surface, causes the dimensional inaccuracy and worsens the surface finish. Gradual decrease in depth of cut which is proportional to the width of average auxiliary flank wear ($V_S$) increases the diameter of the job in straight turning with the progress of machining and the irregularity developed in the auxiliary cutting edge due to wear impairs the surface finish of the product.

In the process of systematic growth of cutting tool wear, the cutting tools usually first undergo rapid wear called break-in wear at the beginning of machining due to attrition and micro-chipping and then uniformly and relatively slow mechanical wear followed by faster wear at the end. The mechanism and the rate of growth of cutting tool wear depend much on the mechanical and chemical properties of the tool and the work materials and their behavior under the cutting conditions. While machining this hardened medium carbon steel, no notching was found to develop in any of the inserts even under dry machining condition possibly for the good chemical stability and uniform hardness of this steel.

In during turning of relatively soft and ductile materials by uncoated or coated carbide tools at reasonably high speed-feed condition, crater wear in governed mainly by adhesion and diffusion for rubbing at higher stresses and temperature and flank wear mainly by abrasion for less pressure and temperature. But adhesion and diffusion type temperature sensitive wear may also occur, in addition to abrasion wear, at the tool flanks if the flank temperature becomes high. Turning of strong metals like hardened medium carbon steel at reasonably high velocity and feed (119 m/min and 0.14 mm/rev respectively) under dry condition is expected to cause sufficiently high temperature at the tool flanks. Adhesion and diffusion, therefore. are also likely to have contributed to the flank wear in the present case, and seemingly high pressure coolant jet has prevented such temperature sensitive adhesion and diffusion as well as reduced abrasion wears.

Fig.3.18, Fig.3.19, Fig. 3.20 and Fig. 3.21 show the SEM views of the worn out inserts after machining of hardened medium carbon steel at effective in cutting velocity of 119m/min, feed rate 0.14 and depth of cut 0.8mm for different periods of time which qualitatively point toward the conclusion that the application of high pressure coolant jet has provided substantial reduction in overall wear of the inserts. Fig. 3.18 and Fig. 3.19

also show that the principal flank wear is more uniform under the high pressure coolant condition than under dry condition.

## 4.5 Product Quality

If hard turning is to replace any grinding operation, it must be capable of producing surfaces of acceptable quality. This includes both the surface topography (surface finish) and surface integrity, which is achieved when "the surface of a component meets the demands of a specific stress system and environment" [22]. Kahles et al. [23] defined an "extended surface integrity data set" which includes: surface finish, microstructure, microhardness, fatigue resistance, residual stress state, and frictional characteristics.

There are two major types of surface damage that can be caused by hard turning. The first is white layer, which has generally been assumed to result from temperatures generated at the workpiece surface that exceed the austenitizing temperature of the material, followed by rapid cooling. The second type of damage is the formation of undesirable residual stress profiles at, and just below, the workpiece surface. Mechanical loading, plastic flow, and phase transformation can affect residual stresses, but negative effects are primarily due to the elevated temperatures during machining. Thus, the two types of damage (white layer and tensile residual stress) are related and have generally been investigated together. It is generally believed that generation of white layer requires both excessive heat at the workpiece surface and subsequent rapid cooling. Heat generation is attributed to large amounts of energy generated in the shear region during chip formation and to the frictional energy between the tool flank and workpiece surface.

However, experimental results disagree about the source of rapid cooling. Tonshoff performed hard turning experiments with and without coolant and found the white layer magnitude was identical, indicating that workpiece self-cooling, and not coolant, must be responsible for quenching of the workpiece surface [26, 27]. This argument is reasonable because the heat-affected zone is small in hard turning, and because the cutting velocities are large enough that the contact time between the tool and workpiece is minimal. Therefore, it is possible that the bulk workpiece material acts as a heat sink and draws heat from the surface to create a self-cooling effect. However, Konig et al. [28] found that cutting with a worn tool produced white layer, but that similar cutting conditions with the application of coolant resulted in undamaged surfaces.

In this research work, surface roughness has been measured at two stages; first, after an interval of 45 seconds of machining with sharp tool and second, with the progress of machining while monitoring the growth of tool wear with machining time.

In both stages, the surface roughness values under the high pressure coolant condition shows better results as compared to dry condition as referred by Table 4.5. It also shows that the maximum reduction in surface roughness for SNMG inserts is up to 23% and for SNMM inserts it goes up to 19%.

Table 4.5 Percentage reduction in surface roughness ($R_a$) in turning hardened medium carbon steel

| Feed (mm/rev) | Cutting speed (m/min) | Length of cut (mm) | Insert | |
|---|---|---|---|---|
| | | | SNMG | SNMM |
| | | | Percentage reduction in $R_a$ | Percentage reduction in $R_a$ |
| 0.10 | 114 | 10 | 33 | 30 |
| | | 20 | 40 | 31 |
| | | 30 | 29 | 25 |
| | | 40 | 33 | 31 |
| | | 50 | 33 | 26 |
| | | 60 | 27 | 26 |
| | | 70 | 19 | 16 |
| | | 80 | 21 | 20 |
| | | 90 | 22 | 19 |
| | | 100 | 20 | 13 |
| | | 110 | 17 | 13 |
| | | 120 | 16 | 12 |
| | | 130 | 16 | 14 |
| | | 140 | 14 | 13 |

The dimensional deviation increases along the length of cut due to gradual wear of the tool tip. The same thing is observed in this research work. Under HPC condition, the tool wear was delayed by reducing the temperature and forces, as a result, from Fig. 2.5 we found that the reduction in dimensional deviation is much more significant under this condition than under dry condition.

The investigation on the dimensional deviation was carried out at a cutting speed of 114m/min and at a feed rate of 0.10 mm/rev with 1.0 mm depth of cut. Table 4.6 shows that under high pressure coolant condition the reduction in dimensional deviation for SNMG insert goes up to 40 % and for SNMM insert it goes up to 31 % depending on the length of cut.

Table 4.6 Percentage reduction in dimensional deviation in turning hardened medium carbon steel

| Feed (mm/rev) | Cutting speed (m/min) | Insert | |
|---|---|---|---|
| | | SNMG | SNMM |
| | | **Percentage reduction in dimensional deviation** | **Percentage reduction in dimensional deviation** |
| 0.12 | 83 | 13 | 10 |
| | 119 | 12 | 12 |
| | 166 | 17 | 13 |
| | 237 | 21 | 19 |
| 0.14 | 83 | 18 | 10 |
| | 119 | 17 | 7 |
| | 166 | 18 | 15 |
| | 237 | 23 | 15 |
| 0.16 | 83 | 20 | 12 |
| | 119 | 19 | 9 |
| | 166 | 15 | 7 |
| | 237 | 15 | 12 |
| | Average | 17 | 12 |

Again for SNMG inserts, the reduction in dimensional deviation is better than for SNMM inserts. Because the groove in SNMG inserts provided better cooling and chip removal than the SNMM inserts which have provided less tool wear resulting in less dimensional deviation.

The reasons for this reduction in dimensional deviation can be attributed to the proper cooling at the chip-tool interface. The less generation of heat produced less thermal expansion of the work material eventually decreasing the dimensional deviation. Proper cooling also provided retention of tool sharpness and delayed tool wear which also contributed to the decreased dimensional deviation.

# Chapter-5

## Conclusions and Recommendations

### 5.1 Conclusions

This research work justifies the capability of the hard turning process under high pressure coolant condition with coated carbide inserts. The goal of this study was to evaluate the effects of high pressure coolant system on the wear behavior of the coated carbide cutting tools and on the resultant surface quality along with the cutting force and temperature. The following conclusions can be drawn from the aforesaid results and discussion.

i. The present high pressure coolant system enabled the reduction in average chip-tool interface temperature up to 13% for both SNMG and SNMM inserts depending on the cutting conditions. This apparently diminutive reduction enabled considerable improvement in the major machinability indices.

ii. The shape and color of the machined chips became favorable due to the application of high pressure coolant as it provided effective cooling at the cutting zone. The high pressure jet also improved the nature of interaction at the chip-tool interface which results in about 10% decrease in the chip-tool interface temperature.

iii. The investigation shows that the application of high pressure coolant jet trimmed down the main cutting force up to 24% for SNMG inserts and up to 15% for SNMM inserts. The feed force is reduced up to 19% for SNMG inserts and up to 15% for SNMM inserts. The high pressure coolant assisted hard turning facilitated the retention of tool edge sharpness for a longer period and also provided effective lubrication at the shear zone. These resulted in less friction and ultimately the less cutting temperature which seems to be the main reason for the decrease in cutting forces.

iv. Increased cutting speed has a detrimental effect on tool performance as the research reveals. Feed has a much less detrimental effect on the chip-tool interface temperature and cutting forces, rather feeds actually have a positive effect on cumulative volume. This means that increased feeds actually lead to an increase in the number of parts that can be machined with a tool before it fails, despite the fact that the tool fails sooner than at smaller feeds.

v. Application of high pressure coolant jet produced reduced tool wear, good dimensional accuracy and surface finishes that are acceptable for most applications. In general, this study shows that hard turning is capable of producing precision parts and can replace grinding for many applications.

vi. By selecting the coated tools, it is possible to cut faster due to the improved wear resistance of the tools, which in turn allows decreased feeds (and thus better surface finish), produces higher material removal rates, and reduces the cost per part. The results also uncover the fact that SNMG inserts performs better than SNMM inserts under both conditions.

vii. Acceptable dimensional accuracy and surface finishes are possible by hard turning. The quality of hard turned surfaces is generally good. Even when white layers exist, they are below 2 μm and would be removed by superfinishing, which often follows hard turning or grinding. Surface finish is slightly poorer than grinding values due to plastic flow of the material around the nose of cutting tools. This plowing action is inevitable due to the negligible chip thickness that occurs at the two boundaries of the contact area between the tool and workpiece. Flank wear progression is non-linear, but corresponds to a linear increase in the volumetric wear loss. Cutting speed has a much more detrimental effect on tool life than feed. Increased feeds are actually advantageous if the goal is to maximize the number of parts per tool instead of cumulative cutting time. The improved performance under the high pressure coolant condition allows cutting at higher speeds, which in turn yields lower chip-tool interface temperature and cutting forces, improved surface finish, higher material removal rates, reduced machining time per part, and reduced cost.

## 5.2 Recommended Future Works

This research work fills a void in hard turning research by establishing techniques to quantify wear behavior and developing a cooling system that accounts for minimizing the detrimental effects of increased cutting zone temperature. Independent studies of abrasion, adhesion, diffusion, and chemical reactions should be undertaken to identify the potential contribution of each of these mechanisms to material loss at different stress, temperature, and environmental conditions. It is expected that different mechanisms will be dominant at different cutting regimes, and hopefully independent models can be combined into a useable wear model that describes in a more physical way the effects of cutting conditions on wear behavior.

i. In our experiment, we used one cooling jet, but if we use three cooling jet pinching towards the rake face, principal and auxiliary flank face, the result may get better which is yet to be investigated.

ii. The pressure and flow rate we selected are 70 bars and 6 liters/minute respectively. These two parameters can be changed and its effects can be further analyzed to find the optimum result.

iii. In measuring chip-tool interface temperature, we considered the average values only. The peak values are yet to be tested to uncover the temperature distribution in the chip-tool contact length.

iv. Another area that needs significant attention is tool design. All testing presented in this research work used identical tool geometry, although it is not expected that this geometry is optimal for any or all cases. Previous works have shown that tool geometry affects nearly everything about the process: tool wear and failure, cutting force behavior, surface roughness, residual stresses and white layer generation. Both experimental and modeling work should be used to identify the best tool geometry and edge preparation for different materials, cutting conditions and applications.

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