EFFECT OF HIGH PRESSURE COOLANT JET ON TEMPERTURE, CHIP AND CUTTING FORCES IN TURNING STAINLESS STEEL BY COATED CARBIDE INSERT

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Submitted to the Department of Industrial & Production Engineering, Bangladesh University of Engineering & Technology, Dhaka, in partial fulfillment of the requirements for the degree of Master of Engineering Industrial and Production Engineering

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The thesis titled "Effect of high pressure coolant jet on temperature, chip and cutting forces in turning stainless steel by coated carbide insert" submitted by Mohammad Shah Alam, Roll No: 100508015F, Session October 2005 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **MASTER OF ENGINEERING IN INDUSTRIAL & PRODUCTION ENGINEERING** on 20 February 2008

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Declaration

I do hereby declare that this 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 except for publication.

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Acknowledgements

The author is deeply indebted to his project supervisor Dr. Nikhil Ranjan Dhar, Professor of the Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka for his continuous help and encouragement throughout the progress of the project work.

The author is highly thankful to Md. Kamruzzaman, PhD student, IPE department, BUET, Dhaka.

The author is deeply indebted to his parents for providing mental strength to continue study smoothly.

Author is also grateful to all the teachers and employees of the department of Industrial and Production Engineering, BUET, Dhaka. Special thanks also go to all the staffs of machine shop of BUET for their help in conducting the experimental work.

20 February 2008

Author

Abstract

High production machining, inherently generates large amount of heat leads to high cutting zone temperature for its higher cutting velocity, feed and depth of cut. Such high cutting temperature if not reduced impairs surface integrity of the product and reduce dimensional accuracy as well as tool life. Conventional cutting fluid can not maintain this situation properly. Though in lower velocity a small amount of fluid enter in to the interface for its capillary action but in higher velocity it is not evident. As cutting fluid can not reach into the chip-tool and work-tool interface due to low pressure and low boiling temperature, it cannot effectively lubricate and cool the tool and job. Low boiling temperature cause vaporization of cutting fluid and prevent it to enter into cutting interface making a barrier to flow. High-pressure coolant (HPC) jet is an effective alternative to reduce temperature and tool wear. HPC jet applied diagonally to the inserts cutting edge removes heat and reduce tool wear and also provide better lubrication in the tool tip and cutting interface.

Keeping these in view, objective of the present work is to make an experimental investigation on the role of high pressure cooling jet in turning stainless steel.

Contents

List of Figures

List of Tables

Chapter-1

Introduction

1.1 Introduction

Machining is the process in which a tool removes material from the surface of a less resistant body, through relative movement and application of force. The material removed, called chip, slides on the face of tool, known as tool rake face, submitting it to high normal and shear stresses and, moreover, to a high coefficient of friction during chip formation . Most of the mechanical energy used to form the chip becomes heat, which generates high temperatures in the cutting region. Due to the fact that the higher the tool temperature, the faster it wears, the use of cutting fluids in machining processes has, as its main goal, the reduction of the cutting zone temperature, either through lubrication reducing friction wear, or through cooling by conduction. or through a combination of these functions.

In fact, high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product. High-speed machining for a given material can be defined as that speed above which shear –localization develops completely in the primary shear zone, a huge amount of heat generates at the chief tool interface, which lead a very high cutting temperature. Currently, this problem is tried to be controlled by reducing heat generation and removing heat from the cutting zone through optimum selection of machining parameters, proper cutting fluid selection and application. Some recent techniques have enabled partial control of the machining temperature by using heat resistant tools like coated carbides, CBN etc .However ,CBN tools are very expensive and the practice in the industry are still not wide spread .

Moreover, possibility of controlling high cutting temperature in high production machining by some alternative methods has been reported .Cutting forces and temperature were found to reduce while machining steel with terminologically modified carbide inserts. Cryogenic machining with liquid nitrogen and machining with minimum quantity lubrication has improved machinability of steel to a certain extent under normal cutting conditions .It has also been reported that the machining of steel liquid nitrogen improves the mach -inability index but cryogenic machining is costly due to high cost of Cryogenic.

In present, due to technological innovations, machining without cutting fluid, i.e. dry cutting, is already possible, in some situations. During dry cutting operations, the friction and adhesion between chip and tool tend to be higher, which causes higher temperatures, higher wear rates and, consequently, shorter tool lives. Therefore, the permissible feed and depth of cut have to be restricted. Up to this moment. completely dry cutting is not suitable for many machining processes since cutting fluid is necessary to prevent the chips from sticking to the tool and causing its breakage. Though injection of conventional coolant in a form of mist (MQL) improves machinablity index to some extent, it cannot remove the problems associated with the conventional cutting fluid.

Besides, technological evolution has provided some options for the use of cutting fluids in machining processes. Tool material properties have been improved and new tool materials have been developed in order to avoid or minimize the use of cutting fluids. Therefore, properties such as resistance against abrasion and diffusion, hot hardness and ductility have been greatly improved with the new tool materials. Tool coatings have provided high hardness, low friction coefficient and chemical and thermal stability to the tool. Tool geometries have been optimized to better break chips and also to produce lower surface roughness values in the work piece. New concepts of machine tool design have allowed machining speeds to become faster, and increased rigidity enables more severe cutting operations to be used.

The concept of high pressure coolant presents itself as a possible solution for high speed machining in achieving slow tool wear while maintaining cutting force /power as responsible levels, if the high pressure cooling parameters can be strategically tuned. Coolant applied at the cutting zone through a high pressure jet nozzle could reduce the contract length and coefficient of friction at chip-tool interface and thus could reduce cutting force and improve tool life to some extent. High –pressure coolant injection technique not only provide reduction of cutting force and temperature but also reduce the consumption of cutting fluid by 50% .It has been reported that the coolant and lubrication is improved in high speed machining of difficult –to-machine materials by the use of high pressurized coolant /lubricant jet .

The success of implementing this technology across the metal removal industries will, therefore depend on increased research activities provides the credible data for in depth understanding of high pressure coolant supplies at the tool-chip interface and integrity of machine components. The view of the literature suggests that high pressure cooling provides several benefits in machining.

Chapter-2

Literature Review

2.1 Introduction

Until now, abundant research and investigations have been done in different parts of the world on machinability of different materials mainly in respect of chip morphology, cutting forces, cutting temperature, chip tool interaction, dimensional accuracy, surface integrity and wear and life of cutting tool with and without (dry machining) using cutting fluid. Research has also been initiated on control of such pollution by HPC machining and their technological effects particularly in temperature intensive machining. A brief review of some of the interesting and important contributions in the closely related areas is presented in this section.

2.2 Literature Review

The manufacture of a product had been attempted to be done as rapidly and inexpensively as possible. Now that more environmental regulations are being put in place, manufacturers are forced to re-evaluate their manufacturing processes and reduce or eliminate their waste streams. The waste streams present in machining include cutting fluid flow, chip flow, and cutting tool usage. The machining temperature could 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 **[Muraka 1979; Dieter 1981 and Jawahir 1988]**. Some recent techniques have enabled partial control of the machining temperature by using heat resistance tools like coated carbides, CBN etc. The thermal deterioration of the cutting tools can be reduced **[Narutaki** and **Yamane 1979]** by using CBN tools. If properly manufactured, selected and used, CBN tool provides much less cutting forces, temperature and hence less tensile residual stresses **[Davies et al. 1996]**. But CBN tools are very expensive.

Kosa et al [1989] 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.

Vleugels et al. [1995] 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. Maximum temperature is found to develop on the rake face of the tool. at a certain distance from the cutting edge, where catering occurs. The amount of energy dissipated through the rake face of the tool also raises the temperature at the flanks of the tool.

Reed et al. [1983] 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 high cutting temperature also causes mechanical and chemical damage of the finished surface.

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 [**Chattopadhyay and Bhattacharya 1968; Chattopadhyay and Chattopadhyay 1982 and Singh et al. 1997**]. On the other hand such high temperature, if not controlled, impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, micro cracks and subsurface cracks. This problem is further intensified while machining for faster material removal in bulk and finishing very hard, strong and difficult-to-machine materials, which are gradually adverting with vast and rapid developments in the modern areas, like aerospace technology and nuclear science.

The effect of the heat generated at the primary shear zone is less significant for its lesser intensity and distance from the rake surface. But 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 [**Trent 1984**]. 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.

Previous research has been focused on the temperature and its distribution in the cutting zone because it is believed that it has a direct impact on tool life [**Chao and Trigger 1955**]. The primary function of cutting fluids is to reduce this cutting temperature and increase tool life [**Shaw et al. 1951**]. 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 [**Beaubien 1964**]. 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 [**Heginbotham and Gogia 1961**].

Usually the high cutting temperature is maintained by profuse cooling [**Alaxender et al. 1998; Kurimoto and Barroe 1982 and Wrethin et al. 1992**]. 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 for precision machining, the control of machining temperature by more effective and efficient cooling has become extremely essential.

A tribological experiment was attempted [**Farook et al. 1998**] to modify the contact surface of turning inserts by deposition of a soft bearing material by EDM. It was observed that although the modified inserts offer reduced cutting force, their beneficial effect on surface finish is marginal. At higher cutting velocities the brought on layers are fast depleted with cutting time and makes no contribution to wear resistance of the tool, especially at the flanks. It was reported [**Alaxender et al. 1998**] that coolant injection offers better cutting performance in terms of surface finish, tool force and tool wear when compared to flood cooling.

Force modeling in metal cutting is important for thermal analyses, tool life, estimation, chatter, prediction and tool condition monitoring purpose. Significant efforts have been devoted to understanding the force position in metal cutting. Along with a laborious experimental approach, several numerical and analytical approaches have been proposed to model the chip formation force associated cutting forces. There are some problematic areas in the cutting process. Cutting forces can lead to dangerous vibrations and high temperatures in the contact area between the chip and the tool. This causes tool wear and affects the work-piece and chip breaking, in which long chips can obstruct the cutting process and can destroy both the tool and the work-piece. The high cutting forces generated during machining will induce intensive pressure at the cutting edge.

Several mechanisms have been proposed [**Solaja 1958**] to explain grooving wear. Such as (i) development of a work-hardened/abrasive oxide layer on the cut surface (ii) formation of thermal cracks due to steep temperature gradient (iii) presence of side-spread material at the edges of a newly cut surface and (iv) fatigue of tool material due to cutting force fluctuations at the free surface caused by lateral motions of the edges of the chip. Trent [**1983**] 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 then crater wear begins and grooves intensively. The application of cutting fluid may 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 **[Shaw et al. 1951]** that there was more tool wear when cutting with coolant than cutting dry in case of machining AISI 1020 and AISI 4340 steels by M-2 high speed steel tool cutting.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained **[Satoshi et al. 1997]** by such cutting fluid But surface finish did not improve significantly.During machining, the cutting tool generally undergoes **[Trent 1983]** both flank wear and crater wear. 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. 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 **[Nedess and Hintze 1989]**.

Generally, suitable cutting fluid is employed to reduce this problem through cooling and lubrication at the cutting zone. But it has been experienced **[Cassin and Boothroyed 1965]** 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. The ineffectiveness of lubrication of the cutting fluid at high speed machining is attributed **[Shaw et al. 1951]** to the inability of the cutting fluid to reach the actual cutting zone and particularly at the chip-tool interface due to plastic contact at high cutting speed.

The cooling and lubricating effects by cutting fluid **[Merchant 1958** and **Kitagawa et al. 1997]** influence each other and diminish with increase in cutting velocity. 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. Mazurkiewicz [1989] 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.A cutting fluid may impart two more actions, namely the mechanical strength reducing action and the electro-chemical action. The mechanical strength reducing action (known as the Rebinder effect) seemed to be negligible when steel jobs are machined at moderate cutting speeds with carbide tools [**Kurimoto** and **Barroe 1982**].

A recent development [**Chandrasekaran et al. 1998**] in this context is the use of CO_2 snow as the coolant in machining. 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). Earlier investigations [**Thoors** and **Chandrasekaran 1994**] observed that CO_2 snow could function as a good cutting fluid/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.

The temperatures generated by the cutting speeds of today's advanced tooling can actually prevent low-pressure flood coolant from entering the cutting zone. The majority of the cooling and lubricating aspects of a flood coolant stream are lost as the coolant is vaporized prior to entering the cutting zone [**Frederick Mason 2001**]. It is the great problem for machining, HPC play well role to minimize this type of problem. Frederick Mason [**2001**] found better solution from it and he states that HPC systems generate high velocity coolant streams moving at several hundred mph. This high-speed coolant easily penetrates the vapor barrier to effectively lubricate and cool the tool. In fact, when machinists apply high-pressure coolant to a long standing process, which has always produced blue chips, they are often amazed that the same or even higher speeds and feeds produce shiny, silver chips that are cool to the touch. Cutting fluids have the dual tasks of cooling the cutting surface and flashing chip. In some operations such as turning, for example, cutting fluid is important to remove the chips from work-piece. [**Klocke 1997 and Derflinger 1999**]. They also help to control cutting-face temperature and this can prolong tool life, improve cut quality, and positively influence part finish. It has the benefit of a power full stream that can reach onto the cutting area, provides strong chip removal and in some cases enough pressure to deburr [**Robert 2004**].

Possibility of controlling high cutting temperature in high production machining by some alternative method has been reported. High-pressure coolant injection technique provided reduction in cutting forces and temperature [**Robert 2004**]. Mazurkiewicz et al. [**1998**] 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.

High–pressure jet of conventional coolant has been reported to provide some reduction in cutting temperature [**Robert 2004**]. High-pressure coolant can often cut cycle times in half or better and improve surface finish and double or quadruple tool life while delivering a reduction in cycle time [**Frederick Mason 2001**].The idea of delivering coolant under high pressure to the cutting region in order to increase tool life during machining began in early 1950s [**Pigott and Colwel 1952**]. The primary objective of this machining technique is to significantly reduce the temperature generated at the tool and work-piece and tool-chip interfaces when cutting at higher speed conditions. This is achieved by directing coolant under high pressure at the chip-tool interface.

This process can also achieve high chip breakability and control through increased chip up curl and compressive stress [**Ezugwu 2004**]. Ezugwu [**2004**] stated that ability to deliver coolant at high pressure very close to the critical point on the secondary shear zone can improve machinability at higher speed conditions. The credibility of this technique of coolant delivery has been thoroughly investigated over the years. The high speed coolant jet traverses the surface faster, thus significantly lowering the film boiling action of the coolant at the cutting area. This consequently minimizes heat transfer to the cutting tool. The high-pressure coolant jet creates a hydraulic wedge between the tool and the work piece, penetrating the interface with a speed exceeding that required even for high speed machining and also alters the chip flow conditions [**Mazurkiewicz 1989**]. The penetration of the high energy jet into the tool-chip interface reduces the temperature gradient and eliminates the seizure effect, offering an adequate lubrication at the tool-chip interface with a significant reduction in friction [**Ezugwu 2004**].

High-pressure coolant also provides lubricity by blasting lubricating fluid between the chip and the cutting edge at hundreds of miles per hour. Combined with much lower temperature. this increased lubricity often causes surface finishes to be twice as good. With conventional coolant, the cutting edge comes up to a very high temperature as it enters the cut, and stays hot until it finishes the cut and is exposed to an extreme thermal shock as the coolant quenches the exposed tool.

2.3 Summary of Literature Review

High-pressure coolants always provide a much better surface finish than dry cut. Chips produced by dry cutting are long spiral, turn and half turn type where as for coolants; most of the chips are spiral Under dry cut, the chip is tightly curled and its radius of curvature is relatively smaller than that produced when using the coolant. This is because chips in dry cutting are subjected to intense heat, resulting in more plastic deformation than those obtained by coolant. The serration of chips with the application of high-pressure coolant is wider and larger than those using conventional coolant.

The hydraulic wedge created as the result of high-pressure coolant, forms a cushion at the tool–chip interface that reduces tool–chip contact length. This accelerates chip breakage and improves surface finish and tool life. The chips obtained in the case of high-pressure coolant jet cooling are much smaller than those obtained under similar cutting conditions in the case of dry cooling. The temperature is significantly reduced by administering coolant under high pressures directly to the cutting interface. This could therefore, minimize thermally related wear mechanisms.

Chapter-3

Objectives

3.1 Introduction

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, harden ability and lesser thermal conductivity. Cutting fluids are widely used to reduce the cutting temperature. In this regard, it has already been observed through previous research that proper application of HPC 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 HPC system needs to be properly designed considering the following important factors: (i) effective cooling by enabling HPC jet reach as close to the actual hot zones as possible.(ii) avoidance of bulk cooling of the tool and the job, which may cause unfavourable metallurgical changes.(iii) minimum consumption of cutting fluid by pin-pointed impingement and only during chip formation

3.2 Objectives

The objective of this project is to evaluate the effectiveness of high pressure coolant in improving the cutting parameters on work materials of stainless steel of different cutting velocity and feed rates. The performance of high-pressure coolant investigated by focusing on the effects of high pressure coolant on the machinability characteristics of stainless steel at different cutting velocities and feeds in terms of

- chip morphology i.e. chip shape, chip color and chip reduction coefficient.
- cutting forces i.e. main cutting force and feed force.
- average chip–tool interface temperature and work tool temperature

Chapter-4

Experimental Investigation

4.1 Introduction

A lot of heat is created during high speed machining. Low pressure cutting fluid of flood cooling is vaporized due to high temperature when it comes in contact with the tool-chip-work, makes a barrier (film), for this no cutting fluid reach in the tool-chip interface or cutting zone [**Ezugwu 2004**].The film boiling temperatures of conventional cutting fluids is about 350°C [**Ezugwu** and **Bonney 2003**]. But in HPC machining coolant is supplied with high pressure (min 40 bars). Due to high pressure coolant reach sufficiently in to the tool-chip interface and break down the vapor barrier and easily enter into the cutting zone.

4.2 HPC Delivery System

HPC set up contains motors, vena pump, flow control valve, regulating composite device and filter is shown in Fig.4.1. These devices are mounted at the top of a tank that is made of mild steel sheets and angle bars. This tank contains the cutting oil that is used as a coolant. And the capacity of the coolant tank is 200 litters. A coolant indicator is mounted beside the wall of coolant tank; it is used to know the quantity of coolant present in the tank during machining. A 5 hp motor is used to operate the vena pump. A gear coupling is used between the vena pump and motor to transmit power. This pump pressurized the coolant to pass through the flow control. Flow control valve controls the amount of flow.

The flow control valve is turned to minimize and maximize flow during machining. A relief valve has mounted with the flow control regulating composite. Relief valve control the pressure and discharge excess oil to the tank. A pressure gauge is also mounted to observe the pressure of coolant. A direction control valve is used for changing the direction of supply. A perfect nozzle is used to supply high pressure coolant towards the cutting zone. From the nozzle pressurized fluid impinged at the chip-tool interface and reduces the cutting temperature. A recycling pump and a filter are used to recycle the used coolant.

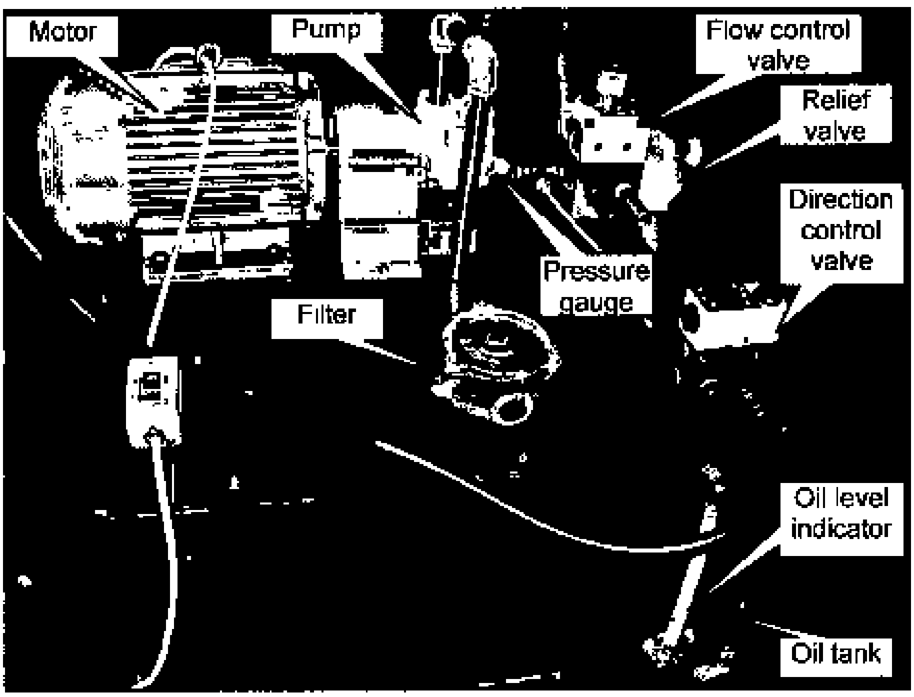
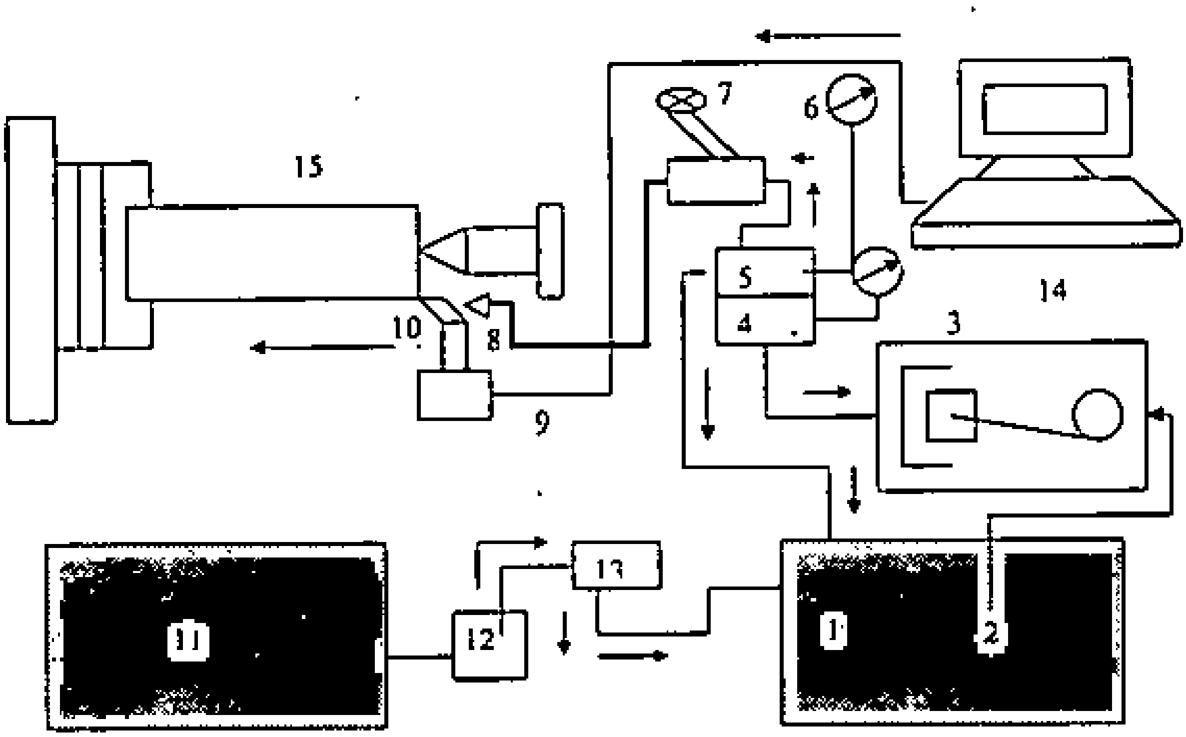


Fig.4.1 Photographic view of high-pressure coolant delivery system



1.Coolant Tank	6.Pressure Gauge	11. Coolant Tank
2.Floot Valve	7.Direct Control Valve	12.Supply Pump
3.High Pressure Pump	8.Nozzel	13.Filter
4. Flow Control Valve	9. Dynamometer	14.Computer
5. Relieve Valve	10. Machine Tool	15.Work-piece

Fig.4.2 Schematics diagram of experimental set-up.

4.3 Experimental Results

The machining trials were carried out by turning a austenitic stainless steel (o 140 mm × 600 mm) rod in a powerful and rigid lathe (10 HP) at different cutting velocities (Vc) and feed (S_o) under dry and high-pressure coolant condition. The high pressure coolant was supplied at an average flow rate of 6.0 l/min and pressure of 60 bars and directed via a nozzle on the tool holder to the region where the chip breaks contact with the tool. The photographic view and schematic diagram of the experimental setup are shown in Fig .4.1 and Fig.4.2. Coated carbide insert (TiCN + Al_2O_3) with ISO tool designations

SNMG and SNMM 120408 was used for the machining trials. The following cutting conditions and environments were employed in this investigation:

Table-1: Excremental conditions

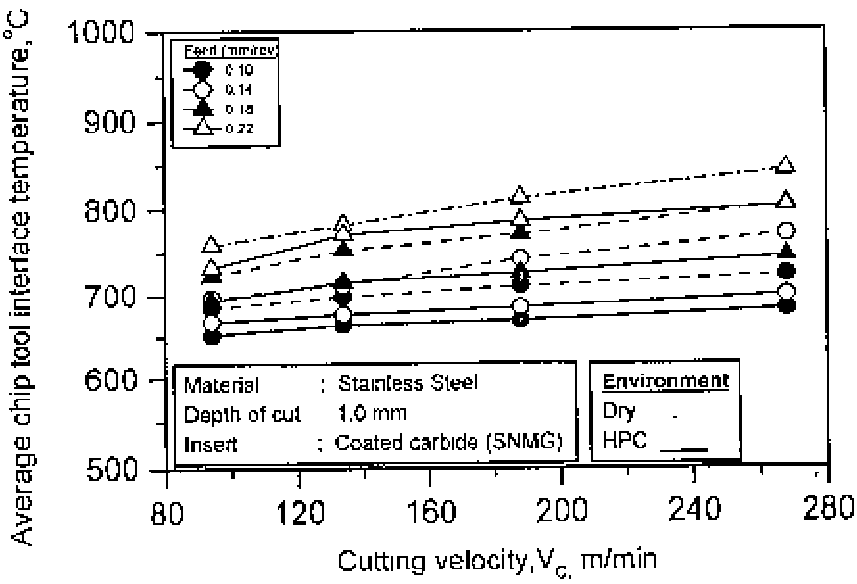
Machine	:	Lathe machine (10 hp), China
Material	:	Stainless steel.
Size	:	ø 140 mm × 600 mm
Insert	:	Coated carbide insert (SNMG and SNMM)
Process parameter	:	
Cutting velocity, V_c	:	94, 134, 188 and 268 m/min
Feed rate, S_o	:	0.10, 0.14, 0.18, 0.22 mm/rev.
Depth of cut, t	:	1.0 mm
Coolant supply pressure	:	60 bar
Coolant flow rate	:	6.0 liter/min
Cutting environment	:	High pressure coolant and dry condition

The average cutting temperature was measured under all cutting conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. The machining chips were collected during all the treatments for studying their nature of interaction with the cutting insert at its rake surface. The roughness of the machined surface after each cut was measured by a Talysurf (Sutronic 3^+, Rank Tylor Hobson limited).

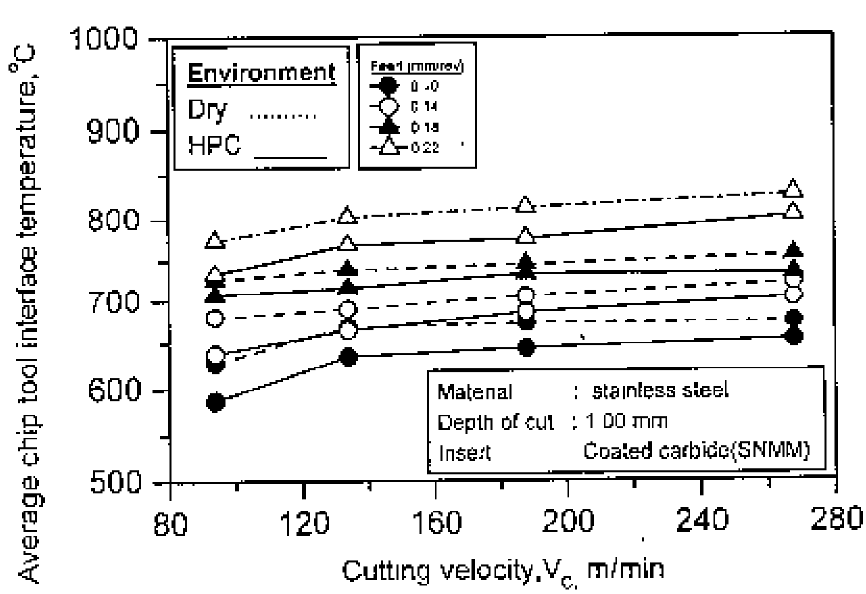
4.3.1 Cutting Temperature

During machining any ductile materials. heat is generated at the (i) primary deformation zone due to shear and plastic deformation (ii) chip-tool interface due to secondary deformation and sliding (iii) work-tool interfaces due to rubbing. All such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. Therefore, attempts are made to reduce this detrimental cutting temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface where the temperature is high. This is mainly because the flowing chips make mainly plastic contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Plastic contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V_c when the chip-tool contact becomes almost fully plastic.

In the present work, the average chip-tool interface temperature could be effectively measured under dry and HPC condition very reliably throughout the experimental domain. However, the distribution of temperature within the tool, work and chip cannot be determined effectively using experimental techniques. The evaluated role of HPC on average chip-tool interface temperature in turning the steel by the coated carbide SNMG and SNMM insert at different V_c and S_o under dry and HPC conditions has been shown in Fig 4.3.



(a) SNMG insert



(b) SNMM insert

Fig. 4.3 Variation of temperature with different cutting velocity, V_c and feed rates, S_o under **Dry** and **HPC** environment in turning stainless steel by coated (a) **SNMG** (b) **SNMM** insert.

4.3.2 Machining Chips

The form, color and thickness of the chips also 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 work-tool and V_c-S_o combinations under dry and HPC conditions. The form and color of all those chips were noted down (Table-2 & Table-3). Thickness of the chips was repeatedly measured by a slide caliper to determine the value of chip reduction coefficient, ζ (ratio of chip thickness after and before cut), which is an important index of machinability. The chip samples collected while turning the steel by the insert of configuration SNMG and SNMM insert at different V_c-S_o combinations under dry and HPC conditions have been visually examined and categorized with respect to their shape and color. The results of such categorization of the chips produced at different conditions and environments by the steel at different feed rates have been shown in Table- 2 and Table- 3. Fig.4.4 to fig.4.11 show the actual shape of the chip produced during turning stainless steel by both SNMM AND SNMG inserts under dry and HPC condition at different Vc, So and t combination.

Table- 2 Comparison of chip shape and colour by different V_c and S_o under **Dry** and **HPC** conditions by coated **SNMM** insert.

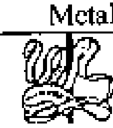
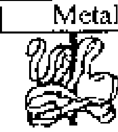
Feed rate, S_o (mm/rev)	V_c (m/min)	Environment			
		Dry		HPC	
		Shape	Colour	Shape	Colour
0.10	94	Spiral	Metallic	Tubular	Metallic
	134	Full Turn	Metallic	Tubular	Metallic
	188	Half Turn	Metallic	Half Turn	Metallic
	268	Full Turn	Metallic	Half Turn	Metallic
0.14	94	Spiral	Metallic	Spiral	Metallic
	134	Spiral	Metallic	Tubular	Metallic
	188	Full Turn	Metallic	Tubular	Metallic
	268	Full Turn	Metallic	Spiral	Metallic
0.18	94	Spiral	Metallic	Spiral	Metallic
	134	Spiral	Metallic	Spiral	Metallic
	188	Spiral	Metallic	Spiral	Metallic
	268	Full Turn	Metallic	Spiral	Metallic
0.22	94	Spiral	Metallic	Spiral	Metallic
	134	Spiral	Metallic	Spiral	Metallic
	188	Spiral	Metallic	Spiral	Metallic
	268	Half Turn	Metallic	Ribbon	Metallic
Chip shape					
Group	Half turn	Tubular/helical	Spiral	Ribbon	

Table -3 Comparison of chip shape and colour by different V_c and S_o under **Dry** and **HPC** conditions by coated **SNMM** insert.

Feed rate, S_o (mm/rev)	V_c (m/min)	Environment			
		Dry		HPC	
		Shape	Colour	Shape	Colour
0.10	94	Spiral	Metallic	Spiral	Metallic
	134	Spiral	Metallic	Full Turn	Metallic
	188	Spiral	Metallic		Metallic
	268	Spiral	Metallic	Full Turn	Metallic
0.14	94	Spiral	Metallic	Full Turn	Metallic
	134	Spiral	Metallic	Full Turn	Metallic
	188	Spiral	Metallic	Full Turn	Metallic
	268	Spiral	Metallic	Full Turn	Metallic
0.18	94	Spiral	Metallic	Full Turn	Metallic
	134	Spiral	Metallic	Full Turn	Metallic
	188	Spiral	Metallic	Half Turn	Metallic
	268	Half Turn	Metallic	Half Turn	Metallic
0.22	94	Half Turn	Metallic	Half Turn	Metallic
	134	Half Turn	Metallic	Half Turn	Metallic
	188	Half Turn	Metallic	Half Turn	Metallic
	268	Full Turn	Metallic	Half Turn	Metallic
Chip shape					
Group	Half turn	Tubular/helical	Spiral	Ribbon	

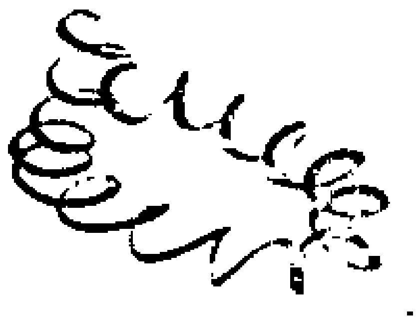
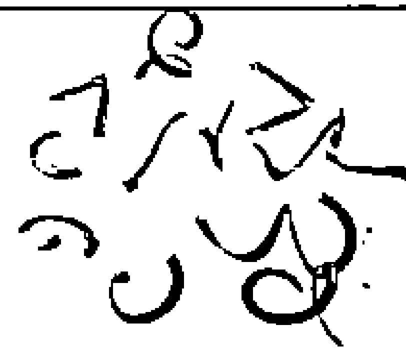
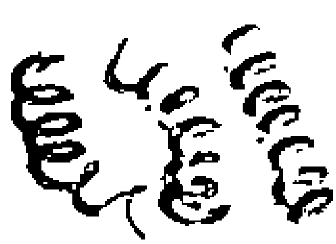
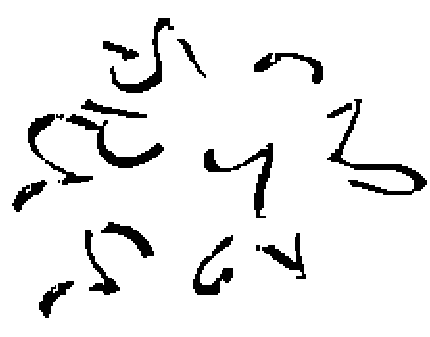
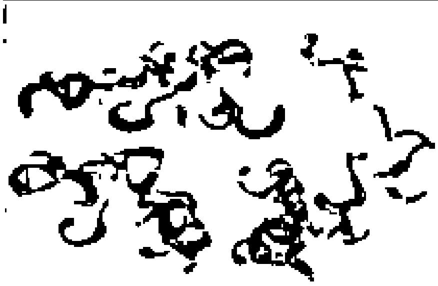
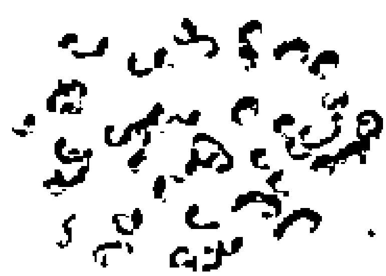
Feed rate, S_o, mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

Fig. 4.4 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 94 m/min and different feeds by coated SNMG insert.

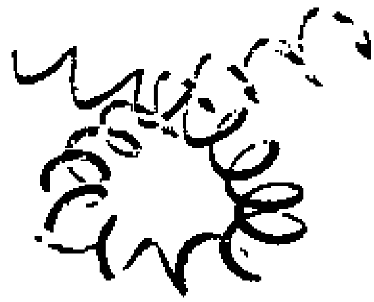
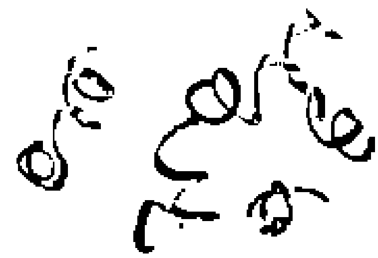
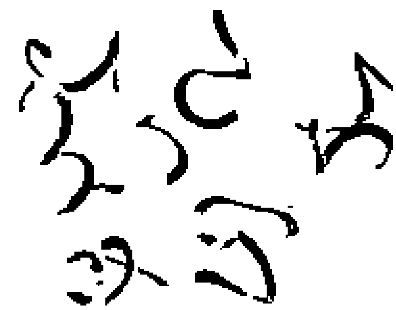
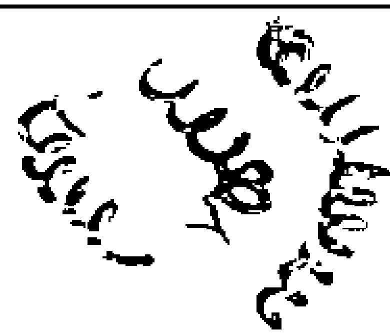
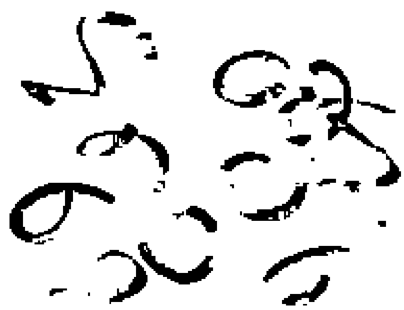
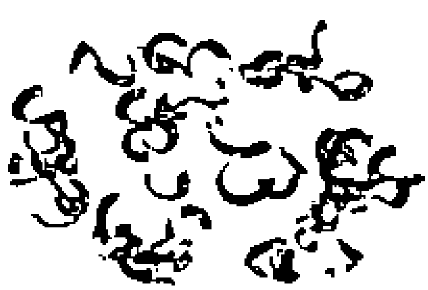
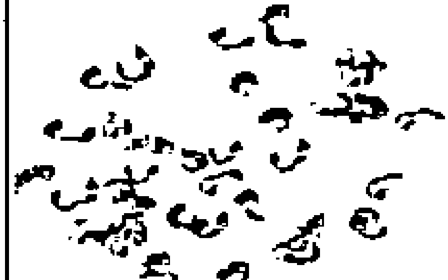
Feed rate, S_o mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

Fig. 4.5 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 134 m/min and different feeds by coated SNMG insert.

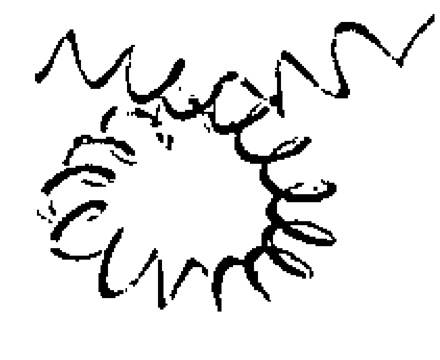
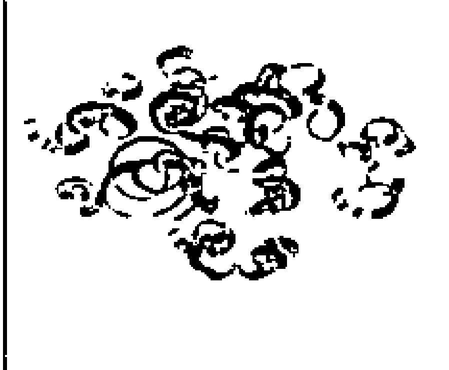
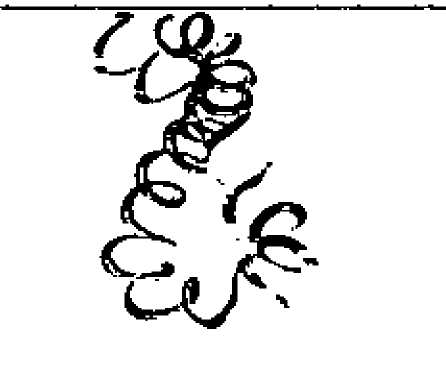
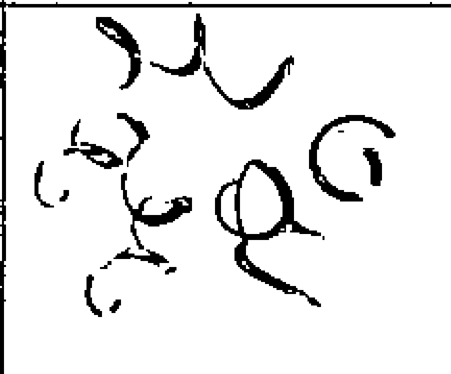
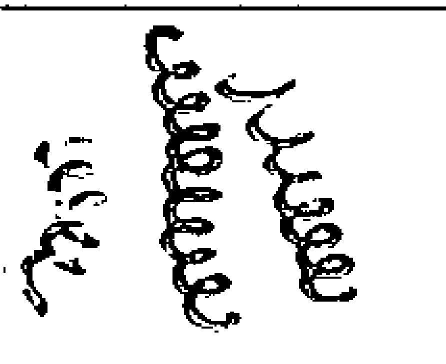
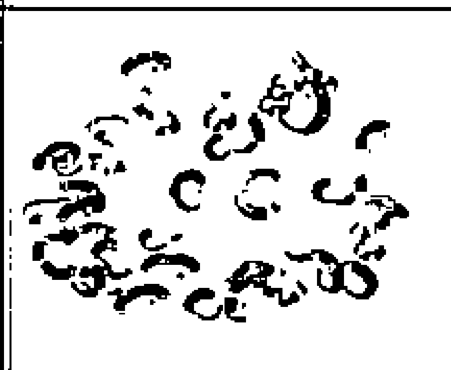
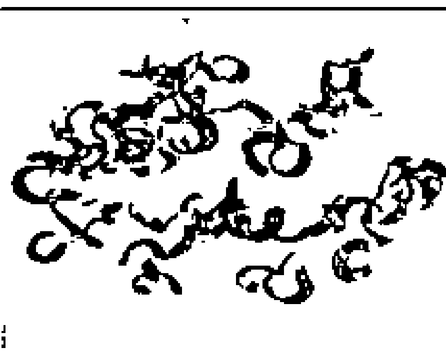
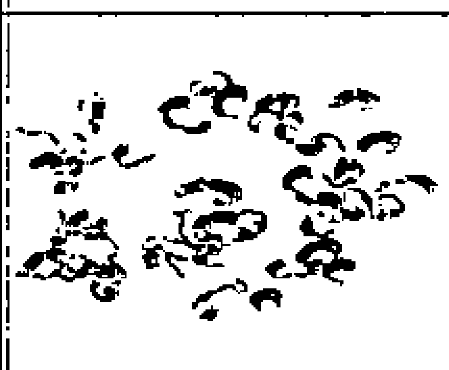
Feed rate, S_o mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

Fig. 4.6 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 188 m/min and different feeds by coated SNMG insert.

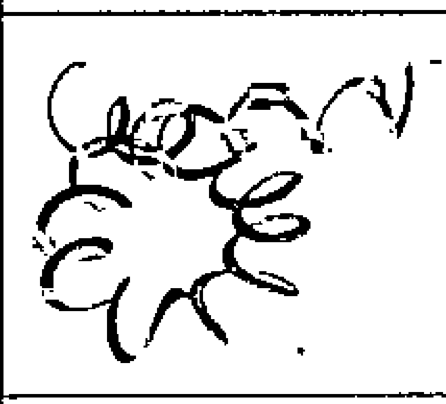
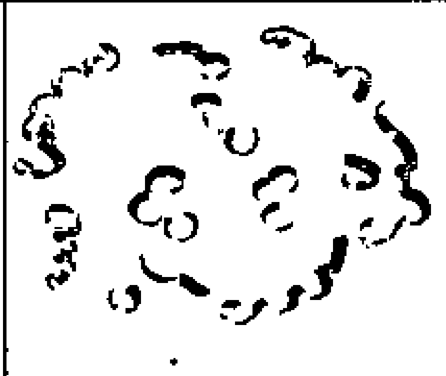
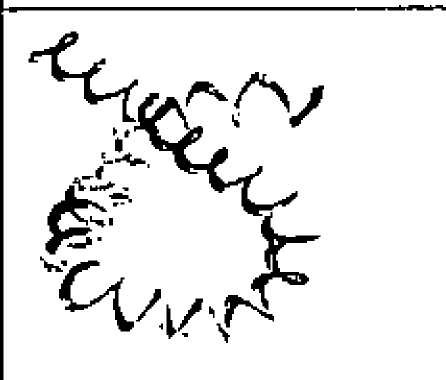
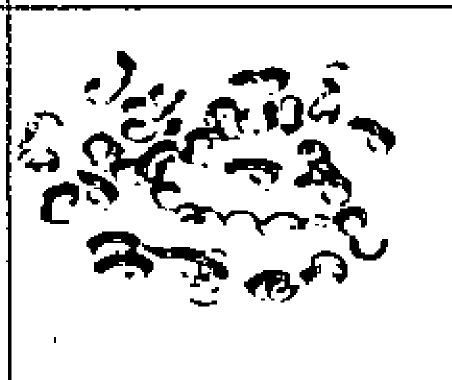
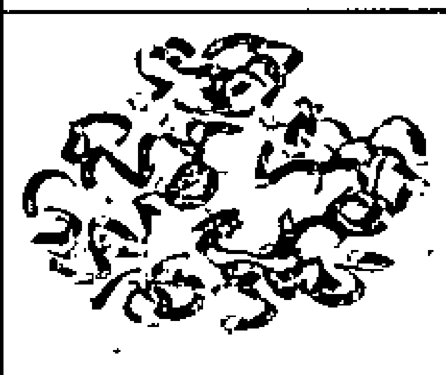
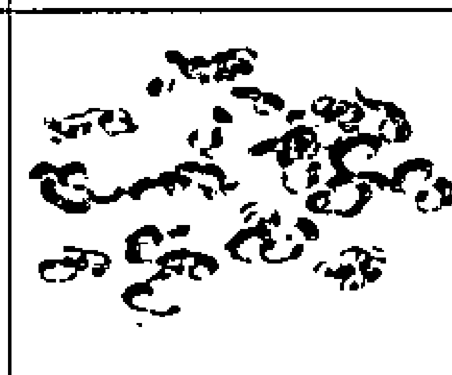
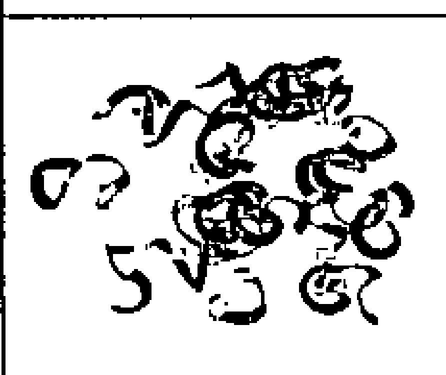
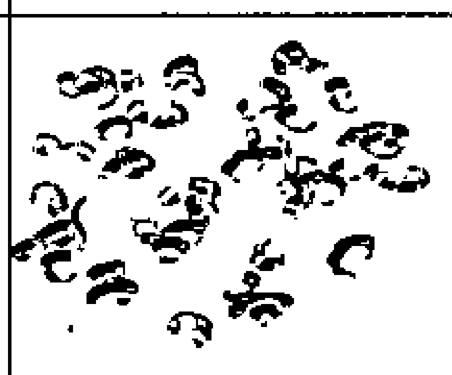
Feed rate, S_o mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

Fig. 4.7 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 268 m/min and different feeds by coated SNMG insert.

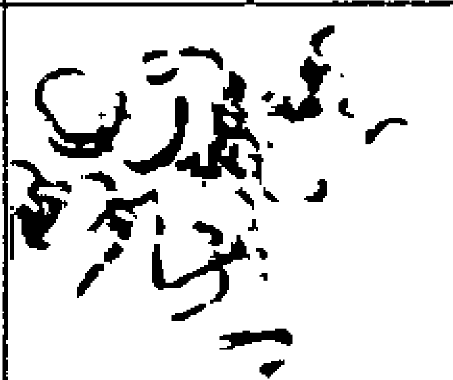
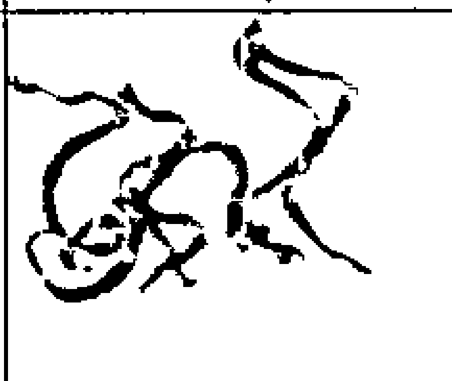
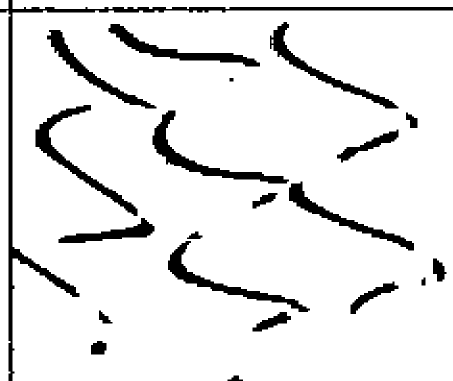
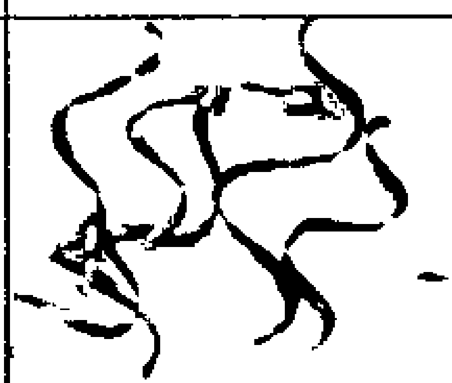
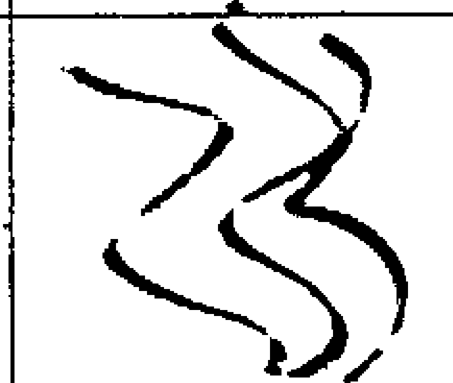
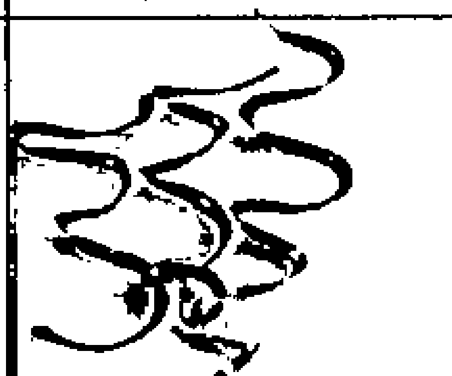
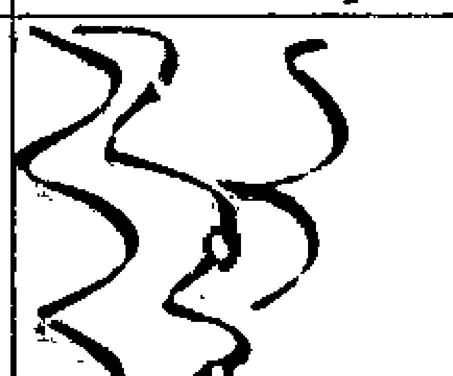
Feed rate, S_o mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

Fig. 4.8 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 94 m/min and different feeds by coated SNMM insert.

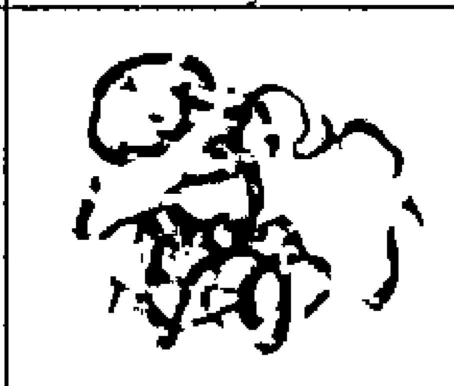
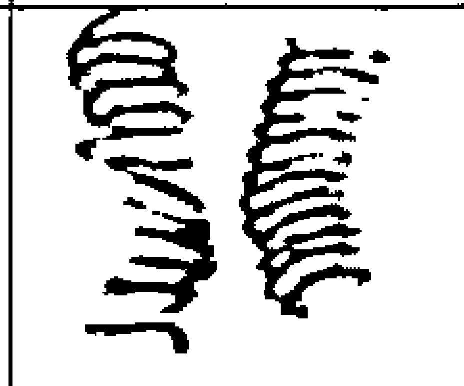
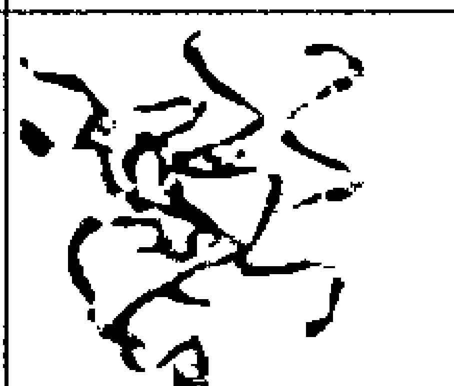
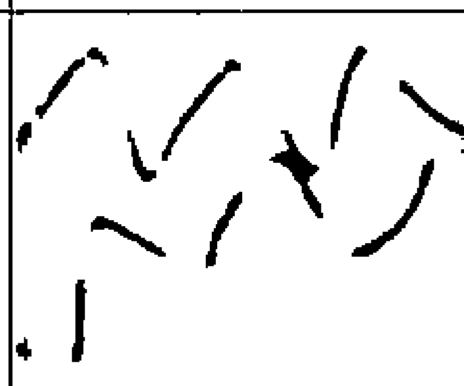
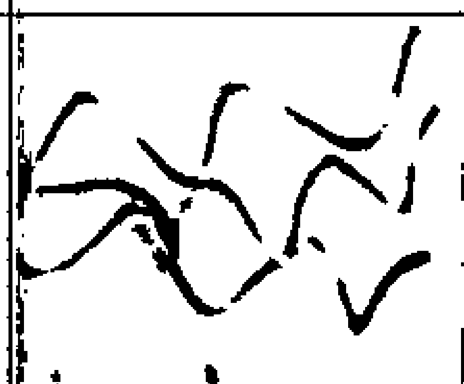
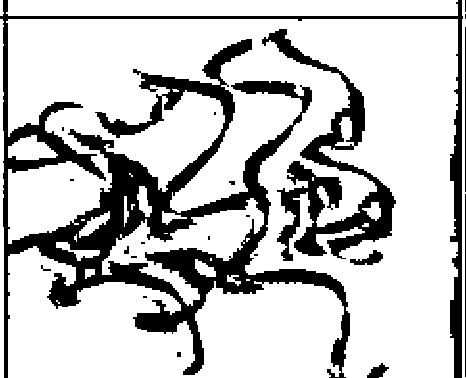
Feed rate, S_o mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

Fig. 4.9 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 134 m/min and different feeds by coated SNMM insert.

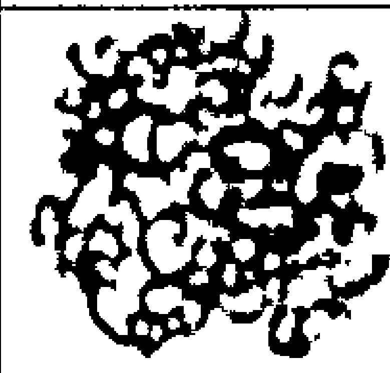
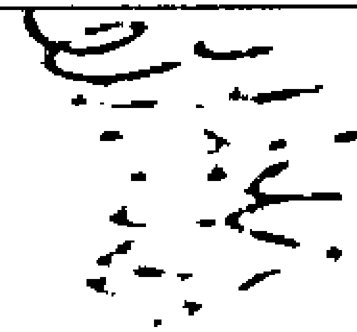
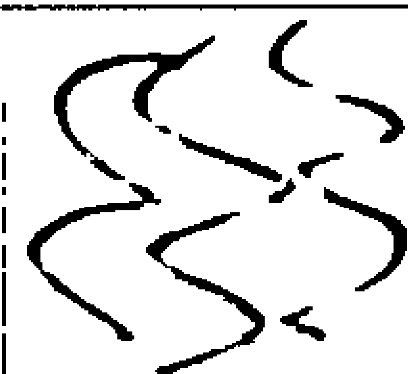
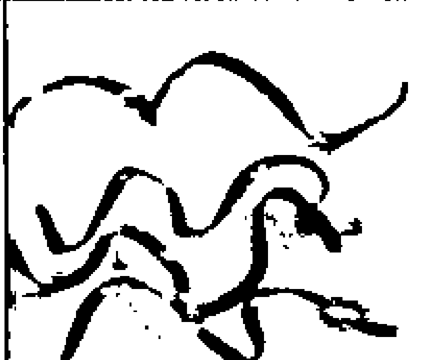
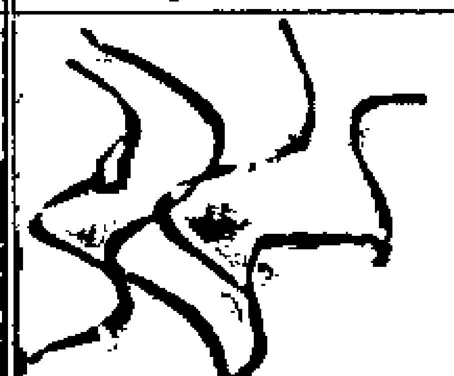
Feed rate, S_o mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

Fig. 4.10 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 188 m/min and different feeds by coated SNMM insert.

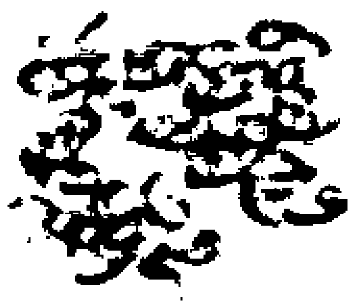
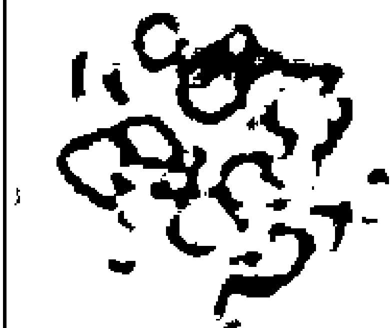
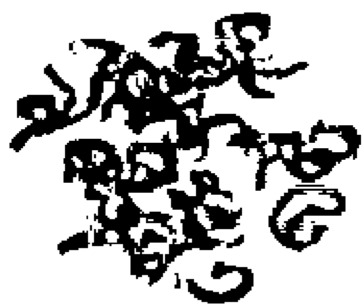
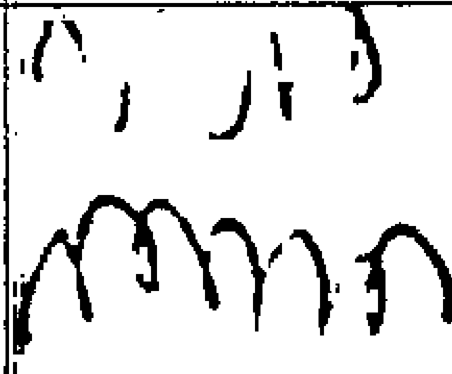
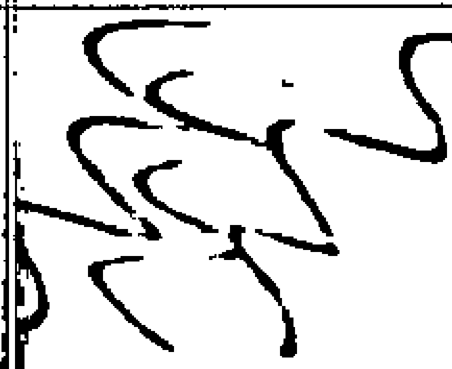
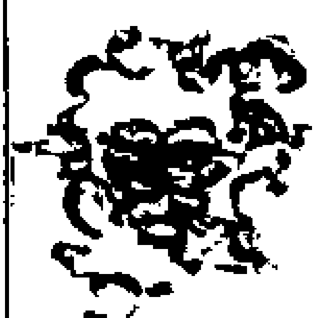
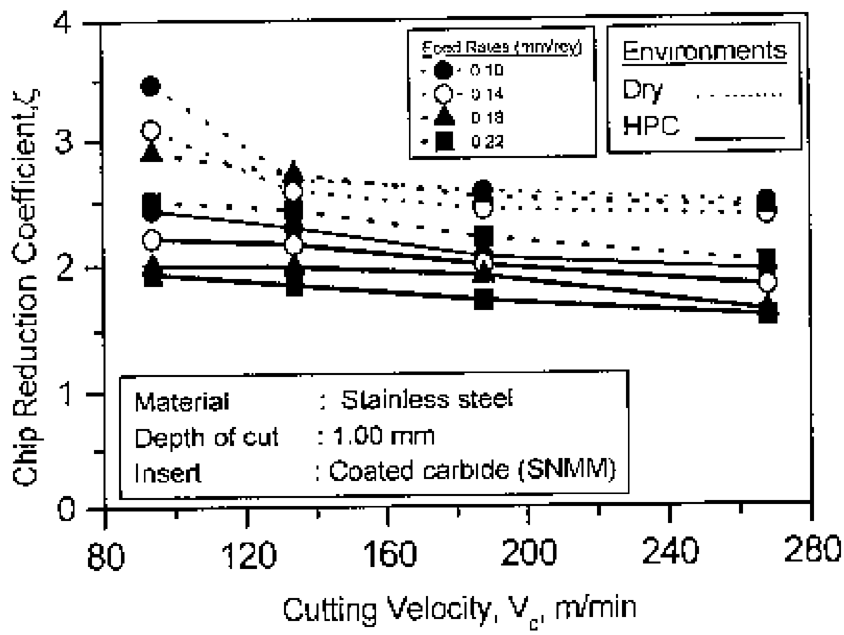
Feed rate, S_o mm/ rev	Environments	
	Dry	HPC
0.10		
0.14		
0.18		
0.22		

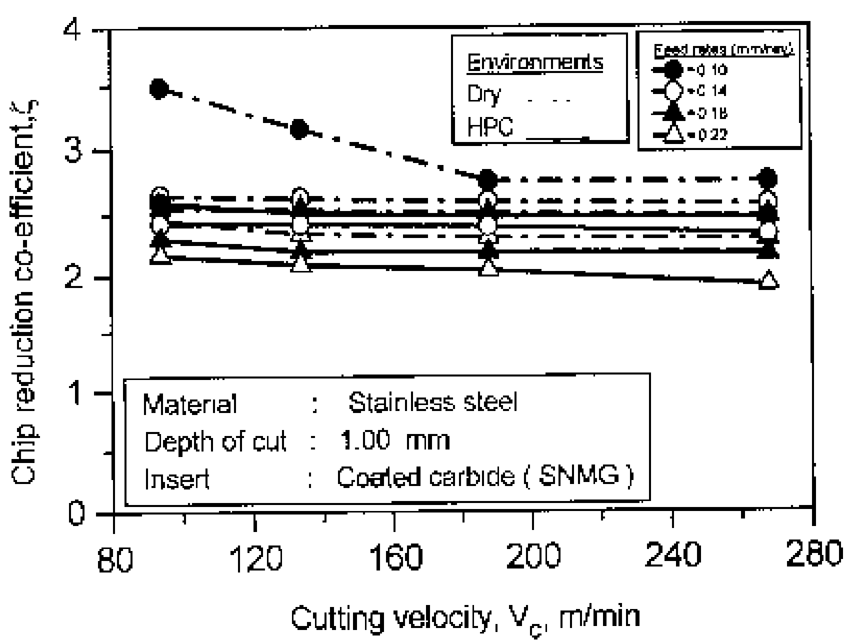
Fig. 4.11 Actual shape and color of chips produced during machining stainless steel under Dry and HPC environment at Vc = 268 m/min and different feeds by coated SNMM insert.

4.3.3 Chip Reduction Coefficient

Another important machinability index is chip reduction coefficient, ζ (ratio of chip thickness after and before cut). For given tool geometry and cutting conditions, the value of chip reduction coefficient, ζ depends upon the nature of chip-tool interaction, chip contact length and chip form all of which are expected to be influenced by liquid nitrogen in addition to the levels of V_c and S_0. The variation in value of chip reduction coefficient, ζ with cutting speed, V_c and feed rates, S_o as well as machining environment evaluated has been plotted and shown in Fig. 4.12.



(a) **SNMM insert**



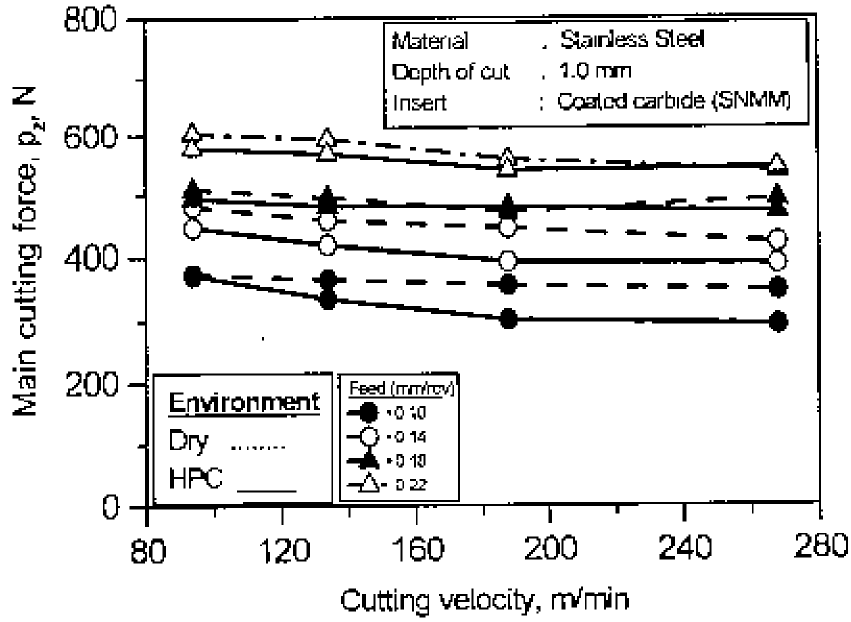
(b) **SNMG insert**

Fig. 4.12 Variation in chip reduction coefficient with different cutting velocity, V_c and feed rates, S_o in turning stainless steel by coated (a) **SNMM** (b) **SNMG** insert under **Dry** & **HPC** environment.

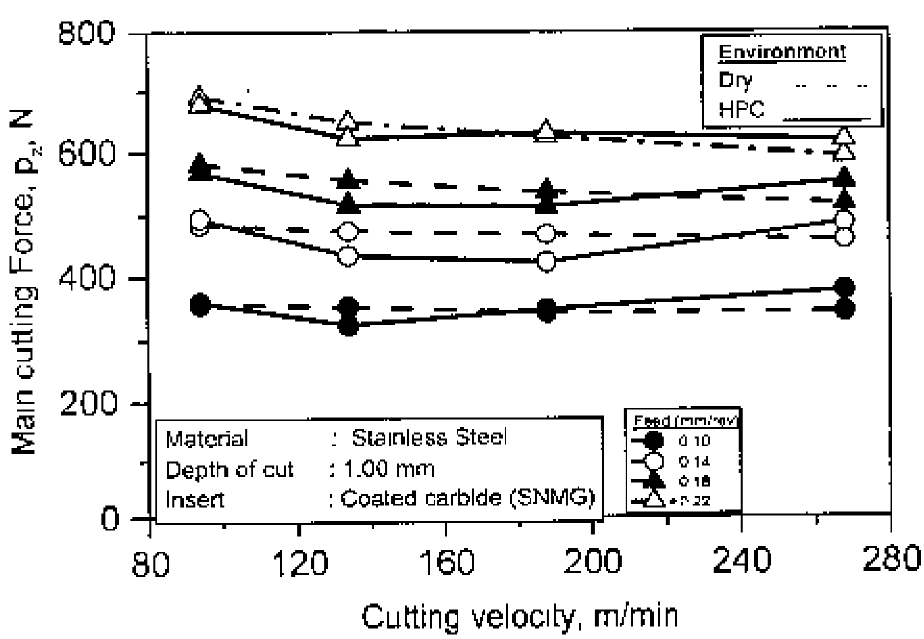
4.3.4 Cutting Forces

Main cutting forces, P_z generated during the machining trials were recorded with the aid of a dynamometer after each complete pass. The signals of the forces generated during machining were fed into a charge amplifier connected to a dynamometer. This amplifier converts the analogue signal to digital signal that can be read on a digital oscilloscope.

Lower cutting forces were recorded with increasing coolant supply pressure when machining austenitic stainless steel with coated carbide inserts SNMG & SNMM. This is because coolant supply at high-pressure is able to access the cutting interface, ensuring effective cooling, lubrication and reducing the cutting interface temperature. The reduction in main cutting forces, P_z observed is also partly due to the chip segmentation when machining with high-pressure coolant supplies (Fig. 4.13, Fig. 4.14).Higher forces were recorded when machining with conventional coolant flow where continuous type chips were generated (Table-2 & Table-3).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. Chip segmentation is considerably enhanced, as the chip curl radius is reduced significantly, due to targeted maximum coolant force on to the chip which aids the chip shearing process and consequently lowering cutting forces. The chip curl radius also depends on the coolant pressure and the flow rate. Therefore at a given power, smaller chip curl radius could be achieved at a lower coolant pressure with a high coolant flow rate .The chips generated when machining with coated carbide tools under both dry and high-pressure coolant supplies are basically small discontinuous full turn type. The chips are of the catastrophic shear localized type with sharp serrated edges. The mechanism for shear localized chip formation involves initially plastic instability and strain localization at a narrow band with a gradual build-up of segments on the shear plane with negligible deformation by upsetting work material by the advancing tool.

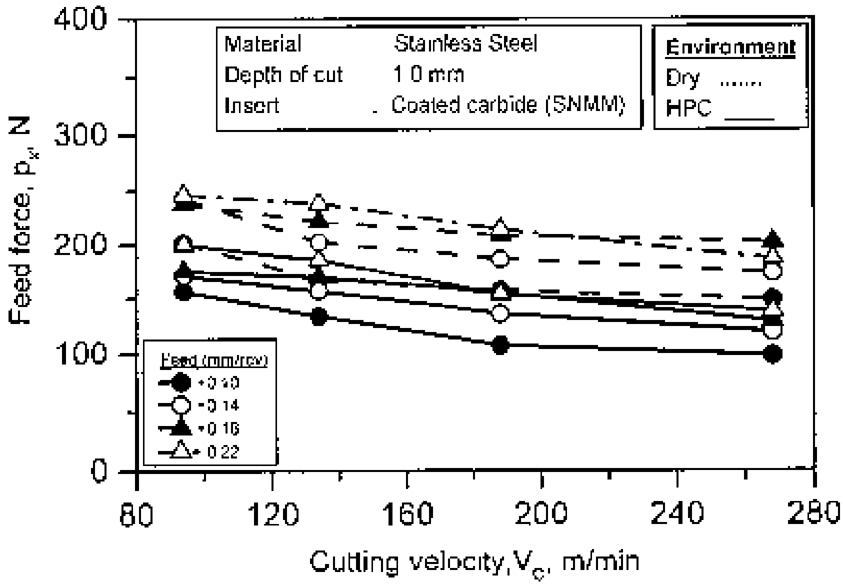


(a) **SNMM insert**

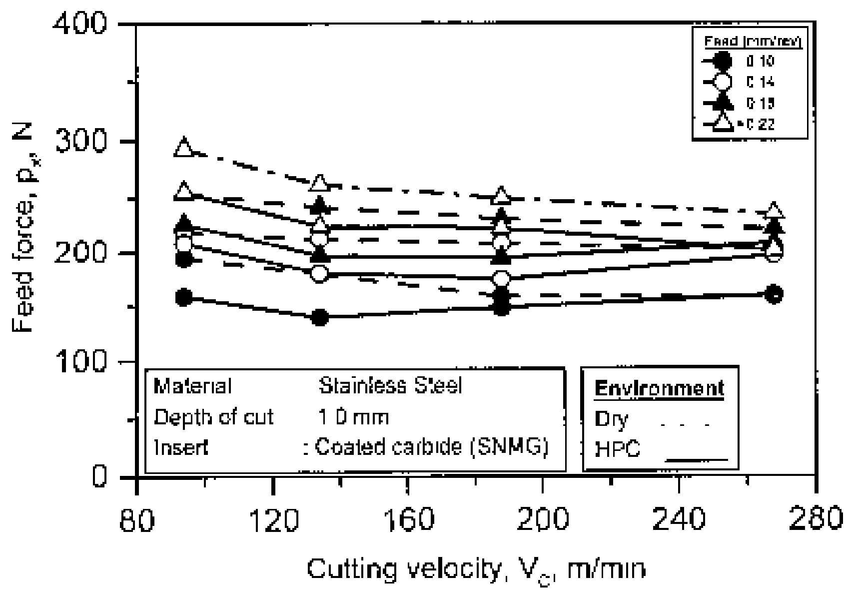


(b) **SNMG insert**

Fig. 4.13 Variation in main cutting force, P_z with different cutting velocity, V_c and feed rates, S_0 under **Dry** & **HPC** environment in turning stainless steel.



(a) SNMM insert

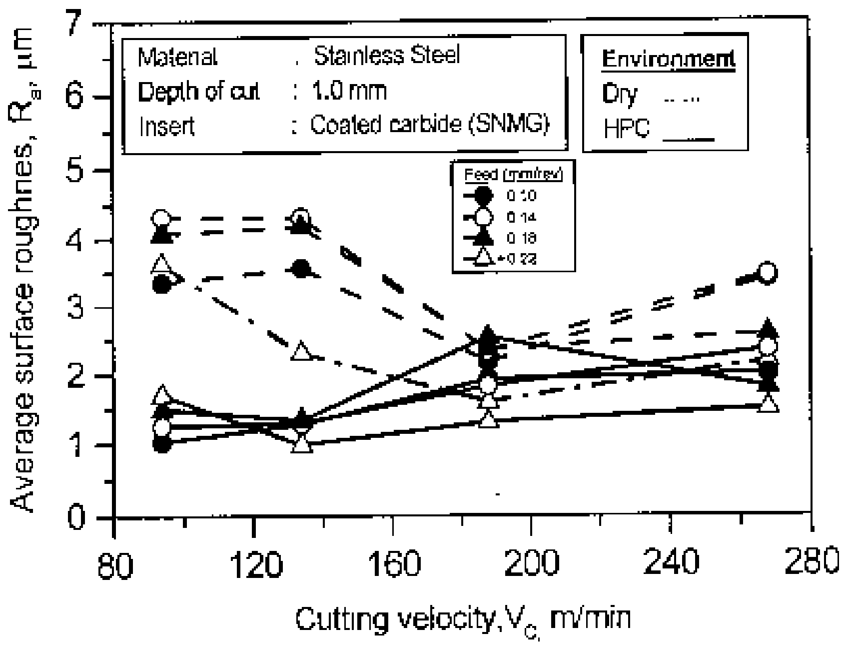


(b) SNMG insert

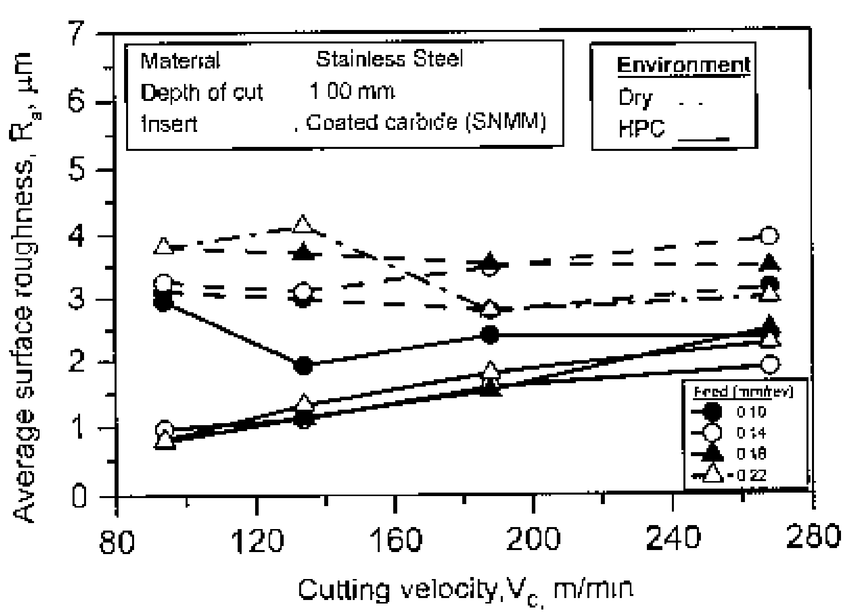
Fig .4.14 Variation in feed force, $\mathbf{P_x}$ with different cutting velocity, Vc and feed rates, S_o under **Dry** & **HPC** environment in turning stainless steel.

4.3.5 Surface Roughness

After machining the stainless steel bar by the coated carbide SNMM and SNMG insert, at different V_c-S_o combinations under dry and HPC conditions. Surface roughness values were recorded after each complete pass with a portable stylus type instrument. The average of three readings represents the surface roughness value of the machined surface. Surface roughness is an important index of machinability, which is substantially influenced by the machining environment for given tool-work pair and speed-feed, V_c-S_o combinations. Surface roughness has been measured after a few seconds of machining with sharp tool while recording the chip-tool interface temperature at various V_c-S_o combinations under dry and HPC conditions are shown in Fig. 4.15.



(a) SNMG insert



(b) SNMM insert

Fig. 4.15 Variation in surface roughness with different cutting velocity, V_c and feed rates, S_0 under **Dry & HPC** environment in turning stainless steel.

Chapter-5

Result and Discussion

5.1 Cutting Temperature

In machining heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. That is why; attempts are made to reduce this detrimental cutting temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly and effectively at the chip-tool interface where the temperature is maximum. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V_c when the chip-tool contact becomes almost fully plastic.

Therefore, application of HPC at chip tool interface is expected to improve upon the aforesaid machinability characteristics that play vital role on productivity, product quality and overall economy in addition to environment-friendliness in machining particularly when the cutting temperature is very high.The average chip-tool interface temperature, T has been determined using the tool work thermocouple technique and plotted against cutting velocity for different feeds and environments undertaken. The Fig. 4.3 and is showing the effect of high pressure coolant (HPC) on average chip-tool interface temperature, T under different cutting velocity, V_c and feed rate, S_0 as compared to dry HPC conditions.

However, it is clear from the aforementioned figures that with the increase in V_c and S_o, average chip-tool interface temperature, T increased as usual, even under HPC condition, due to increase in energy input. The roles of variation of process parameters on percentage reduction of average interface temperature due to HPC have not been uniform. This may be attributed to variation in the chip forms particularly chip-tool contact length, which for a given tool widely vary with the mechanical properties and behaviour of the work material under the cutting conditions. The value of chip-tool contact length affects not only the cutting forces but also the cutting temperature. Post cooling of the chips by HPC jet is also likely to influence temperature, T to some extent depending upon the chip form and thermal conductivity of the work materials.Apparently, more reduction in average chip-tool interface temperature, T is expected by employing HPC but actually it is not so because the HPC could not reach the intimate chip-tool contact zone.

During machining at lower cutting speed. V_c when the chip-tool contact is partially elastic. where the chip leaves the tool, HPC is dragged in that elastic contact zone in small quantity by capillary effect and is likely to enable more effective cooling. With the increase in V_c the chip makes fully plastic contact with the tool rake surface and prevents any fluid from entering into the hot chip-tool interface.

As shown in Fig. 4.3, HPC cooling effect also improved to some extent with the decrease in feed particularly at lower cutting velocity. Possibly, the thinner chips, especially at lower chip velocity, are slightly pushed up by the high pressure Coolant (HPC) jet coming from opposite direction and enable it come closer to the hot chip-tool contact zone to remove heat more effectively.

Further, at high cutting velocity, the coolant may not get enough time to remove the heat accumulated at the cutting zone resulting in less reduction in temperature under HPC condition.With the increase in feed rate, S_0 the chip-tool contact length generally increases but the close curvature of the grooves parallel and close to the cutting edges of the insert has reduced the chip-tool contact length and thus possibly helped in reducing the chip-tool interface temperature further. However, it was observed that the HPC jet in its present way of application enabled reduction of the average cutting temperature by about 5% to 10% depending upon the levels of the process parameters cutting velocity, V_c and feed rates, S_o.

Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

5.2 Chip

The pattern of chips in machining ductile metals are found to depend upon the mechanical properties of the work material, tool geometry particularly rakes angle, levels of V_c and S_o, nature of chip-tool interaction and cutting environment. In absence of chip breaker, length and uniformity of chips increase with the increase in ductility and softness of the work material, tool rake angle and cutting velocity unless the chip-tool interaction is adverse causing intensive friction and built-up edge formation.

Table-2 & Table-3 shows that when stainless steel is machined by the pattern type coated SNMG and SNMM insert under both dry and HPC condition produced spiral type continuous chips at lower feed rates and more or less turn & half turn type discontinuous chips at higher feed rates. When machined with HPC the form of these ductile chips change appreciably and their back surface appeared much brighter and smoother. This indicates that the amount of reduction of temperature and presence of HPC application enabled favourable chip-tool interaction and elimination of even trace of built-up edge formation. The colour of the chips have also become much lighter i.e. metallic or golden (Table-2 & Table-3) depending upon cutting velocity, V_c and feed rates, S_o due to reduction in cutting temperature by High pressure coolant.

Almost all the parameters involved in machining have direct and indirect influence on the thickness of the chips during deformation. The degree of chip thickness ratio plays vital role on cutting forces and hence on cutting energy requirements and cutting temperature.

Fig. 4.12 clearly shows that throughout the present experimental domain the value of chip thickness ratio, ζ gradually decreased with the increase in cutting speed, V_c though in different degree under both dry and HPC by conditions. The value of chip thickness ratio, ζ usually decreases with the increase in cutting speed, V_c particularly at its lower range due to plasticization and shrinkage of the shear zone for reduction in friction and built-up edge formation at the chip-tool interface due to increase in temperature and sliding velocity. In machining steel by coated carbide tool, usually the possibility of built-up edge formation and size and strength of the built-up edge, if formed gradually increase with the increase in temperature due to increase in cutting speed, V_c and also feed rates, S_o and then decrease with the further increase in cutting speed, V_c due to too much softening of the chip material and its removal by high sliding speed.

Fig. 4.12 shows that HPC has reduced the value of chip thickness ratio, ζ particularly at lower values of cutting speed, V_c and feed rates, S_o. By HPC applications, chip thickness ratio, ζ is reasonably expected to decrease for reduction in friction at the chip-tool interface and reduction in deterioration of effective rake angle by built-up edge formation and wear at the cutting edges mainly due to reduction in cutting temperature.

5.3 Cutting Forces

Main cutting forces were recorded with increasing coolant supply pressure when machining stainless steel. This is because coolant supply at high-pressure is able to access the cutting interface, ensuring effective cooling, lubrication and reducing the cutting interface temperature. This will consequently result in uniform flank wear and the gradual wear rate recorded. The reduction in cutting forces observed is also partly due to the chip segmentation when machining with high-pressure coolant supplies, higher forces were recorded when machining with conventional coolant flow where continuous type chips were generated. 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. Chip segmentation is considerably enhanced, as the chip curl radius is reduced significantly, due to targeted maximum coolant pressure on to the chip which aids the chip shearing process and consequently lowering cutting forces. The chip curl radius also depends on the coolant pressure and the flow rate. Therefore at a given power, smaller chip curl radius could be achieved at a lower coolant pressure with a high coolant flow rate.

Lower cutting forces where generated when machining stainless steel with coated carbide insert while machining at higher coolant supply pressures due to improved cooling and lubrication (low frictional forces) at the cutting interface and also as a result of chip segmentation caused by the high-pressure. Very low surface roughness values were recorded when machining stainless steel with the coated carbide insert.

The measurement of main cutting force, P_z components is highly essential to analyses more effectively the machinability factors of austenitic stainless steel. Dry turning operations were performed to evaluate the main cutting forces, P_z. The feed force, P_x in the direction of the tool travel and main cutting force, P_z in the direction of cutting velocity vector were measured for analyzing the machinability characteristics of stainless steel. Fig. 13 and Fig. 4.14 show the influence of cutting speed on the feed force, P_x and cutting force. P_z. The turning operations were performed at variable feed and 1.0 mm depth of cut. Experimental results represent that the feed force, P_x is high at low cutting speed and cutting force, P_z is low at low cutting speed as compared to the high cutting speed. From the figure. it can be observed that the cutting force components, P_z and feed force component, P_x are decrease by increasing cutting speed during turning of stainless steel. Fig.1 3 and Fig. 4.14 shows the influence of feed on the feed force and cutting force during turning of stainless steel.

The feed force, P_x and main cutting force, P_z are increased by increasing feed. The feed force and cutting force both are low at low feed and both are high at high feed. The tool is a coated carbide insert in HPC condition force (P_z & P_x) were found 10 to 15% less, than that of turning austenitic stainless steel under dry condition while machining by both insert SNMM and SNMG.

5.4 Surface Roughness

The quality of any machined product of given material is generally assessed by dimensional accuracy and surface integrity, which govern the performance and service life of that product. For the present study, only surface finish has been considered for assessment of quality of product under dry and HPC machining. Surface roughness is an important measuring criteria of machinability because performance and service life of the machined component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface micro-cracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part.

The major causes behind development of surface roughness in continuous machining processes like turning, particularly of ductile metals are:

i. Regular feed marks left by the tool tip on the finished surface.
ii. Irregular deformation of the auxiliary cutting edge at the tool-tip due o chipping, fracturing and wear.
iii. Vibration in the machining system.
iv. Built-up edge formation, if any.

The variation in surface roughness observed with progress of machining of stainless steel by the SNMG and SNMM insert at a particular set of cutting velocity, V_0, feed rate, S_0 under dry and HPC conditions has been in shown in Fig. 4.15 .

Conventionally applied cutting fluid did not reduce tool wear compared to dry machining. It appears from Fig. 4.15 that surface roughness grows quite fast under dry machining due to more intensive temperature and stresses at the tool-tips. HPC appeared to be effective in reducing surface roughness.

However, it is evident that HPC improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary curting edge by abrasion, chipping and built-up edge formation.

Chapter-6

Conclusion

The results obtained from this study show the capability of high-pressure coolant jet in improving the machining performance while machining austenitic stainless steel. As already stated, with the application of high-pressure coolant jet, the rate of main cutting force, P_z temperature are reduced which contributes to the improvement in surface finish. The high pressure coolant jet serves to reduce the tool-chip contact area. This was evident from the fact that the chip size (which depends upon the tool-chip contact length) is much smaller at high pressure. The overall findings of this experiment are

- There is a drastic reduction in the main cutting forces, P_z and feed forces, P_x required to remove material from the work-piece with the application of high pressure coolant jet.
- The surface finish obtained with the use of high pressure coolant jet in both SNMM and SNMG inserts is much better than obtained in the case of dry cooling.

Finally, the results achieved by this investigation were very encouraging. Cutting forces were reduced, chip shape, surface quality and tool life improved, thereby increasing the metal removal rate, and improving the overall performance of the machining operation in case of high pressure coolant. The reduction of cutting force accompanied by improvement in tool life ,surface finish and chip shape with the use of high pressure coolant jet as a coolant/lubricant leads to improvement in the metal removal rate and consequently the efficiency of single point cutting tool operations especially in case of stainless steel.

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