Optimization of Pressure and Flow Rate in HPC Jet Assisted Turning of Steel

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List of Symbols

V_c	Cutting Velocity
S_0	Feed Rate
t	Depth of cut
a_2	Chip thickness after cut
a_1	Uncut Chip thickness
ξ	Chip thickness reduction coefficient
θ_{avg}	Average Chip-tool interface temperature
P_Z	Main Cutting force
P_X	Feed Force
P_Y	Thrust force or radial force
P	Pressure
Q	Flow rate
R_a	Surface roughness
α	Major cutting edge angle (MCEA)
β	End cutting edge angle (ECEA)
BUE	Built-Up Edge
CBN	Cubic Boron Nitride
HSM	High Speed Machining
M-F-T-W	Machine-Fixture-Tool-Work
MRR	Material Removal Rate
HPC	High Pressure Coolant
MQL	Minimum Quantity Lubrication
DOE	Design of Experiment
SAW	Simple Additive Weighting
MODM	Multiple Object Decision Making
MADM	Multiple Attribute Decision Making

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Abstract

Although MRR increases with increase in velocities and feed rates but it raises temperature remarkably and such high cutting temperature adversely affects, directly or indirectly, chip formation, cutting forces, tool life, dimensional accuracy and surface integrity of the products. HPC (high pressure coolant) jet assisted turning is an effective method of machining, which allows overcoming the problems presented in the conventional turning of steels. The application of cutting fluid with HPC technique causes a hydraulic wedge between the chip and the rake face of the tool with very positive effect on machining which noticeably reduces the temperature gradient and eliminates the seizure effect, offering adequate lubrication at the tool–chip interface with a significant reduction in friction in addition to alteration of the chip flow conditions resulting in the lowering of component forces and consequently tool wear rate.

But, to get the greatest benefit from the HPC (High Pressure Coolant) system it is very vital to use the optimum amount of pressure and flow, recognize the type of nozzle or orifice to place at the end of the tube that will properly direct the coolant stream, and setting the correct angle and distance from the work piece required to properly hit the exact high temperature zone of the cutting area. This paper deals with experimental investigation on the role of HPC having various pressure and flow rate by cutting oil (HC straight run, VG 68) on cutting temperature, chip morphology, surface roughness in turning AISI-4320 steel at industrial speed-feed combinations by uncoated SNMG insert. Then, optimization has been carried out with the help of Design of Experiment along with Multiple Attribute Decision Making method and multiple graphical plots. The analysis of results show that the optimal combinational effect of average chip-tool interface temperature, chip reduction co-efficient and surface roughness can be achieved by optimizing cutting speed, feed rate along with the pressure and flow rate of HPC coolant jet. Other significant effects such as the interaction between the process parameters are also investigated. Finally, cutting forces (main cutting force and feed force) and dimensional deviation has been measured under HPC (having optimum pressure and flow rate) and dry environment to compare with one another based on forces and dimensional deviation. In total, the encouraging results include significant reduction in temperature, force, dimensional inaccuracy and surface roughness by HPC application mainly through reduction in the cutting zoue temperature and favorable change in the chip-tool and work-tool interaction.

Chapter-1

Introduction

1.1 Introduction

Manufacturing processes convert raw material into desired parts to make usable and saleable products. All manufacturing processes are evaluated and then selected for specific applications based on the type and amount of energy involved the process mechanism and its capability (including accuracy and repeatability), environmental effects, and economy. In addition to these measures, manufacturing processes also need to be evaluated on the quality after the removal of material in one cycle, as well as the achievable precision of the related manufacturing equipment. The growing demand for higher productivity, product quality and overall economy in manufacturing by machiuing, grinding and drilling, 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. But, high production machining and grinding with high cutting velocity, feed and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product by inducing tensile residual stresses and surface and subsurface micro cracks in addition to rapid oxidation and corrosion [**Leskover and Grun 1986 , Tonshoff and Brinkomeier 1986**].Moreover, in high speed machining, conventional cutting fluid application fails to penetrate into the chip-tool interface and thus cannot remove heat effectively **[Shaw et al. 1951 , Paul et al. 2000]**. Besides, conventional cutting fluid application generates high consumption and disposal costs as well as it affects the environment severely.

In order to reduce the environmental and economical effects, a number of attempts were made in the past to improve cooling/lubrication in high speed machining and in the case of machining of difficult-to-machine materials by the use of a high pressurized coolant/lubricant jet to overcome these problems. The results achieved by these investigators were very encouraging **[Pigott 1952, Mazurkiewicz 1989, Machado 1994, Ezugwu 1990 and Crafoord 1999]**. 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. Again, addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip-tool interface to provide lubrication and cooling [**Cassin and Boothroyed 1965]**. It was found that high-pressure jet of coolant, when applied at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent by introducing a hydraulic wedge between chip-tool interface [**Mazurkiewicz et al. 1989, Alexander** et al. 1998, **Dhar et al. 2006 and Carmen Sanz** et al. 2007].

Adding a high-pressure system to virtually any cutting station will yield some improvement in tool wear and machine efficiencies. However, getting the greatest benefit from the equipment requires a thorough understanding of the cutting application so that the system can be properly installed. Thoroughly understanding the application is critical to properly specifying and installing a high-pressure unit. So it is important to use the optimum amount of pressure and flow, recognize the type of nozzle or orifice to place at the end of the tube that will properly direct the coolant stream, and set the correct angle and distance from the workpiece to properly hit the appropriate cutting area. Moreover, the mechanism behind the formation of surface roughness is very dynamic, complicated, and process dependent and it is very difficult to calculate its effectiveness through theoretical analysis. Therefore, machine operators usually use "trial and error" approaches to set-up machine cutting conditions in order to achieve the desired surface roughness. Obviously, the "trial and error" method is not effective and efficient and the achievement of a desirable value is a repetitive and empirical process that can be very time consuming. The dynamic nature and widespread usage of machining operations in practice have raised a need for seeking a systematic approach that can help to set-up turning operations in a timely manner and also to help achieve the desired surface roughness quality and good dimensional accuracy.

Optimization of machining processes plays a key role in meeting the demands for high precision and productivity. The primary challenge for machining process optimization often stems from the fact that the procedure is typically highly constrained. Again, the problem of optimizing process parameters with multiple performance criteria is challenging because there is no single criterion that can adequately capture the effect or impact of each experiment and this makes it hard to determine which process parameter setting is the optimal. Moreover, new and advanced technology of manufacturing processes required more study and research to get successful and reliable data to implement in practical field. which leads to the following study of optimization of flow rate and pressure in case of high-pressure coolant jet at the tool-chip interface.

1.2 Effect of High Cutting Temperature

Machining is a process of material removal in which the loss of material is caused by affecting a relative motion between tool and workpiece. Due to removal of material in the form of chips, new surfaces are cleaved from the workpiece accompanied by a large consumption of energy. The mechanical energy necessary for the machining operation is transformed into heat, leading to conditions of high pressure, high temperatures and severe thermal/frictional conditions at the tool-chip interface. The greater the energy consnmption, the more severe are the thermal/frictional conditions, consequently making the metal cutting process more and more inefficient in terms of tool life, dimensional accuracy and material removal rate. With the advent of carbide tools and other new methods of machining, the efficiency of the metal cutting operations has improved to a certain extent under normal cutting conditions. However, improving the performance of metal cutting operations in high speed machining and in the case of machining difficult-to-machine materials is still a major concern. It was found that the efficiency of metal cutting operations depends to a large extent on the effectiveness of the cooling/lubrication provided. High temperature generated during machining at high cutting speed and feed results in high tool wear, reduced tool life, poor surface finish and dimensional accuracy and larger force is required for machining.

The mechanical energy consumed in the cutting area is converted into heat and the main sources of heat are the shear zone, the interface between the tool and the chip where the friction force generates heat, and the lower portion of the tool tip which rubs against the machined surface. The interaction of these heat sources, combined with the geometry of the cutting area, results in a complex temperature distribution. The temperature generated in the shear plane is a function of the shear energy and the specific heat of the material. Temperature increase on the tool face depends on the friction conditions at the interface. A low coefficient of friction is of course desirable. Temperature distribution will be a function of, among other factors, the thermal conductivities of the workpiece and the tool materials, the specific heat, cutting speed, depth of cut, the use of a cutting fluid and cutting condition. As cutting speed increases, there is little time for the heat to be dissipated away from the cutting area and so the proportion of the heat carried away by the chip increases.

The temperature reached in metal cutting is important since it affects the thermally activated mass transport phenomena in the cutting tool-workpiece contact zone. While primarily dependent on the cutting speed and the work piece material properties, the cutting temperature is also affected by the cutting tool properties. Almost all of the mechanical energy expended in metal cutting is transformed into heat. Much of these heats is conducted into and removed with the chips from the cutting region with nearly the entire remaining portion conducted into the workpiece and cutting tool. Again, the magnitude of the cutting temperature increases though in different degree with the increase of cutting velocity, feed and depth of cut. At snch elevated temperature the cutting tools if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting force, dimensional inaccuracy of the product and shorter tool life [**Kitagawa et al. 1997**]. This problem increases further with the increase in strength and hardness of the work material.

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 adventing with vast and rapid developments in the modern areas, like aerospace technology and nuclear science.

Longer cuts under high cutting temperature causes thermal expansion and distortion of the job particularly if it is slender and small in size, which leads to dimensional and form inaccuracy. On the other hand, high cutting temperature accelerates the growth of tool wear and also enhances the chances of premature failure of the tool by plastic deformation and thermal fracturing. In Machining, tool wear depends on the following parameters:

- material and shape of the tool

- material of the machined parts
- cutting condition and coolant
- machining process (turning, milling or drilling, etc)

Tool wear generated due to high temperature could have significantly effects on dimensional. forms and surface roughness errors. As a tool become worn, the geometry of the tool tip is changed .The wear of the tool tip on the clearance side will result in loss of the effective depth of cut, which can generate both dimensional and form errors of the workpiece by change of alignment between the tool and workpiece. Worn tool also increases the surface roughness. Due to the thermal effect of tool wear, the material in the cutting zone becomes so viscous that it fills the groove and flows in the uniform and homogenous way to the side of the cutting tool forming high ridges.

The surface quality of the products also deteriorates with the increase in cutting temperature due to built-up-edge formation, oxidation, rapid corrosion and induction of tensile residual stress and surface micro-cracks. Such problem becomes more acute and serious if the work materials are very hard, strong and heat resistive and when the machined or ground part is subjected to dynamic or shock loading during their functional operations. Therefore, it is essential to reduce the cutting temperature as far as possible.

1.3 Controlling of Cutting Temperature

Machining of metal inherently generates high cutting temperature, which not only reduces tool life but also impairs the product quality. So the primary function of cutting fluid is cooling and lubrication to avoid the high temperature impact on a machined surface. A fluid's cooling and lubrication properties are critical in decreasing tool wear and extending tool life. Cooling and lubrication are also important in achieving the desired size, finish and shape of the workpiece [**Sluhan and May 1994**]. A secondary function of cutting fluid is to flush away chips and metal fines from the tool/workpiece interface to prevent a finished surface from becoming marred and also to reduce the occurrence of built-up edge (BUE).

In the metal cutting operation, temperature is the apprehensive element and if we are able to reduce or minimize the temperature, quality will also be developed. Temperature can be reduced by using cutting fluid. Cutting fluid not only reduces temperature but also provide lubrication between the tool and work interface. Temperature can be reduce in deferent ways like flood cooling, near dry cooling or micro lubrication, MQL cooling, , cryogenic cooling and high pressure jet cooling. Near dry cooling is based on air coolant, a little amount of temperature is reduced. Though MQL reduces temperature, a large amount of small particles are produced which affect inhalation of the operator [**Bennett et al. 1985 and Eisen et al. 1994**]. Flood cooling reduces temperature to some extent by bulk cooling but is not very much effective because it cools only the top surface of the job and the tool due to its overhead application. It has some bad effects too, when cooling fluid comes in contact with the human body, it creates skin irritation, lung cancer etc. Cryogenic coolant effectively reduces temperature from the cutting zone but it is very costly and in nitrogen rich atmosphere notch wear of the tool takes place. Best performance is found in high pressure cooling jet (HPCJ). High–pressure jet of conventional coolant has been reported to provide some reduction in cutting temperature [**Aronson 2004**]. It reduces temperature very quickly due to high pressure jet coolant reaches very easily in to the chip - tool interface. Mazurkiewicz et al. [**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.

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 et al. 1979**]. 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.

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.

However, in manufacturing machining industries, the temperature and its detrimental effects are generally reduced by:

- proper selection of process parameters and geometry of the cutting tools
- proper selection and application of cutting fluid
- using heat and wear resistant cutting tool materials like carbides, coated carbides and high performance ceramics (CBN and diamond are extremely heat and wear resistive but those are too expensive and are justified for very special work materials and requirements where other tools are not effective).

1.4 Scope of the Thesis

The thesis is subdivided into six chapters including this one and the relevant chapters are organized in the following manner:

Chapter 2 describes the literature review as well as objectives of the present research work.

Experimental investigations of various responses such as temperature, chip-reduction coefficient, surface roughness, cutting forces and dimensional deviation are described in chapter 3 and the optimization of pressure and flow rates are presented in chapter 4.

Chapter 5 narrates the discussion on results that have been found through experiment.

Chapter-2

Literature Review

2.1 Introduction

The high temperature generated during machining combining with tool cutting edge deformation may result in poor machining performance in terms of form accuracy and surface quality. Currently in industries, this high temperature problem is partially tried to be controlled by reducing heat generation and removing heat from the cutting zone through optimum selection of machining parameters and geometry of the cutting tools, proper cutting fluid application and using heat resistant cutting tool materials like carbides, coated carbides and high performance ceramics (CBN). HPC jet assisted machining is capable to reduce this huge amount of heat generated during machining and it's appreciation increases rapidly day by day. 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 cooling technology has now been perfected by the provision of efficient high-pressure cooling systems and tooling which is very appealing to industry in terms of costs **[Pigott 1952, Mazurkiewicz 1989, Machado 1994, Ezugwu 1990 and Crafoord 1999]**. Mainly HPC has used in high production manufacturing industries where product quality and dimensional accuracy are needed within acceptable limit and difficult-to-machine materials are processed to get the desired job. High speed machining is needed to increase productivity in manufacturing technology and is largely related with high temperature, such high temperature generates lot of troubles. So, for reducing this high temperature HPC jet is used as a heat removing as well as lubricating agent. The success of implementing this technology across the metal removal industries specially for high speed machining will therefore depend on increased research activities providing credible data for in depth understanding of high-pressure coolant supplies at the tool–chip, tool–work piece interfaces and integrity of machined components. A brief review of some of the interesting and important contributions in the closely related areas is presented in this section.

2.2 Conventional Application of Coolant and Its Drawbacks

The exact mechanism of metal cutting briefly stated is that a cutting tool exerts a compressive force which causes stress on the work piece. The stress in front of the cutting edge is increased when the cutting tool starting to advance into the workpiece **[Astakhov et al. 1997]**. Under this compressive force the metal of the work piece is stressed beyond the yield point causing the material to deform plastically and shear off. The plastic flow takes place in the localized region called shear plane which extend from the cutting oblique up to uncut surface ahead of the tool. The sheared material begins to flow along the cutting tool face in the form of small pieces called chips. The compressive force applied to form the chips is called cutting force. The flowing chips cause wear of cutting tool. Heat is produced during shearing action. The heat generated raises the temperature of the work, cutting tool and the chips. The temperature rise in the chip-tool interface tends to soften it and causes loss of keenness in the cutting edge leading to its failnre. The cutting force, heat and abrasive wear are thus the basic features of the metal cutting process.

It is believed that heat is carried away from the tool and the work by means of cutting fluid which at the same time reduce the friction between the tool and the chip and work and also facilitates the chip formation. The conventionally applied cutting fluid can do this job properly at normal cutting conditions where the feed and depth of cut are very low. But the main problem **[Wertheim 1992]** with conventional coolant is that it does not reach the real cntting area. In case of ductile metal and under high speed-feed condition conventionally applied coolant is completely ineffective to do so as the bulk and progressive contact between tool face and the flowing chips cannot allow the coolant to enter into the interface where maximum temperature attains. Moreover, water soluble coolant is a major source of environmental pollution, soil contamination and carrier of bacteria borne diseases like lung cancer, dermatitis and others.

For a long time, the machining of difficult to machine materials has caused urgent problems in injection mould manufacturing **[Malz et al. 2000 and Choudhury et al. 1999]** and High speed machining technology is one of the important aspects of advanced manufacturing technology **[Dolinsek et al. 2001 and Li et al. 2002]**. To minimize the cost of workpiece machining, cutting parameters must permit to minimize production time and obtain specified specifications such as roughness **[Paulo 2001, 2003 and Arezoo 2000]**.But high production machining of metal inherently generates high cutting zone temperature and this high temperature causes dimensional deviation and premature failure of cutting tools. The application of cuttiug fluid during machining operation reduces cutting zone temperature to prevents overheating and increases tool life and acts as lubricant as well **[Beaubien**

and Cattanco 1964]. It reduces cutting zone temperature either by removing heats as coolant or by reducing the heat generation as lubricant. In addition, it serves a practical function as a chip-handling medium. However, 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 in evident. 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. On the other hand, the cooling and lubricating affects of cutting fluid influence each other and diminish with increase in cutting velocity [**Kitagawa et al. 1997**]. Since the cutting fluid does not enter the chip-tool interface during high speed machining, the fluid action is limited to bulk heat removal only.

Usually, the plastic deformations in the metal cutting process are classified as primary and secondary deformation zones .The majority of total deformation of the work piece material in metal machining takes place in the primary deformation zone. Most of the energy generated in the plastic deformation converts into heat, which can then cause the temperature rise in the primary deformation zone. However, only a very small amount of heat transfer occurs between the work pieces and tools due to the very short time of the deformation. Thus the temperature can be localized in some areas of the chips. This deformation and temperature localization will increase with increasing cutting speed. The shear instability in the primary deformation zone occurs as soon as a critical condition is achieved, leading to a serrated chip. As a result of the serrated chip formation, the white adiabatic shear bands in the primary deformation zones and the white layers in the secondary deformation occur. Both are similar in appearance, and moreover the white layers seem to be branches of the adiabatic shear bands, but they are formed due to different mechanisms. The white shear bands result from the adiabatic shear development, whereas the white layers mainly occur due to the intense friction between the bottom of the chip and the rake surface of the tool **[Chunzheng et al. 2005]**.

Conventional flood cooling has some negative aspects during machining, specially when speed and feed is high. Since, vast amount 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).That's why 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 so that coolant can reach sufficiently due to its high pressure into the tool-chip interface and break down the vapor barrier and can easily do its function at cutting zone.

Chip generating has completely different features depending on cutting conditions. Couventional machining **[Ekinovic et al. 2005]** prevails plastically deformation in generating chips whereas in high-speed machining chip generating is followed by segmentation process. Anyway, this transformation from plastically deformed chip to serrated chip definitely performs under special cutting conditions and has duration. no matter how fast it is.

Usually the high cutting temperature is controlled 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.

The hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate [**Reed et al. 1983**]. 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 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 [**Vleugels et al. 1995**]. Maximum temperature is found to develop on the rake face of the tool. at a certain distance from the cutting edge, where cratering occurs. The amount of energy dissipated through the rake face of the tool also raises the temperature at the flanks of the tool. The flow of the chip on the tool rake face often causes crater wear indeed the tool chip contact occurs under extreme condition.

Pashby et al. [1993] proposed that although discontinuous chips were produced at all conditions while cutting ductile iron with ceramic tool, their form varied with material heat treatment condition and cutting speed, four distinct types were observed as Curled, corrugated, birds foot and needle. Curled chips were produced when machining annealed material, whereas cutting the austempered material produced corrugated chips at low speed changing to birds foot as speed increases then individual needles at the higher speeds. But the cutting speed at which a change in chip form occurred varied from tool material to tool material.

Despite recent advances in cutting tool materials, machining of nickel base superalloys at high speed conditions generally reduces the hardness and strength of cutting tools due to associated rise in cutting temperature. A temperature close to the melting point of Inconel 718 (1300°) has been recorded when machining with mixed oxide ceramic tool at a speed of 120mmin−1 and a feed rate of 0.1mmrev−1 [**Kramer 1987**]. This generally weakens the bond strength of the tool substrate, thus accelerating tool wear by mechanical and/or thermally related wear mechanisms and possibly plastic deformation of the cutting edge of the tool.

The application of coolant does not necessarily reduce tool wear as is commonly believed. Under some conditions, Seah et al. [**1995**] showed that the use of coolant apparently increases tool wear. For the first stage of metal cutting (ie. first 40 seconds or so), machining with coolant causes a higher rate of tool wear than dry cutting. Later on, the wear rate stabilizes and is somewhat the same for both cutting with coolant and dry cutting. Further research is needed to further confirm under what circumstances the use of coolant will be beneficial to the machining process and how the temperature distribution on the tool is altered.

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. Tool wear has a large influence on the economics of the machining operation. So it is useful to predict tool wear for optimizing process chains, improving product surface quality and automatic tool management to predict tool wear before cutting **[Luo 2004]**. The need for accurate assessment of tool wear has increases considerably in order to produce the required end products in an automated industry so that a new tool may be introduced at the instant at which the existing tool has worn out, thus preventing from hazards occurring to the machine or deterioration of the product surface finish. The model of the tool wear analysis is used to reduce the planning uncertainties and to optimize tool application.

Past 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**]. 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 workpiece 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 bulk or plastic contact at high cutting speed.

Improvements in tooling materials are closely followed by developments of innovative cutting technologies together with lubrication and cooling procedures .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. 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]**.

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, workpiece and the tool, which are accessible to the coolant. Removal of heat by conduction through the chip and the workpiece is likely to have relatively little effect on the temperature at the chip-tool and work-tool interface.

Machining Ti–6Al–4V alloy with different grades of CBN tools **[E.O. Ezugwua et al. 2005]** gave lower performance, in terms of tool life, compared to uncoated carbide tool in finish turning Ti–6Al–4V (IMI 318) alloy at high cutting conditions, up to 250 m/min, with various coolant supplies. Tool life generally increased with increasing the coolant pressure compared to conventional coolant flow. This can be attributed to the CBN content of the cutting tools which shows that with an increase in the CBN content tend to accelerate notch wear rate, consequently diminishing tool life under the cutting conditions investigated. There is no adverse effect on surface finish generated when machining the Ti–6Al–4V alloy with CBN tools.

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 **[Kurimoto and Barroc 1982]**. The influence of the electric current flowing through the cutting zone on the rate of tool wear is also well known [**Ellis and Barrow 1969**]. However, most commercial cutting fluids are non electro-conductive, and as such the situation with respect to current flow will not vary significantly from the dry cutting case. The electrochemical action is treated as a corrosion phenomenon in respect of tool wear.

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.

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.

It was observed [**Jawahir and van Luttervelt 1993**] 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. In addition to usual flank wear and crater wear the cutting tools often attain notching on the flanks and grooving on the rake surface at the outer ends of the engaged portions of the cutting edges. On the major cutting edge, the grooving wear occurs at the extreme end of the depth of cut and is characterized by deeper abrasion of the tool edge. On the end cutting edge, the grooving wear is characterized by smaller multiple notches.

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 the maximum almost at the centre of the chip-tool contact surface where then crater wear begins and grooves intensively.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 workpiece 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 bulk or plastic contact at high cutting speed.

In machining of steels [**Grzesik 1999**] the use of the proper coating structure can contribute to substantial reduction of the friction action between the rake and the chip and result in a decrease in heat generation and lower the tool–chip interface temperature. Besides, in practical aspects, it enables controlling heat transfer into the tool body. The selection of a workpiece material with low thermal conductivity and low heat capacity and a coating material with low thermal conductivity leads to a reduction in the contact length, resulting in the effect of a thermal barrier. As a consequence, heat is concentrated within the thin top layer of the coating to protect the tool against diffusion.

The presence of chemical substances like sulfur, phosphorous, chlorine or any other extreme pressure additives in the coolant introduces health hazard to the operator [**Tonshoff et al. 1997**]. It is well documented that 7–17% of machining cost of a work-piece is due to coolant-lubricant deployment **[Klock 1997]**. The disposal of used chemical coolants involves incineration and partially contributes to global warming [**Klock et al. 1998]**. Also, use of flood coolants does not inhibit the air boundary layer and a protocol was made for further investigation of coolant flow mechanism **[Ebbrell 2000]**. Skin exposure is the dominant route of exposure, and it is believed that about 80 percent of all occupational diseases are caused by skin contact with fluids [**Bennett et al. 1985**]. Cutting fluids are 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. Non-water-miscible fluids usually cause skin disorders such as foliculitis, oil acne, keratoses and carcinomas.

2.3 Alternative Techniques for Controlling Cutting Temperature

In the pursuit of profit, safety, and convenience, a number of alternatives to traditional machining are currently under development. Dry machining has been around for as long as traditional machining, but has seen a recent surge in interest as more people are realizing the true cost of cutting fluid management. Minimum Quantity Lubrication (MQL) is an obvious, but very intricate balance between dry machining and traditional methods. Other novel cutting fluids, such as liquid nitrogen, are also being explored for their unique properties. Recently, it was found that a high pressure coolant/ lubricant jet injected into the tool-chip interface provides effective cooling/lubrication and consequently improves the machining performance of the tool **[Ezugwua et al. 2005 and Dhar et al. 2006]**. The following sections provide a few details about each of these technologies.

2.3.1 Dry Machining

Machining without the use of cutting fluids has become a popular option for eliminating the problems associated with cutting fluid management. One of the greatest obstacles to acceptance of dry machining is the false belief that cutting fluids are needed to produce a high-quality finish. Studies have shown that with proper equipment and tooling, machining without fluids can produce a high-quality finish, and be less costly than machining with fluids **[Winkler 1998]**. Even machining with coolant causes a higher rate of tool wear than dry cutting (first 40 seconds) **[Seah et al. 1995]**. The advantages of fluidless or dry cutting include cleaner parts, no waste generation, and in some cases, more precise machining **[Case Study, Los Alamos National Laboratory, U.S. Dept. of Energy]**. In addition to these benefits, worker health concerns related to metalworking fluid exposure are eliminated. Recycling is simpler because chips generated from this technique have no residual oil on them and can be combined with other scrap metal. These advantages do have a cost. The most prohibitive part of switching to dry machining is the large capital expenditure required to start a dry machining operation. Machines and tools designed for cutting fluids cannot be adapted to dry cutting. New, more powerful machines must be purchased, and special tooling is often needed to withstand the very high temperature generated by dry cutting **[Vaughn 1999]**. Tools are often treated with a coating that insulates the tool and the part from the heat of the cut. These tools are more expensive than traditional tools and must be replaced more often. Tool wear can increase so much that certain extreme cuts must be divided into separate processes to facilitate tool replacement **[Heine 1996]**. Compressed air is used to remove chips that might otherwise interfere with the machining operations **[Vaughn 1999]**. Dry machining leaves an unprotected surface, which on some materials may be prone to rapid oxidation (rust) **[Dry Machining of Plutonium Parts, Case Study, Los Alamos National Laboratory, U.S. Dept. of Energy]**.

There is an increased tool wear in dry machining mainly caused by the formation of an adhesive layer and a built-up edge (BUE), which affect the quality of the generated surface **[Braga et al. 2002, Kelly et al. 2002, Nouari et al. 2003, Carrilero et al. 2002]**.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. 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 **[Sheng and Munoz 1993]**.

The optimization of cutting conditions to make them more suitable for dry cutting is done through the increase of feed and decrease of cutting speed. With this, roughly the same amount of heat is generated, but the area of the tool, which receives this heat, is bigger, making the temperature lower and the amount of chip removed per minute constant (without increasing cutting time). This action may damage the workpiece surface finish due to the increase of the feed. Therefore, it is also necessary to increase the tool nose radius in order to keep the surface roughness at the same level **[Klocke and Eisenblatter 1997]**. The capital expenditure required may prevent many small shops from seriously considering dry machining as an option. However, if the true cost of cutting fluid management is figured into the decision, dry machining may be a competitive or even superior investment.

2.3.2 Minimum Quantity Lubrication (MQL) Machining

Minimum Quantity Lubrication (MQL), also known as Near Dry Machining (NDM) or semi-dry machining, is another alternative to traditional use of cutting fluids in machining to achieve both environmental and economical benefits **[Weinert et al. 2004, Khan et al. 2006]**. There are many similarities between dry machining and MQL; in fact, many research papers treat true dry machining and MQL as the same technology. As the name implies, MQL uses a very small quantity of lubricant delivered precisely to the cutting surface .The use of MQL to replace flood coolant has been demonstrated successfully over the years **[Heisel et al. 1994, Kishawy et al. 2005, Dhar et al. 2005, 2006 and Heinemann et al. 2006]** but the technology is still new and issues snch as tool wear, machine reliability, and maintenance requirements remain open-ended. Often the quantity used is so small that no lubricant is recovered from the piece. Any remaining lubricant may form a film that protects the piece from oxidation or the lubricant may vaporize completely due to the heat of the machining process. This process, like dry machining, generates no waste cutting flnid. Small quantities of cutting fluid may need to be removed by a subsequent cleaning step. In some cases, the fluid is selected so that residual fluid does not interfere with future processing. Depending on the application, the fluid may be left on as a protective coating or anti-oxidation layer. With the large volumes of cutting fluid used in traditional machining, misting, skin exposure and fluid contamination are problems that must be addressed to assure minimal impact ou worker health. With MQL, the problem of misting and skin exposure is greatly reduced, and fluid does not become contaminated because it is not re-used. However, fluid is still present. Proper veutilation is required to prevent buildup of vaporized fluid. In MQL operations, fluid selection is one of the most critical decisions. The most common fluids are vegetable oil, ester oil, or a synthetic equivalent because of their superior lubrication and high-pressure performance [**Makiyama et al. 2000**]. These fluids are often much more expensive than traditional cutting fluids but, if properly selected and used, they may result in less cost per cut than the combined cost of fluid, fluid disposal, and a continuous fluid management system. As with dry machining. special equipment and special tooling may be required. However, it may be possible to adapt some existing equipment to MQL operation. Fluid delivery is a critical operation. Cutting fluid must be delivered to the part where it is needed most. In some instances, brushing a layer of fluid over the part is sufficient. In more extreme applications, a precisely controlled stream or mist must be introduced to the cutting surface at an exact location. The degree of lubrication required and the delivery system chosen will depend on the material, the extremity of the cut, and the design of the equipment used. While MQL may not require as large capital expenditure as dry machining, it is a very technical method and requires detailed knowledge of metallurgy, chemistry, and the physics of cutting in order to be implemented correctly.

2.3.3 Cryogenic Machining and Grinding

One solution to the problem of cutting fluid management currently under development is the use of liquid nitrogen as a coolant and lubricant. This technique is not the same as cryogenic machining, where the material to be cut is cooled to a very low temperature prior to the machining operation. Rather, the method currently under development uses liquid nitrogen to perform the cooling and lubricating job of the cutting fluid. Much of the part remains at ambient temperature while the flow of nitrogen is carefully delivered to the point where it is needed. The small flow rate of liquid nitrogen makes this technique a very attractive alternative. This technique can be used on equipment that has been designed for use with cutting fluids, and because the nitrogen evaporates harmlessly into the air, there is no cutting fluid to dispose. If successful, this technique will provide an alternative to businesses that want to eliminate the use of traditional cutting fluids but cannot afford the capital expenditure required to purchase new dry-machining equipment. Reportedly, tool life and finish quality are also improved by this techniqne due to the low temperatures at the tool/part interface [**Paul and Chattopadhyay 1995 and Dhar et al. 2002**]. Liquid nitrogen is an inexpensive chemical that is environmentally inert. Nitrogen is the most abundant gas in earth's atmosphere and, when liquid nitrogen warms, it simply mixes with and diffuses harmlessly into the air. Chips generated from this technique have no residual oil on them and can be recycled as scrap metal.

Liquid nitrogen is hazardous to workers due to its extremely low temperature. Exposure can result in mild to extreme frostbite. Nitrogen that is stored in a sealed vessel will increase in pressure dramatically as it warms, potentially resulting in a non-combustion explosion. Large spills can displace all of the oxygen in a room in a short time. However, when proper equipment and handling techniques are used, nitrogen is a very safe and environmentally friendly alternative.

2.3.4 High Pressure Coolant (HPC) Machining

The primary function of cutting fluid is cooling and lubrication. A fluid's cooling and lubrication properties are critical in decreasing tool wear and extending tool life. Cooling and lubrication are also important in achieving the desired size, finish and shape of the workpiece **[Sluhan 1994]**. A secondary function of cutting fluid is to flush away chips and metal fines from the tool/workpiece interface to prevent a finished surface from becoming marred and also to reduce the occurrence of built-up edge (BUE).

Coolants are used to reduce the amount of heat and friction at the point where a tool cuts into a metal workpiece. This heat reduction allows the cutting tool to operate at higher speeds and reduces tool wear. However, at the lower pressures typically used to deliver cutting fluid, the coolant cannot effectively remove the majority of heat at the cutting point because it does not reach the real cutting area **[Wertheim 1992]**. Instead, the coolant washes over the tool, tool holder and workpiece, cooling the surfaces somewhat, but not removing the intense heat within the cutting area, itself. In fact, most of this heat is conducted to the material around the shear zone and to the tooling, thus keeping the temperature at the cutting point higher than desired. By directing the coolant stream more precisely and with the optimum amount of pressure and flow rate, more heat can be removed dramatically from the cut zone. This degree of cooling also enables the cutting tool to remove greater amounts of metal, thus improving machine tool cycle times. Thus, the credibility of high-pressure coolant assisted machining had been thoroughly investigated over the years [**Sharma et al. 1971, Mazurkiewicz et al. 1989, Ezugwu et al. 1990, Machado et al. 1994 and Dhar** et al. **2006**]. Additionally, the high-pressure coolant stream helps break up chips and remove them from the cutting area more efficiently, which means the cutting tool spends less time re-cutting metal chips. The combination of reduced heat and more efficient evacuation of chips prolong tool life and makes replacement more predictable because the cutting tool wears out naturally, rather than failing prematurely because of excessive heat or chip damage.

Recently, the latest machine tools deliver increased spindle speeds while maintaining tolerances better than ever before. However these higher speed and feed rates place greater demands on the cutting tools as they encounter more intense heat, greater stress and increased chip accumulation in the cut zone. As a result, if the cut area is not properly cooled and the chips efficiently evacuated, the cutting tool will require more frequent replacement which reduces overall throughput. Properly applied high-pressure coolant allows users to achieve maximum performance from these faster machine tools. . The coolant jet under such high-pressure is capable of creating a hydraulic wedge between the tool and the workpiece, penetrating the interface deeply with a speed exceeding that necessary even for very high-speed machining. This phenomenon also changes the chip flow conditions [**Kovacevic et al. 1995**]. 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 [**Wertheim et al. 1992, Crafoord et al. 1999**]. This is attributed to a coolant wedge which forms between the chip and the tool forcing the chip to bend upwards giving it a desirable up curl required for segmentation.

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 of machining, HPC plays well role to minimize this type of problem. Frederick Mason [**2001**] found better solution from it and he states that HPC systems generates high velocity coolant streams moving at several hundred mph. This high pressure-speed coolant easily penetrates the vapor barrier to effectively lubricates and cool the tool. In fact,, when machinists apply high pressure coolant to a longstanding process, which has always produced dark blue chips, they are open amazed that the same or even higher speeds and feeds produce shiny, silver chips that are cool to the touch.

With the advent of carbide tools and other new methods of machining, the efficiency of the metal cutting operations has improved to a certain extent under normal cutting conditions but improving the performance of metal cutting operations in high speed machining and in the case of machining difficult-to-machine materials is still a major concern. It was found that the efficiency of metal cutting operations depends to a large extent on the effectiveness of the cooling/lubrication provided. A flood of fluid directed over the back of the chip is the most common method of applying the cutting fluid but this method loses its effectiveness at higher cutting speeds. With the use of high-pressure coolant during machining, the tool life and surface finish are found to improve significantly [**Kovacevic et al. 1994, Lindeke et al. 1991, Mazurkiewicz et al. 1989 and Dhar et al. 2006**], which is said to be due to the decrease in heat and cutting forces generated.

The experimentally observed role of high-pressure coolant (HPC) in drilling AISI-4340 steel by HSS drill [**Dhar et al. 2006**] may be summarized that the formation of chip under HPC condition is more favorable in compare to dry condition because of high lubricant capacity, roundness deviation was smaller at both the entrance and end of the holes under HPC condition in compare to dry condition. When high depth of cut used, the drilling with dry condition was not possible because of poor cooling and lubrication action, taper values and their dispersion were smaller under high-pressure coolant condition. Moreover, in both conditions the average taper values were positive i.e., the diameters in the entrance of the holes were bigger than at the end. The beneficial effects of HPC may be attributed to effective lubrication action, which prevents the chip sticking on the tool and makes the cut feasible.

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 hinder the cutting process and can destroy both the tool and the work-piece [**Kaminski et al. 1977**]. To overcome aforementioned problem, HPC (High-pressure coolant) is on the way to become as standard in metal cutting and can play significant role due to its high potential and good effect on the surface.

It was found about the performance of high-pressure coolant jet on grind ability of steel [**Dhar et al. 2006**] based on the experimental results that high-pressure coolant jet reduces grinding zone temperature significantly due to effective cooling and lubrication at the grinding zone area .HPC grinding yields to a less significant lamellar chips compared with dry grinding and marked no substantial variation in length and shape of the chips can be found due to change in feed though. The sizes of the long lamellar chips observed to be larger than under dry grinding. High-pressure coolant grinding provides considerably less surface roughness in comparison with dry grinding. The aspect of high-pressure coolant grinding has expectedly always been free from surface burning. This can obviously be attributed due to lower temperature, retained grit sharpness and less rubbing.

The hardness of a workpiece plays an important role in the performance of tool which is observed [**Senthil Kumar et al. 2002**] by the variation in cutting forces, surface roughness, flank wear and chip shape with workpiece hardness. The application of high-pressure coolant produces a great reduction in flank wear and hence tool life and produces a significant improvement in surface finish for both uncoated and coated inserts, in a certain range of hardness. This is because the cutting temperature and forces are reduced when using high-pressure coolant. The effective zone of high-pressure coolant in improving tool life and surface finish is found to be 35–40 HRC for the uncoated insert, whereas the optimal condition when using high-pressure coolant with a coated insert is 40 HRC. For both coated and uncoated tools, the use of high-pressure coolant below the optimal hardness is found to be detrimental to the flank wear and hence tool life. This is due to the wear mechanism, and may be prompted by the ductility of the material, resulting in edge chipping that causes large tool wear and thus shortens tool life. However, there is no significant difference in surface roughness with workpiece hardness for both types of insert, with the application of high-pressure coolant. Generally, the values of surface roughness are well below 1.0 μm, which is even better than for grinding or EDM.

Machining of Inconel 718 alloy with SiC whisker reinforced alumina ceramic tool **[Ezugwu et al. 2005]** under high-pressure coolant supplies tends to improve tool life with increasing coolant pressnre up to 15MPa under finish machining conditions. Lower tool life was generated with 20.3 MPa coolant supply pressure due to accelerated notching. Lower cutting forces where generated when machining Inconel 718 with whisker reinforced ceramic tool 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 coolant jet. Accelerated notch wear on both flank and rake faces of the SiC whisker reinforced alumina ceramic tool during machining can also be caused by water jet impingement erosion of the ceramic cutting tool by the high-pressure coolant. Very low surface roughness values were recorded when machining Inconel

718 alloy with the SiC whisker reinforced alumina ceramic tool. This is due to the big contact radius (6 mm) of the ceramic tools. Hardening of the top surface, up to 0.2mmbeneath the machined surfaces occurred when machining with conventional and high-pressure coolant supplies. This is associated with the increase in dislocation density due to plastic deformation of the machined surface. Plastic deformation of the surface layers extends on average to between 30 and 50 μm below the machined surface when machining with ceramic tools under the high-pressure coolant conditions investigated.

In machining Stainless steel AISI 304 **[Kovacevic et al. 1995]** showed two different methods of application of water jet in conjunction with rotary tool operations (face milling and down milling). There is a drastic reduction in the cutting forces required to remove material from the workpiece with the application of high pressure water jet. The surface finish obtained with the use of high pressure water jet is much better than that obtained in the case of flood cooling. While machining stainless steel they found intense shearing action in the case of flood cooling associated with big serrations which were relatively very small in the case of high pressure water jet cooling. The welding of hot chip to the cutting edge which is a common problem while machining titanium is completely eliminated with the application of high pressure water jet, leading to an improvement in surface quality and tool life. In the case of 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 fragmentation of the chip by the impinging jet. Finally, the reduction in cutting force accompanied by improvement in tool life, surface finish, and chip shape with the use of a high pressure water jet as a coolant/ lubricant leads to improvement in the metal removal rate and consequently the efficiency of rotary tool operations especially in the case of difficult-to-machine materials. Further, the enhanced 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.

By using high-pressure coolant in the drilling and turning of low machinability alloy, Lo´pez de Lacalle et al. [2000] showed drills coated with TiN perform well in the drilling of Inconel 718, in which case a cutting speed of 25 m/min was achieved. Internal coaxial cooling proved viable in the drilling of titanium, with 252 holes (V_c: 60m /min and feed: 0.05 mm/tooth). Ceramics behave well in the turning of Inconel. It is effective in the cutting of titanium to use a high-pressure water-jet system (11 Mpa and 11 l/min) and cutting speeds are double the conventional speed with a good drill life.

Ezugwu et al. [1999] conclnded that coolant played a very important role in the machining of nickel-based alloys. The application of coolant reduced the overall temperature of the cutting area and the process of fatigue induced by irregular contact of the hot chip on the cutting tool. The use of high-pressure coolant supply to machine nickel-based alloys gave the benefit of improved chip segmentation. The high-pressure coolant supply caused a significant reduction in the chip–tool contact length and consequently an increase in stresses at the cutting edge.

Lee et al. [2002] demonstrated the effect of high pressure air jet on form accuracy in slot grinding of high hardness materials Tungsten carbide and concluded that the velocity and flow amount of high pressure air jet get greater, the force acting on wheel surface increase more. The high pressure air jet is effective to prevent clogging of wheel by removing the impurities among the grains. Without using high pressure air jet, ground depth decreases due to wheel wear. But the width increases by clogging phenomena on the both sides of the wheel. Form variations become smallest when high pressure air jet is sprayed in the same direction with the wheel rotation. Spraying from the opposite direction result in chattering in the wheel, which deteriorates the form accuracy of the ground slot. The decrease of the wheel wear rate and improvement of form accuracy can be achieved by using high pressure air jet. If the high pressure air jet is used, the high form accuracy can be obtained.

Patrik Dahlman et al. [2004] successfully showed the convenience of using ultra-high-pressure jet-assisted cooling to achieve good chip control. By introducing a hydraulic wedge between the tool and the chip, it is possible to break and curl the chip to the desired form, even with very soft material. The clearest difference between UHPC and dry machined chips was obtained using wiper insert geometry. The ratio between edge contact length and chip thickness is higher for the insert, making wide, thin chips harder to break. The best results were achieved by turning at lower feed rates and applying UHPC, since lower chip thickness allowed the water jet to deform and break the chip in a more effective manner. This is especially important for finish turning. Even though the difference in chip shape is not so large, for the chips created with the standard tool geometry, the packing ratio generated a significant difference in chip waste volume. Significant improvement of the surface finish was achieved using UHPC. All experiments carried out showed lower St values in UHPC than dry machining. Furthermore, UHPC has been demonstrated to be an effective way to prevent BUE defects. Typical intermittent BUE marks were seen in dry machining. The worst case was total surface failure, depending on dry cutting data, due to BUE welded parts on the surface finish. BUE formation was present at high cutting speeds (up to 700 m/min). Normally this phenomenon does not occur with cutting speeds above 60 min. Trent and Wright [**Trent and Wright 2000**] stated that, at higher temperatures, the pearlite can recrystallize, thus preventing BUE. Low alloy decarburized steel should not generate BUE, due to the low strain hardening effect. Introducing effective cooling in the cutting zone should generate more BUE. This was not observed in the experiments. On the contrary, the UHPC effect reduced BUE generation. However, P. Dahlman et al. [**2004**] concluded about the benefits and problems of using UHPC in turning soft decarburized materials that there is BUE present even at very high cutting speeds when turning in the decarburized layer and the use of UHPC significantly improved chip control compared to dry machining, especially when using the wiper insert geometry. The highest impact on chip control is achieved at low cutting feed rates and Chip control was not affected by cutting speed. Surface roughness value St is greatly improved by the introduction of UHPC. A reduction of the St value by about

80% can be observed when using UHPC instead of dry turning, Finally, wear can be drastically reduced by using UHPC with tooling sensitive to thermal cracking.

So, it may conclude that the advantages of high pressure cooling technology include significant improvement to tool life, effective chip segmentation and efficient cooling and lubrication. The penetration of the high-energy jet into the tool–chip interface reduces the temperature gradient and eliminates the seizure effect, offering adequate lubrication at the tool–chip interface with a significant reduction in friction in addition to alteration of the chip flow conditions resulting in the lowering of component forces and consequently tool wear rate.

2.4 Selection and Application of Cutting Fluids

There are now several types of cutting fluids on the market, the most common of which can be broadly categorized as cutting oils or water-miscible fluids. Water-miscible fluids, including soluble oils, synthetics and semi-synthetics, are now used in approximately 80 to 90 percent of all applications [**Aronson 1994**]. Although straight cutting oils are less popular than they were in the past, they are still the fluid of choice for certain metalworking applications. Cutting fluids play a significant role in machining operations and impact shop productivity, tool life and quality of work. With time and use, fluids degrade in quality and eventually require disposal once their efficiency is lost. Waste management and disposal have become increasingly more complex and expensive. Environmental liability is also a major concern with waste disposal. Many companies are now paying for environmental cleanups or have been fined by regulatory agencies as the result of poor waste disposal practices.

Functions of cutting fluids used in machine shops are to control temperature (Primarily) through cooling and lubrication and to remove chips and metal fines (Secondarily) from tool-workpiece interface [**Aronson 1994**]. Thus the application of cutting fluids helps in improving the life and function of cutting tools and achieving the desired size, finish and shape of the workpiece [**Sluhan 1994**]. However, the use of cutting fluid generally causes economy of tools and it becomes easier to keep tight tolerances and to maintain workpiece surface properties without damages [**Sales et al. 2001**]. These are, therefore, the key factor in machine shop productivity and production of quality machined parts [**Aronson 1994, Sluhan 1994** and **Tuholski 1993**].

Choosing the right cutting fluid, for a particular operation, can be confusing and time consuming. To select a fluid for an application, advantages and disadvantages of cutting fluid products should be compared through review of product literature and usage history. However, the following factors should be considered when selecting the fluid [**Aronson 1994, Sluhan 1994, Bienkowski 1993** and **Lukas 1994**]:

- Cost and life expectancy
- Fluid compatibility with work material and machine components
- Speed, feed and depth of cutting operation
- Type, hardness and microstructure of the metal being machined
- Ease of fluid maintenance and quality control
- Ability to separate fluid from the work and cuttings
- The product's applicable temperature operating range

- Optimal concentration and P^H ranges
- Storage practices
- Ease of fluid recycling or disposal

Above all, during cutting fluid selection, benefits of a fluid's versatility should be weighed against its performance in each metal working application [**Aronson 1994**, and **State of Ohio EPA 1993**]. The most common cutting fluids used today belong to one of two categories based on their oil content [**Sluhan 1994** and **Bienkowski 1993**]: (i) **Oil-Based Cutting Fluids**- including straight oil and soluble oils and (ii) **Chemical Cutting Fluids**- including synthetics and semi-synthetics.

Cutting fluids vary in suitability for metalworking operations. Petroleum-based cutting fluids are frequently used for drilling and tapping operations due to their excellent lubricity while water-miscible fluids provide the cooling properties required for most turning and grinding operations. Straight oils, so called because they do not contain water, are basically petroleum or mineral oils. These oils may have additives designed to improve specific properties [**Aronson 1994** and **Tuholski 1993**]. Generally no additives are required for such easiest task as light-duty machining of ferrous and nonferrous metals [**Bienkowski 1993**], whereas, for more severe applications i.e. heavy-duty operations, some wetting agents (typically up to 20% fatty oils) need to be added to coat the cutting tool, workpiece and metal fines [**Koelsch 1994**] and thus, improve ability of the oil to handle large amounts of metal fines and help guarding against microscopic welding in heavy-duty machining. However, straight oils offer good rust protection, extended sump life, easy maintenance and resistance to rancidity [**Bienkowski 1993**]. Soluble oils, also known water-soluble oils, are generally comprised of 60-90% petroleum or mineral oil, emulsifiers, and other additives [**Aronson 1994, Bienkowski 1993** and **IWRC 1990**]. These offer improved cooling capabilities and good lubrication due to blending of oil and water [**Koelsch 1994**] and suitable for light and medium duty operations involving the variety of ferrous and nonferrous application [**IWRC 1996**]. But the presence of water makes soluble oils more susceptible to rust control problems, bacterial growth and rancidity, tramp oil contamination and evaporation losses. Moreover, misting of soluble oils may produce a dirty and unsafe work environment, through slippery surfaces and inhalation hazards [**IWRC 1996**].

Chemical cutting fluids, called synthetic or semi-synthetic fluids, are stable, performed emulsions which contain very little oil and mix easily with water. Such type of cutting fluids relies on chemical agents for lubrication and friction reduction [**Bienkowski 1993**].

Synthetic fluids contain no petroleum and mineral oil [**Sluhan 1994**] and generally consist of chemical lubricants and rust inhibitors dissolved in water. These fluids are designed for high cooling capacity, lubricity, corrosion prevention and easy maintenance [**IWRC 1996**] and make them able to handle heavy-duty grinding and cutting operations on tough, difficult-to-machine and high temperature alloys [**Sluhan 1994**]. Despite of the benefits offered, a number of health and safety concerns, such as misting and dermatitis, remain with the use of synthetics in the shop [**Bienkowski 1993**]. Synthetic fluids are also easily contaminated by other machine fluids such as lubricating oils and need to be monitored and maintained to be used effectively [**Aronson 1994** and **Koelsch 1994**].

Semi-synthetic fluids are essentially a hybrid of soluble oil and synthetics. These oils contain small dispersions of mineral oil, typically 2-30%, in a water-dilutable concentrate [**Aronson 1994, Bienkowski 1993** and **Oberg et al. 1992**]. Semi-synthetic fluids provide better control over rancidity and bacterial growth, generate less smoke and oil mist and have good corrosion protection [**IWRC 1996**]. However, the water hardness affects stability of semi-synthetics. These fluids may also cause misting, foaming and dermatitis.

Enormous efforts to reduce or eliminate the use of lubricant in metal cutting are, therefore, being made from the viewpoint of cost, ecological and human health issues [**Aronson 1995, Heisel et al. 1994, Honma et al. 1996** and **Klocke** and **Eisenblätter 1997**]. But with the need for high production machining, the control of cutting zone temperature is an important aspect of modern machining and grinding operations. If we are able to reduce or minimize the temperature, quality will also be developed. Temperature can be reduced by using cutting fluid. Cutting fluid not only reduces temperature but also provide lubrication between the tool and work interface. Temperature can be controlled in deferent ways like flood cooling, near dry cooling or micro lubrication, MQL cooling, cryogenic cooling and high pressure jet cooling. But high-pressure coolant (HC straight run, VG 68) jet assisted machining has been chosen for the following reasons:

- The major advantage of straight oils is the excellent lubricity or "cushioning" effect they provide between the workpiece and cutting tool [**Tuholski 1993**]. This is particularly useful for low speed, low clearance operations requiring high quality surface finishes [**Bienkowski 1993**].
- Although their cost is high, they provide the longest tool life for a number of applications. Highly compounded straight oils are still preferred for severe cuttiug operations such as crush grinding, severe broaching and tapping, deep-hole drilling, and for the more difficult-to-cut metals such as certain stainless steels and superalloys. They are also the fluid of choice for most honing operations due to their high lubricating qualities [**Koelsch 1994**].
- Straight oils offer good rust protection, extended sump life, easy maintenance, and are less likely to cause problems if misused. They also resist rancidity, since bacteria cannot thrive unless water contaminates the oil [**Bienkowski 1993**].

2.5 Optimization of Machining Techniques

It has long been recognized that conditious during cutting, such as feed rate, cutting speed and depth of cnt, should be selected to optimize the economics of machiniug operations. as assessed by productivity, total manufacturing cost per component or some other suitable criterion. The setting of Machining parameters such as cutting speed, feed rate and depth of cut determines the quality characteristics of turned parts. Following the pioneering work of Taylor [**1907**] and his famous tool life equation, different analytical and experimental approaches for the optimization of machining parameters have been investigated.

Bhattacharya et al. [1970] optimized the unit cost for turning, subject to the constraints of surface roughness and cutting power by the use of Lagrange's method. Walvekar & Lambert [1970] discussed the use of geometric programming to selection of machining variables. They optimized cutting speed and feed rate to yield minimum production cost. Petropoulos [1973] investigated optimal selection of machining rate variables, viz. cutting speed and feed rate, by geometric programming. A constrained unit cost problem in turning was optimized by machining SAE 1045 steel with a cemented carbide tool of ISO P-10 grade.

Hinduja et al. [1985] described a procedure to calculate the optimum cutting conditions for turning operations with minimum cost or maximum production rate as the objective function. For a given combination of tool and work material, the search for the optimum was confined to a feed rate versus depth-of-cut plane defined by the chip-breaking constraint. Some of the other constraints considered include power available, work holding, surface finish and dimensional accuracy.

Tsai [1986] studied the relationship between the multi-pass machining and single-pass machining. He presented the concept of a break-even point, i.e. there is always a point, a certain value of depth of cut, at which single-pass and double-pass machining are equally effective. When the depth of cut drops below the break-even point, the single-pass is more economical than the double-pass, and when the depth of cut rises above this break-even point, double-pass is better. Carbide tools are used to turn the carbon steel work material.

Gopalakrishnan & Khayyal [1991] described the design and development of an analytical tool for the selection of machine parameters in turning. Geometric programming was used as the basic methodology to determine values for feed rate and cutting speed that minimize the total cost of machining SAE 1045 steel with cemented carbide tools of ISO P-10 grade. Surface finish and machine power were taken as the constraints while optimizing cutting speed and feed rate for a given depth of cut.

Agapiou [1992] formulated single-pass and multi-pass machining operations. Production cost and total time were taken as objectives and a weighting factor was assigned to prioritize the two objectives in the objective function. He optimized the number of passes, depth of cut, cutting speed and feed rate in his model, through a multi-stage solution process called dynamic programming. Several physical constraints were considered and applied in his model. In his solution methodology, every cutting pass is independent of the previous pass, hence the optimality for each pass is uot reached simultaneously.

Prasad et al. [1997] reported the development of an optimization module for determining process parameters for turning operations as part of a PC-based generative CAPP system. The work piece materials considered in their study include steels, cast iron, aluminium, copper and brass. HSS and carbide tool materials are considered in this study. The minimization of production time is taken as the basis for formulating the objective function. The constraints considered in this study include power, surface finish, tolerance, work piece rigidity, range of cutting speed, maximum and minimum depths of cut and total depth of cut. Improved mathematical models are formulated by modifying the tolerance and work piece rigidity constraints for multi-pass turning operations. The formulated models are solved by the combination of geometric and linear programming techniques.

The latest techniques for optimization include fuzzy logic, scatter search technique, genetic algorithm, Taguchi technique and response surface methodology.

Fuzzy logic: Fuzzy logic has great capability to capture human commonsense reasoning, decision-making and other aspects of human cognition. Kosko [1997] shows that it overcomes the limitations of classic logical systems, which impose inherent restrictions on representation of imprecise concepts. Vagueness in the coefficients and constraints may be naturally modelled by fuzzy logic. Modelling by fuzzy logic opens up a new way to optimize cutting conditions and also tool selection.

Genetic algorithm (GA): These are the algorithms based on mechanics of natural selection and natural genetics, which are more robust and more likely to locate global optimum. It is because of this feature that GA goes through solution space starting from a group of points and not from a single point. The cutting conditions are encoded as genes by binary encoding to apply GA in optimization of machining parameters. A set of genes is combined together to form chromosomes, used to perform the basic mechanisms in GA, such as crossover and mutation. To evaluate each individual or chromosome, the encoded cutting conditions are decoded from the chromosomes and are used to predict machining performance measures.

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probabilistic in nature. Second, it specifies methods for collection of data appropriately, so that assumptions for the application of appropriate statistical methods to them are satisfied. Lastly, techniques for proper interpretation of results are devised. The advantages of design of experiments as reported by Adler et al. [1975] and Johnston [1964] are as follows.

- Numbers of trials are reduced.
- Optimum values of parameters can be determined.
- Assessment of experimental error can be made.
- Qualitative estimation of parameters can be made.
- Inference regarding the effect of parameters on the characteristics of the process can be made.

Cochran & Cox [1962] quoted Box and Wilson as having proposed response surface methodology for the optimization of experiments. The methodology may be applied for developing the mathematical models in the form of multiple regression equations correlating the dependent parameters such as cutting force, power consumption, surface roughness, tool life etc. with three independent parameters, viz. cutting speed, feed rate and depth of cut, in a turning process. In applying the response surface methodology, the dependent parameter is viewed as a surface to which a mathematical model is fitted.

Lambert & Taraman [1973] developed an adequate mathematical model for the cutting force acting on a carbide tool while machining SAE 1018 cold-rolled steel in a turning operation and then utilized the model in the selection of the levels of the machining variables of cutting speed, feed rate, and depth of cut, such that the rate of metal-removal could be at the highest possible valne without violating some given force restriction. By using response surface methodology the three independent variables (cutting speed, feed rate and depth of cut) could be investigated simultaneously to study their effects on the cutting force, resulting in considerable saving in time and money over traditional methods of analysis.

Taraman [1974] investigated multi-machining ontput multi-independent variable turning research by response snrface methodology. The purpose of this research was to develop a methodology that would allow determination of the cutting conditions (cutting speed, feed rate and depth of cut) such that the specified criterion for each of several machining-dependent parameters (surface finish, tool force and tool life) conld be achieved simultaneously. To accomplish this, first mathematical models were developed representing the relationship between the dependent and independent variables of the process. A central composite design was used to develop the models in order to minimize the amount of experimentation. The models were represented by response surfaces and contours of these surfaces were obtained at different levels of each of the independent variables in planes of the other independent variables. By superimposing the contours, a proper combination of the cutting speed, feed rate and depth of cut can be selected to satisfy some specified criteria. Disposable inserts of tungsten carbide were used to turn SAE1018 cold-rolled steel.

Hassan & Suliman [1990] presented mathematical models for the prediction of surface roughness, tool vibration, power consumption and cutting time, when turning medium carbon steel using tungsten carbide tools under dry conditions. The functional relationships of these variables and the machining-independent variables (cutting speed, feed rate and depth of cut) were established by a second-order polynomial multi-regression analysis. The surface roughness model developed was used as an objective function to establish the optimum cutting conditions while the tool vibration level, power consumption and cutting time were considered the functional constraints.

El Baradie [1993] presented a study of the development of a surface roughness model for turning grey cast iron (154 BHN) using tipped carbide tools under dry conditions and for a constant depth of cut (1.00 mm). The mathematical model utilizing the response surface methodology was developed in terms of cutting speed, feed rate and nose radius of the cutting tool. These variables were investigated using design of experiments and utilization of the response surface methodology. The turning operation was performed on a 10 h.p. lathe. The work pieces were cast in the form of cylindrical bars 200mm in diameter and approximately 500mm in length. The cutting tests were carried out using a tungsten carbide insert (grade K10). Surface roughness measurements were made nsing a Taylor–Hobson Surtronic surface roughness measuring instrument. A first-order model covering the cutting speed range of 110–350 m/min and a second-order model covering the cutting speed range of 80–495 m/min are presented in this study. Contours of the surface roughness outputs were obtained in planes containing two of the independent variables. These contours were further developed to select the proper combination of the cutting speed and feed rate to increase the metal removal rate without sacrificing the quality of the surface roughness produced.

2.6 Summary of the Review

A review of the literature on machinability of different commercial steel or other metals places of interest the immense potential of the control of machining temperature and its detrimental effects and indicates that coolant application plays a significant role in the optimization of machining processes. It is realized that the machining temperature has a critical influence on chip reduction coefficient, cutting forces, tool wear and tool life. All these responses are very important in deciding the overall performance of the tool and the economy of machining .At the elevated temperature the cutting tools may undergo plastic deformation and attain rapid tool wear because by adhesive, abrasive, chemical and diffusion wear at the flanks and the crater. The dimensional accuracy and surface integrity of the workpiece also deteriorate due to high temperature.

Increasing the metal removal rate means that more material can be cut in a shorter time and this has been achieved by increasing the cutting speed, the feed rate and the depth of cut. To do this in an economical way depends on many areas related with metal cutting, namely the machine tool, the cutting tool, the cutting fluid and the material. The interface between the chip and the tool is the most critical area as the highest temperature occurs here and coolants are used to reduce the amount of heat and friction at the point where a tool cuts into a metal workpiece. The cutting fluids used with some cutting operations play a very important role and many operations can not be carried out efficiently with out a fluid. This heat reduction by cutting fluids allows the cutting tool to operate at higher speeds and reduces tool wear. However, at the lower pressures typically used to deliver cutting fluid, the coolant cannot effectively remove the majority of heat at the cutting point. Instead, the coolant washes over the tool, tool holder and workpiece, cooling the surfaces somewhat, but not removing the intense heat within the cutting area itself. In fact, most of this heat is conducted to the material around the shear zone and to the tooling, thus keeping the temperature at the cutting point higher than desired.

By directing the coolant stream more precisely and with the optimum amount of pressure, dramatically more heat can be removed from the cut zone. This degree of cooling also enables the cutting tool to remove greater amounts of metal, thus improving machine tool cycle times. Additionally, this high-pressure coolant stream helps break up chips and remove them from the cutting area more efficiently. The combinatiou of reduced heat and more efficient evacuation of chips prolong tool life and makes replacement more predictable because the cutting tool wears out naturally, rather than failing prematurely because of excessive heat or chip damage.

Thoroughly understanding the application of high pressure coolant jet in machining is critical to properly specifying and installing a high-pressure unit. That's why , It is very vital to use the optimum amount of pressure and flow, recognize the type of nuzzle or orifice to place at the end of the tubing that will properly direct the coolant stream, and set the correct angle and distance from the workpiece to properly hit the appropriate cutting area.

The review of literature also shows that various traditional machining optimization techniques like Lagrange's method, geometric programming, goal programming, dynamic programming etc. have been successfully applied in the past for optimizing the various turning process variables. Fuzzy logic, genetic algorithm, scatter search, Taguchi technique and response surface methodology are the latest optimization techniques that are being applied successfully in industrial applications for optimal selection of process variables in the area of machining. A review of literature on optimization techniques has revealed that there are, in particular, successful industrial applications of design of experiment-based approaches for optimal settings of process variables. Taguchi methods and response surface methodology are robust design techniques widely used in industries for making the product/process insensitive to any uncontrollable factors such as environmental variables.

2.7 Objectives of the Present Work

It is exposed from the aforementioned literature review that high-pressure jet–assisted machining is starting to be established as a method for substantial increase of removal rate and productivity in the metal cutting industry. The economy of machining steel is strongly connected to effective chip control, for higher utilization of machines and temperature reduction in the tool, for raising the rates of metal removal. The main advantage with a high-pressure jet directed at the rake face is the possibility to control the chip flow direction by a hydraulic wedge in combination with a reduction of the tool temperature With an established reduction in temperature, there is a significant possibility to extend tool life or increase the maximum cutting speed, which is important for improving the productivity. Therefore, there have been several studies on applying coolant at high pressure at the tool–chip interface, focused on a stationary single cutting edge in a turning operation. However, there is a need to improve machining conditions for the high MRR with minimal costs. So, thorough investigation is essential to explore the potential benefits of high-pressure coolant (HPC) jet assisted machining. But enough work has not been done systematically yet in this direction.

The objectives of the present work is to make an experimental investigation on the roles of high pressure coolant (HPC) jet on the major machinability characteristics in respect of

i. chip morphology (shape, color and chip reduction coefficient)
ii. average chip-tool interface temperature
iii. cutting forces (main cutting force and feed force)
iv. surface finish and
v. dimensional deviation.

in machining steel by the industrially used uncoated carbide tool (SNMG 120408 TTR) at different speeds and feeds combinations and to optimise the pressure and flow rate for favourable chip-tool interaction, sufficient rednction in cutting temperature and cutting forces and improvement of surface finish.

Chapter-3

Experimental Investigations

3.1 Introduction

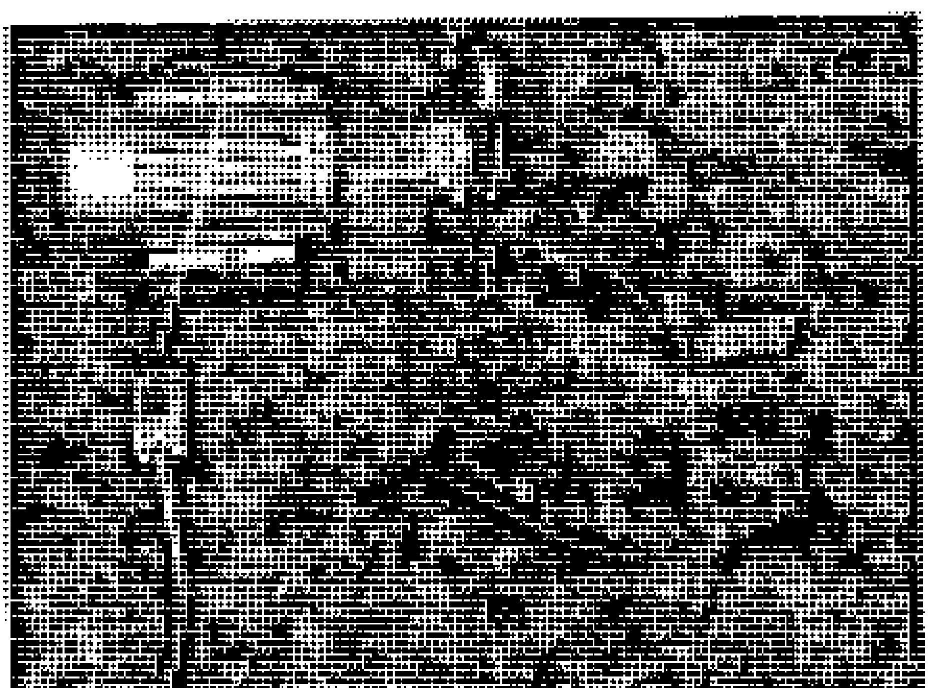
The economy of machining steel is strongly connected to effective chip control, for higher utilization of machines and temperature reduction in the tool, for raising the rates of metal removal. Previous researches have described that chip breakage can be achieved by introducing a high pressure fluid wedge into the gap between the tool and chip interface [**Kaminski et al. 1977, Shane et al. 2001, Vomacka et al. 2000, and Manouchehr Vosough 2002**]. To complement this, a comprehensive survey on the jet preperties of the fluid to enable not only chip breakage but also chip form control was performed. Results from the survey show that by changing pressure level and flow of the jet it is possible to create resulting force acting upon the chip. With an established reduction in temperature, the tool life will be prolonged. The results show significant possibilities to extend tool life or increase the maximum cutting speed, which is important for improving the productivity [**Patrik Dahlman 2000, Konig et al. 1993, Manouchehr Vosough 2002**]. So high-pressure jet–assisted machining is starting to be established as a method for substantial increase of removal rate and productivity in the metal cutting industry [**Pigott et al. 1952, Mazurkiewicz et al. 1991, Shet et al. 2003, Manouchehr Vosough 2004**]. Now high-pressure jet-assisted machining has been widely used on so-called "hard to machine materials" such as high-temperature alloys and titanium [**Lopez et al. 2000**] where materials cannot be cut effectively without cooling.

Cutting with an excess amount of cutting fluids is still very common in conventional machining to control high cutting temperature which adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products. Even if a trend towards dry cutting is starting to grow fast. However, many materials such as high alloy steels and titanium can not be effectively cut without cooling. Research made in the past has shown the high potential with high-pressure jet-assisted machining, compared to conventional cooling in which water, oil and regular cutting fluids were used. The jet can be applied into the gap between the chip and tool-rake face or on the tool clearance. The main advantage with a high-pressure jet directed at the rake face is the possibility to control the chip flow direction by a hydraulic wedge in combination with a reduction of the tool temperature. In the other case i.e. jet towards the clearance face, chip control is not possible since a build-np of a hydranlic wedge beneath the chip does not occur. Nevertheless, this method allows the coolant to reach close to the cutting edge providing effective cooling. High-pressure cutting omits the BUE (Built-up edge) and makes a soft surface area. This factor shows the chips sliding on the rake surface of inserts. The chips were cooled when they left the cutting zone and there was no sign of melting process in them. The method is recommended for difficult machining materials, which are sensitive to temperature variation, and machining with high cutting velocity.

The effectiveness, efficiency and overall economy of machining any work material by given tool depend largely only on the machinability characteristics of the tool-work material under the recommended condition. Machinability is usually judged by (i) cutting temperature which affects product quality and cutting tool performance, (ii) pattern and mode of chip formation, (iii) magnitude of the cutting forces which affects power requirement, dimensional accuracy and vibration, (iv) surface finish and (v) tool wear and tool life. The present work tried to make an experimental investigation on the role of high-pressure coolant in turning AISI-4320 steel with uncoated Carbide inserts (SNMG 120408 TTR) and overall benefits in respects of average chip-tool and work-tool interface temperature, chip morphology surface finish. Then optimize the pressure and flow rate at which there is a reduced optimum temperature and less force required for cutting, improved surface finish and good dimensional accuracy. Finally measure the cutting forces (main cutting force and feed force) and dimensional deviation under both dry and HPC (at optimum P & Q) to investigate the improvement of HPC machining over dry machining.

3.2 HPC Jet Delivery System

HPC set-up consists of an electrical motors (5 hp) coupled to a high-pressure vane pump, a composite unit of flow control valve and pressure compensating relief valve, a direction control valve and a filter as shown in Fig 3.1. 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 HPC 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 vane pump and a gear coupling is used between the vane pump and motor to transmit power. This pump pressurized the coolant to pass through the flow control valve. Flow control valve controls the amount of flow and it is turned to regulate the coolant flow during machining. A relief valve has mounted with flow control valve regulating the composite. Relief valve control the pressure and discharge excess oil to the tank. A pressure gauge is also mounted to detect the pressure of coolant so that we can observe at what pressure the coolant is delivered during machining. 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.



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3.3 Experimental Procedure

Machining ferrous metals by carbides is a major activity in the machining industries. Machining of steel involves more heat generation for their ductility and production of continuous chips having more intimate and wide chip-tool contact. Again, the cutting temperature increases further with the increase in strength and hardness of the steels for more specific energy requirement. Keeping these facts in view the commonly used steel like AISI-4320 steel has been undertaken for the present investigations. Considering common interest and time constraint, only uncoated carbide inserts have been used for the present investigation. The machining trials were carried out by turning AISI 4320 Steel rod having initial diameter 192 mm and length 520 mm in a high power rigid lathe (10 hp) by using uncoated carbide insert (SNMG 120408 TTR) with different combination of cutting velocities (V_c) and feed (S_o) under high-pressure coolant condition having various pressure and flow rates. Depth of cut is kept constant throughout the machining trials. HC straight run, VG 68 cutting oil were used during HPC jet assisted turning. The high pressure coolant was delivered at various pressure and flow rates and directed through a nozzle on the tool holder to the region where the chip–tool contact is intimate. After then, measurement of cutting forces (main cutting force and feed force) under both dry and high pressure coolant (at optimized flow and pressure) conditions were carried out with the help of lathe-tool dynamometer and captured data was analyzed by computer. Dimensional deviation at optimum pressure and flow rate was also measured for the machining trials. The conditions under which the machining tests have been carried out are briefly stated in Table 3.1.

A number of V_c and S_o have been taken over relatively wider ranges keeping in view the industrial recommendations for the tool-work materials undertaken and evaluation of role of variation in V_c and S_o on the effectiveness of high-pressure coolant.

Table 3.1 Experimental Conditions

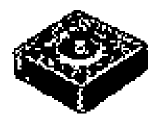
Machine tool	:	Lathe Machine (10 hp)
Work material	:	AISI 4320 Steel (φ192 X 520 mm)
Cutting Insert	:	SNMG uncoated carbide insert. 
Cutting oil	:	HC straight run, VG 68
Tool holder	:	PSBNR 2525M12 (ISO specification)
Working tool geometry	:	Inclination angle : -6°
	:	Rake angle : -6°
	:	Clearance angle : 6°
	:	Auxiliary cutting edge angle : 15°
	:	Principal cutting edge angle : 75°
	:	Nose radius : 0. 8 mm
Process parameters		
Cutting velocity, V_C	:	104 , 148 , 211 and 296 m/min
Feed rate, S_o	:	0.10, 0.14, 0.18 and 0.22 mm/rev
Depth of cut, t	:	1.5 mm
HPC supply	:	Pressure 30, 50, 70 & 90 bar and Flow rate 3, 4, 5 & 6 liter/minute through external nozzle.
Environments	:	Dry and high-pressure coolant (HPC) condition

Fig.3.2 Photographic view of calibration setup

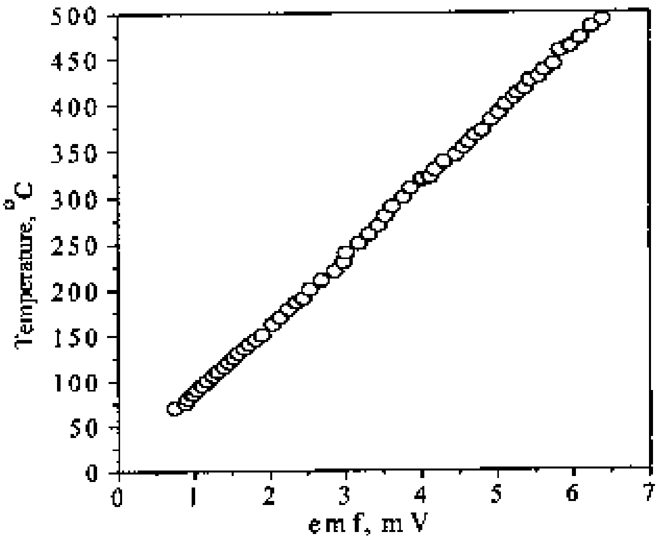


Fig.3.3 Temperature calibration curve

The average cutting temperature (θ_{avg}) was measured by simple but reliable tool work thermocouple technique with proper calibration. A junction of AISI 4320 steel strip and tungsten carbide is embedded in a uniform heating graphite block placed in an electric crucible heater and free terminals of metal strip and carbide are connected to a millivoltmeter. A temperature probe is placed into another hole equidistant from the crucible wall to get the temperature readings. Temperature and millivolt data are recorded, analyzed through polynomial regression and equation for temperature is derived. Fig.3.2& 3.3 are showing the photographic view and temperature-emf graph respectively.

The roughness of the machined surface after each cut was measured by a Talysurf (Sutronic 3^+, Rank Taylor Hobson limited). The results are documented and plotted at various pressure and flow rate having various combinations of velocities and feed.

3.4 Experimental Investigation

It was found by previous researchers that high pressure coolant (HPC) assisted turning provided significant improvements expectedly, though in varying degree, in respect of chip formation modes, cutting forces, tool wear, surface finish, and dimensional deviation throughout the V_C-S_0 range undertaken mainly due to reduction in the average chip tool interface temperature and favorable change in the chip-tool and work-tool interaction. S_0, we have collected and organized various data and plotted graph primarily under HPC condition to show the variation in responses (temperature. zeta, surface roughness) with the change in pressure and flow rate at industrial cutting velocity and feed rate combinations so that most significant value of pressure and flow rate can be determined .After optimization, force and dimensional deviation data at optimized pressure and flow rate are compared to each other under both dry and HPC condition to reflect the improvement by HPC environment. The various graph and related data are given below step by step with their respective topics.

3.4.1 Cutting Temperature

A diversity of physical phenomena, such as large plastic deformation, heat generation, friction. damage etc. exists in the process zone where the chip separation occurs. When ductile materials are machined, the mechanical energy consumed in the cutting area is converted into heat and this heat is generated at the (a) primary deformation zone due to shear and plastic deformation (b) chip-tool interface due to secondary deformation and sliding (c) 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. The interaction of these heat sources, combined with the geometry of the cutting area, resnlts in a complex temperature distribution. The temperature generated in the shear plane is a function of the shear energy and the specific heat of the material. Temperature increase on the tool face depends on the friction conditions at the interface. A low coefficient of friction is, of course, desirable. Temperature distribution will be a function of, among other factors, the thermal conductivities of the work piece and the tool materials, the specific heat, cutting speed, depth of cut, and the use of a cutting fluid. As cutting speed increases, there is little time for the heat to be dissipated away from the cutting area and so the proportion of the heat carried away by the chip increases. Therefore, attempts are made to reduce this detrimental high 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 bulk plastic contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk 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.

HPC Jet systems are able to penetrate the high-temperature cutting zone on turning operations to deliver vital lubricant to the cutting edge of the tool. This means that temperatures are dramatically lowered due to reduced friction, the tools last longer and higher cutting speeds and feed can be adopted. The cutting temperature generally increases with the increase in V_C and S_0, though in different degree, due to increased energy input and it could be expected that HPC would be more effective at higher values of V_C and S_0 which would be clear from Fig. 3.4 to Fig. 3.19.

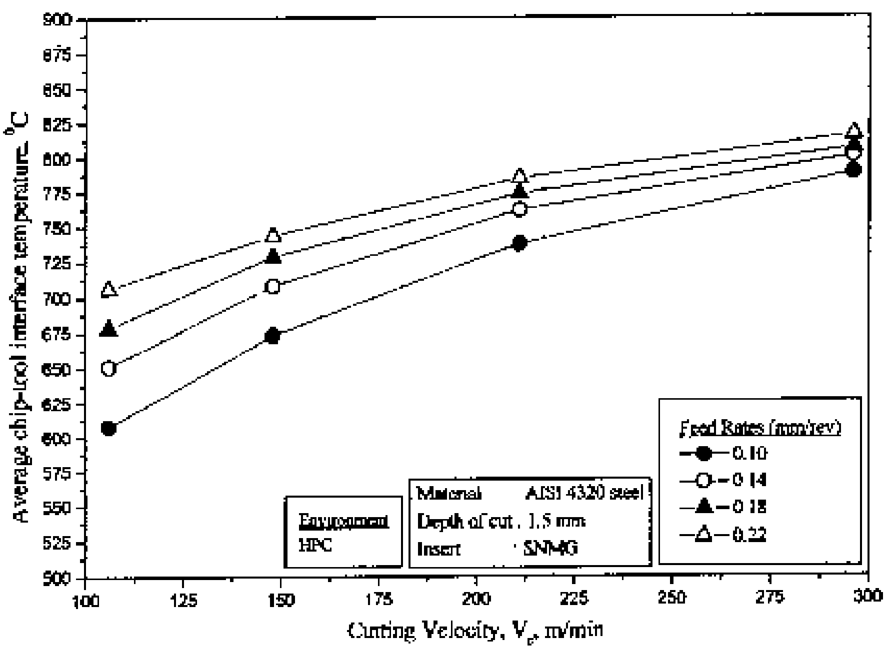


Fig. 3.4 Variation in chip-tool interface temperature with V_c at different S_0 under HPC condition at P=30 bar, Q=3 L/min

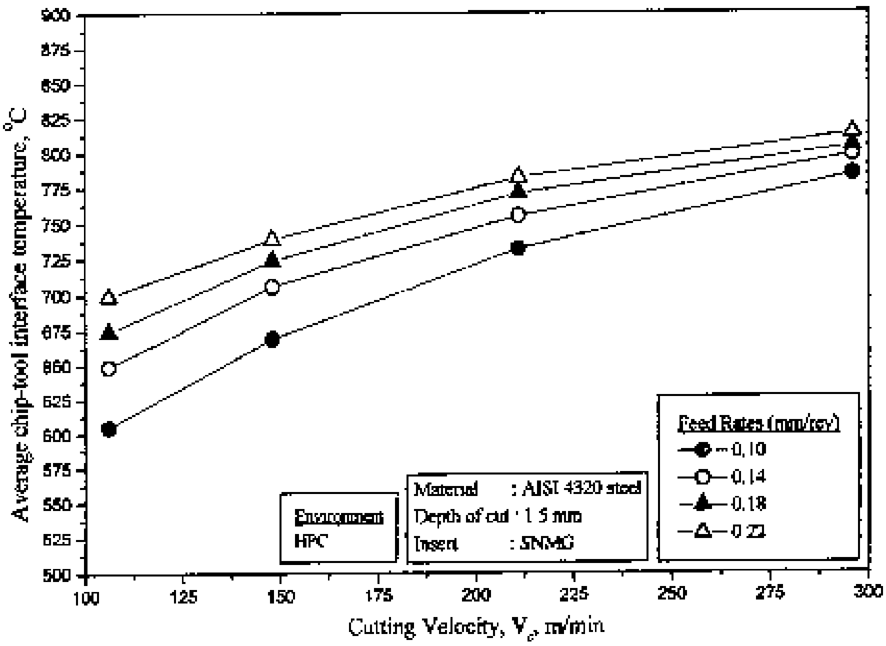


Fig. 3.5 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=30 bar, Q=4 L/min

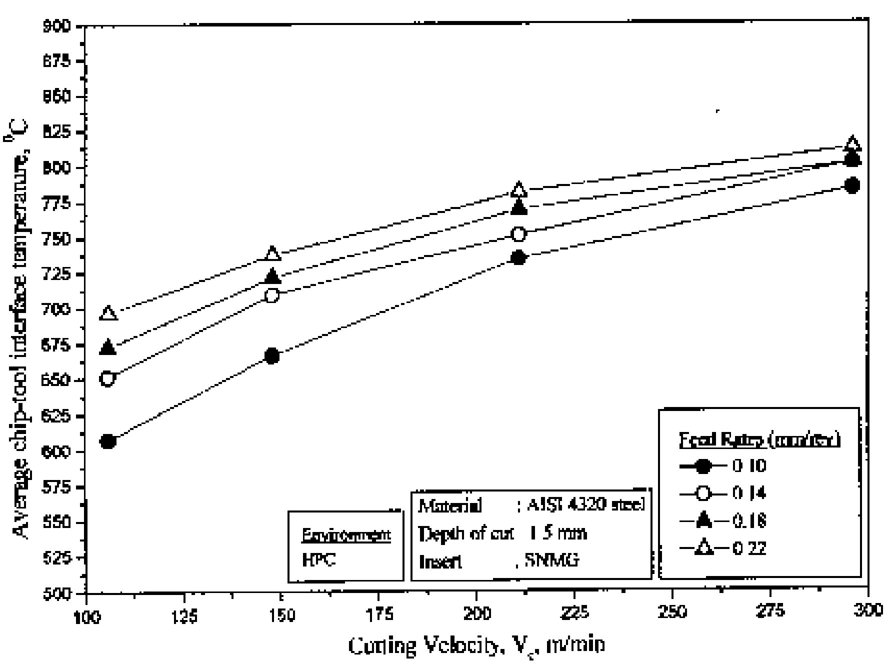


Fig. 3.6 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=30 bar, Q=5 L/min

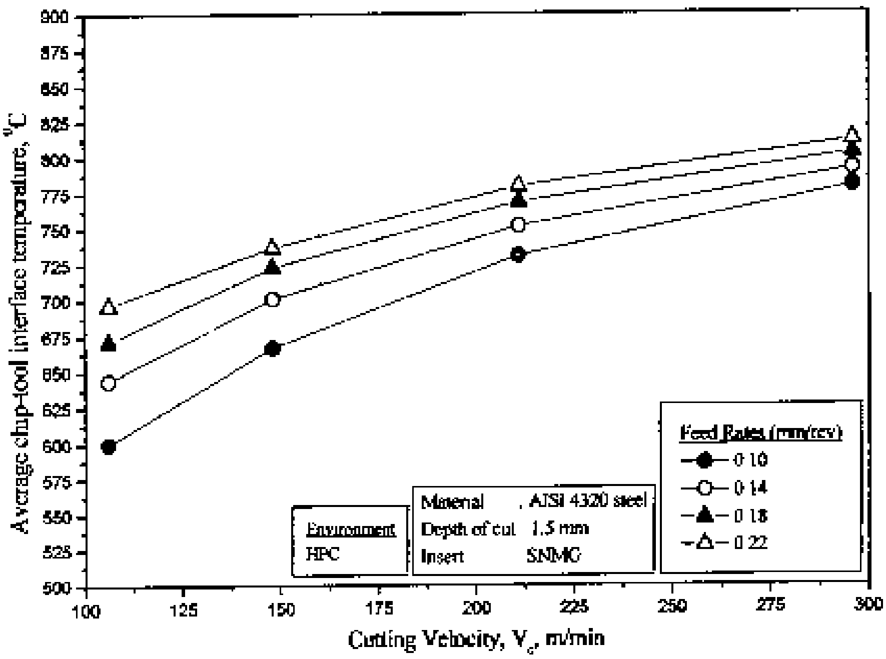


Fig. 3.7 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=30 bar, Q=6 L/min

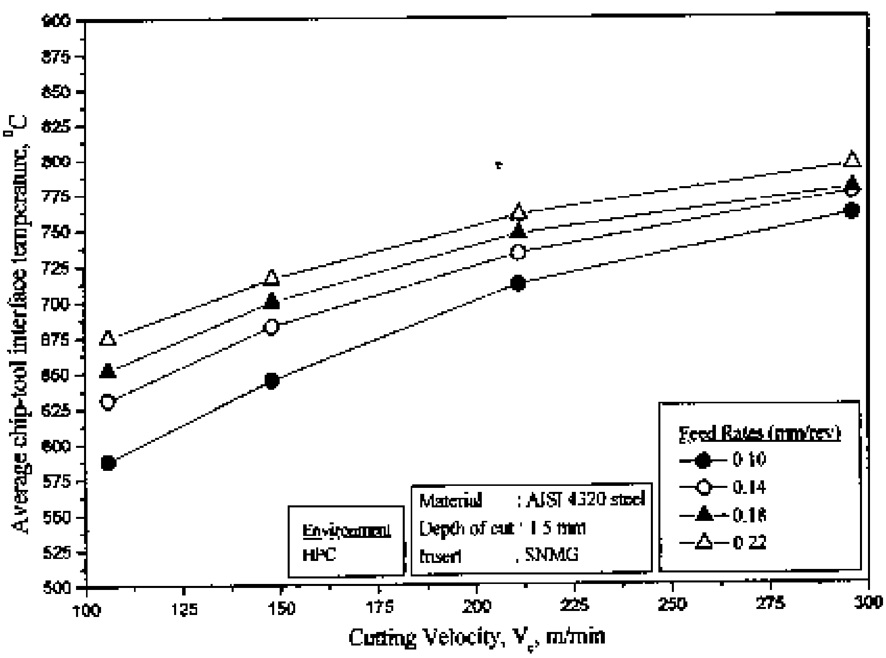


Fig. 3.8 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=50 bar, Q=3 L/min

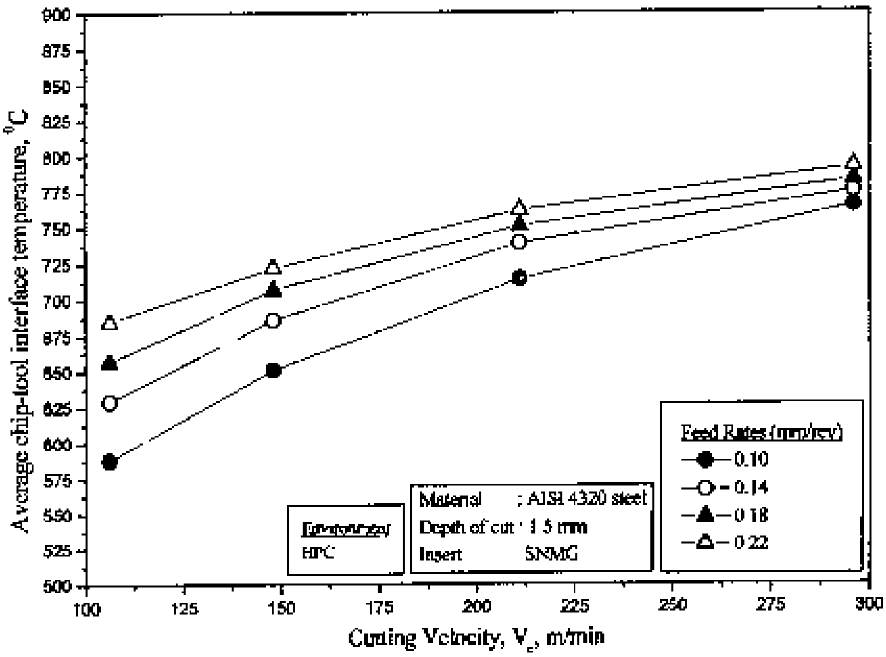


Fig. 3.9 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=50 bar, Q=4 L/min

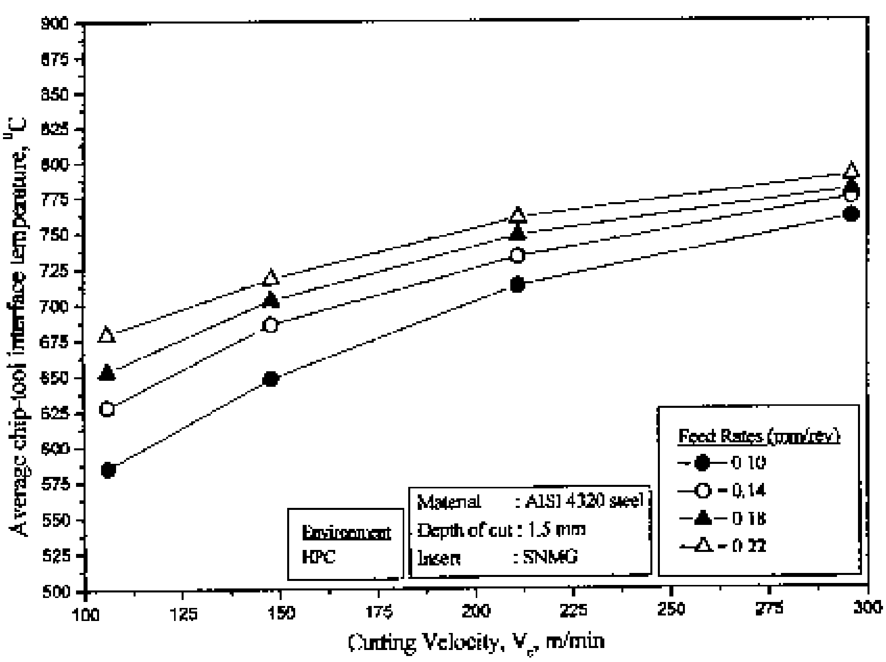


Fig. 3.10 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=50 bar, Q=5 L/min

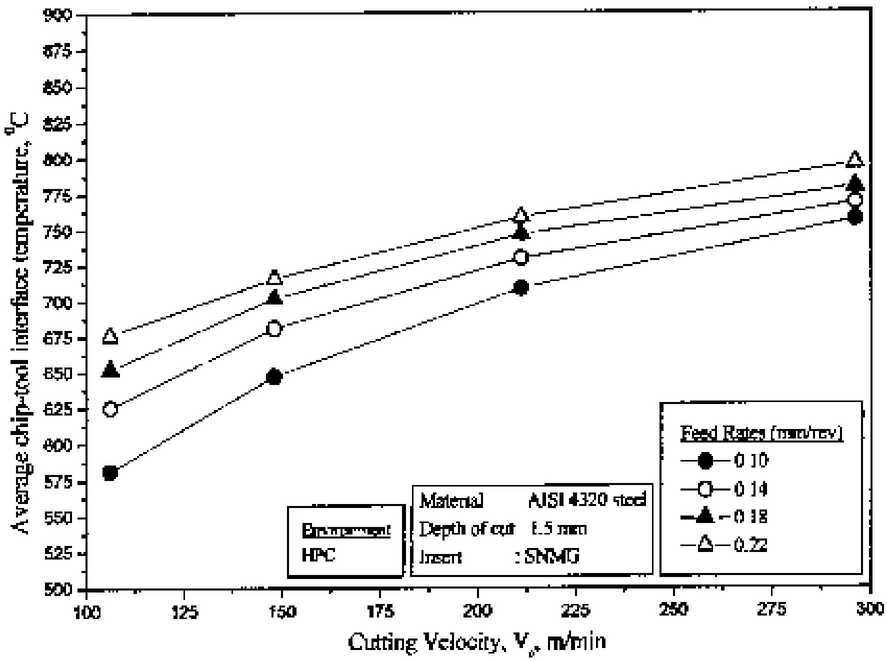


Fig. 3.11 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=50 bar, Q=6 L/min

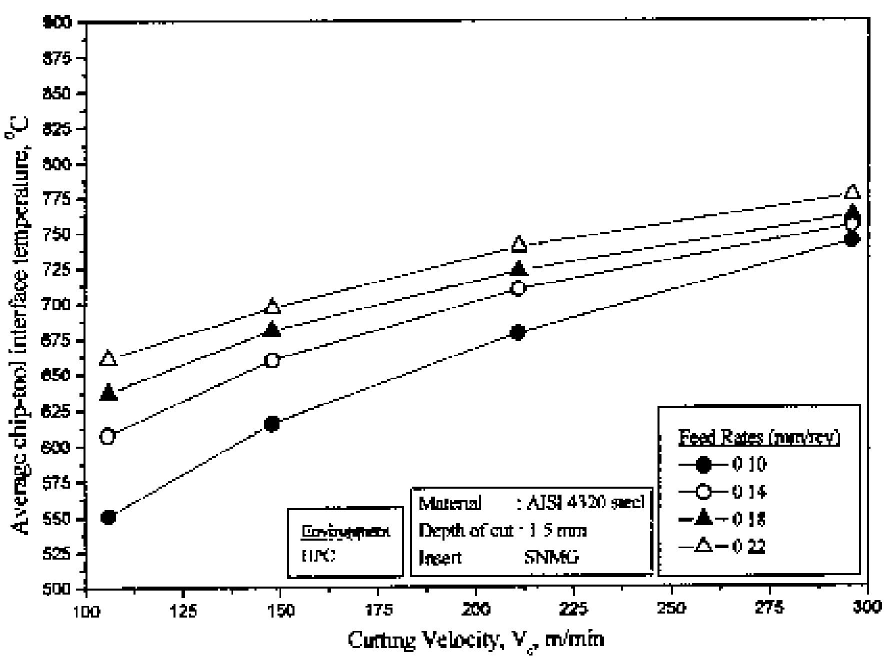


Fig. 3.12 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=70 bar, Q=3 L/min

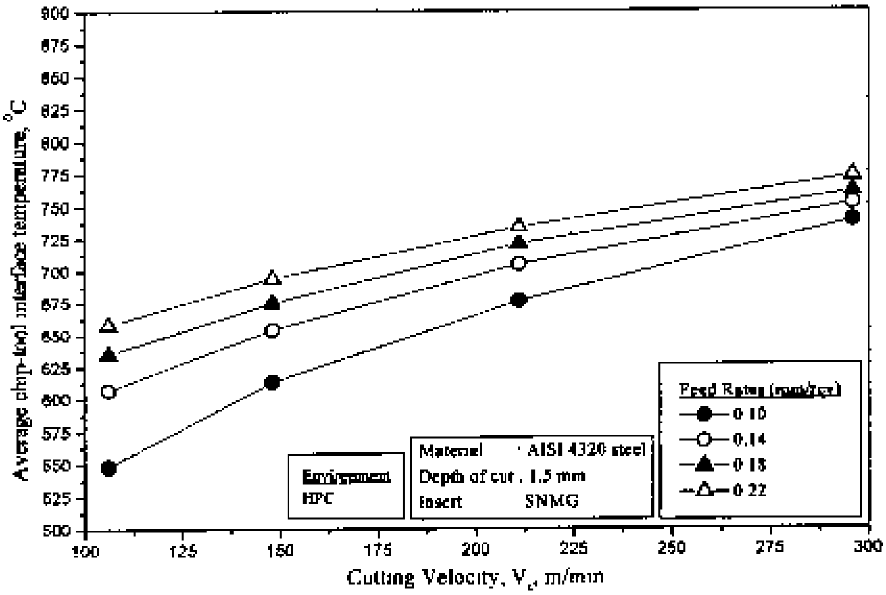


Fig. 3.13 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=70 bar, Q=4 L/min

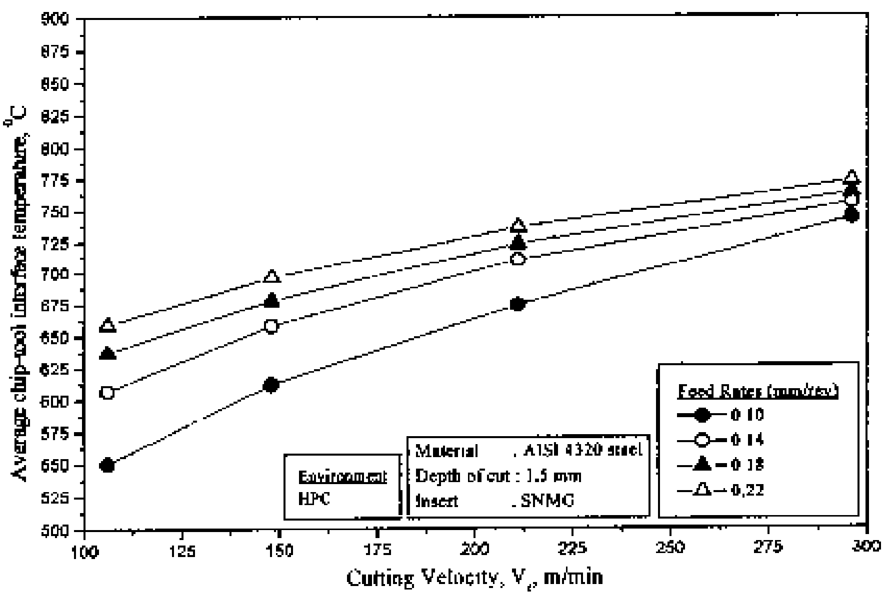


Fig. 3.14 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=70 bar, Q=5 L/min

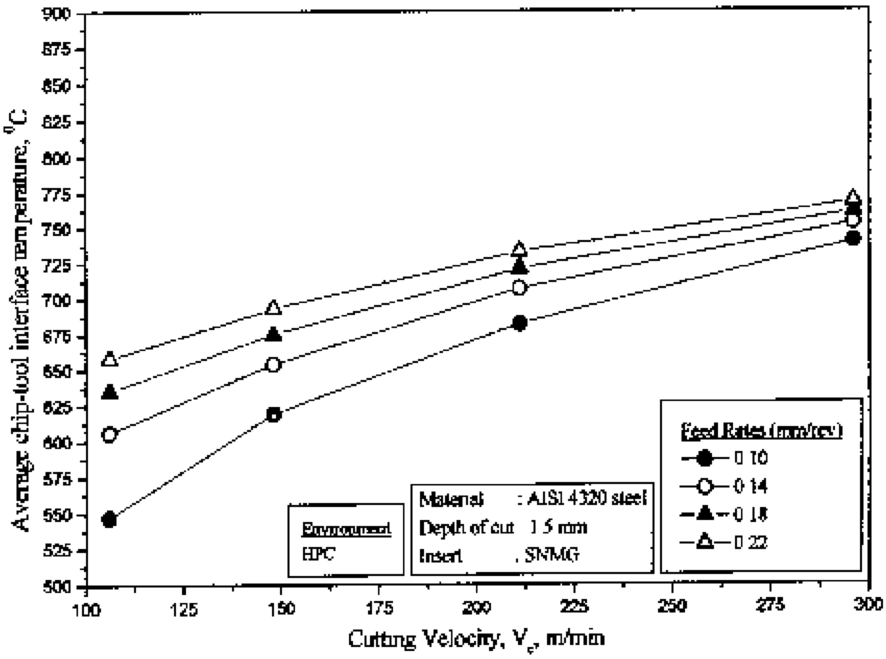


Fig. 3.15 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=70 bar, Q=6 L/min

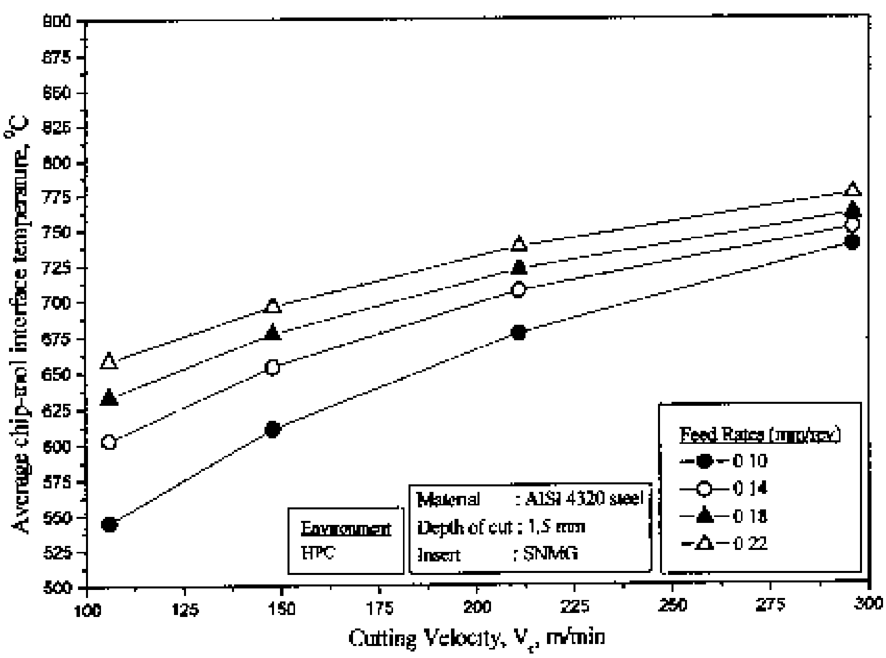


Fig. 3.16 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=90 bar, Q=3 L/min

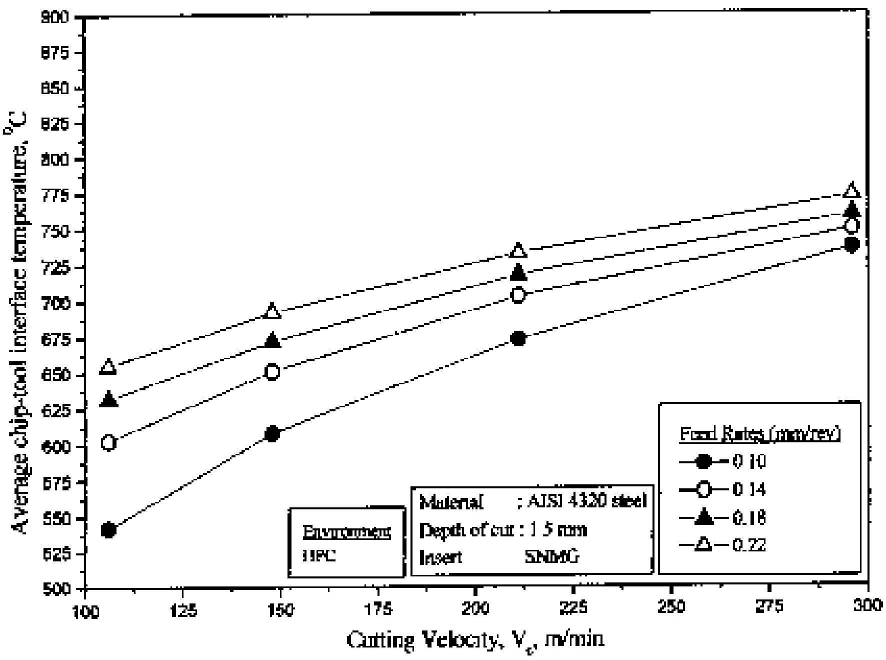


Fig. 3.17 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=90 bar, Q=4 L/min

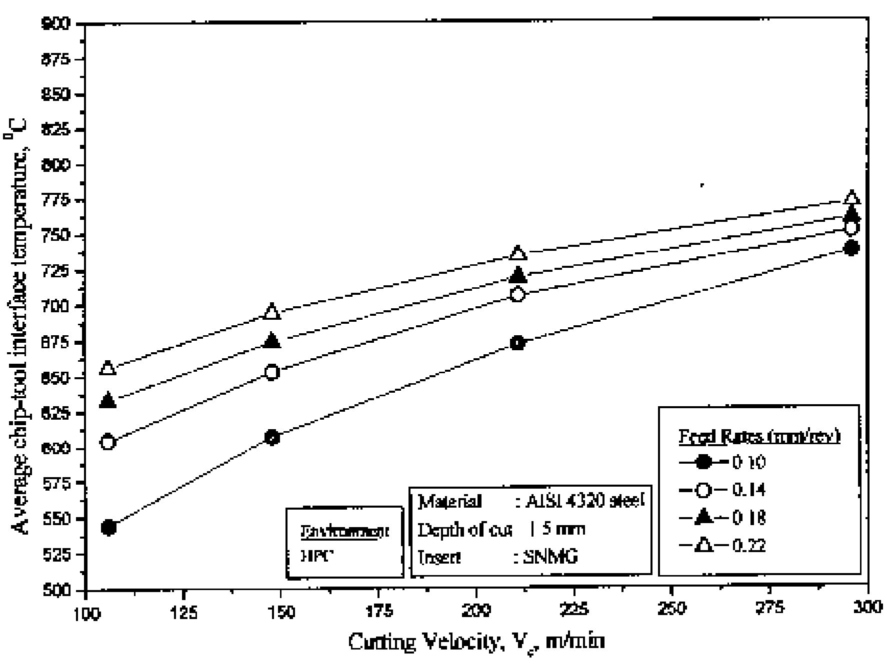


Fig. 3.18 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=90 bar, Q=5 L/min

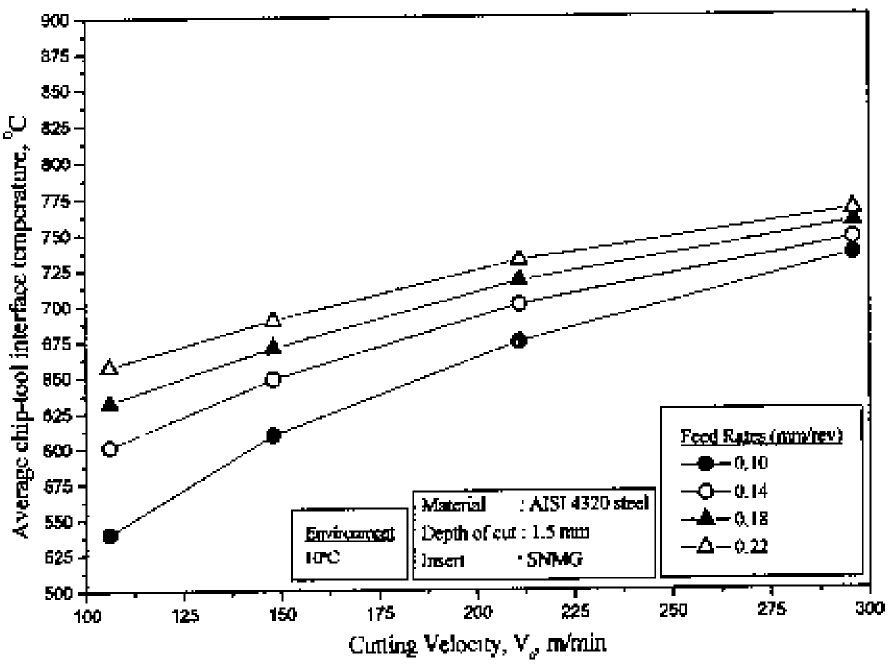


Fig. 3.19 Variation in chip-tool interface temperature with V_c at different S_o under HPC condition at P=90 bar, Q=6 L/min

Generally, coolants are used to reduce the amount of heat and friction at the point where a tool cuts into a metal work piece. This heat reduction allows the cutting tool to operate at higher speeds and reduces tool wear. However, conventional cutting fluids are used to be delivered at typical lower pressures at which the coolant cannot effectively remove the majority of heat at the cutting point. Instead, the coolant washes over the tool, tool holder and work piece, cooling the surfaces somewhat, but not removing the intense heat within the cutting area, itself. In fact, most of this heat is conducted to the material around the shear zone and to the tooling, thus keeping the temperature at the cutting point higher than desired. Poor coolant delivery and low pressure can lead to a number of adverse effects such as premature tool failure due to abrasion and thermal shock, chipping caused by re-cutting swarf, dimensional variation due to thermal growth from frictional heat, work hardening of the surface (which can affect secondary operations) and lower levels of surface finish. In the current work, to investigate effect of coolant pressure on average chip-tool interface temperature, P V_S θ_{avg} graphs are plotted which are shown from Fig. 3.20 to Fig. 3.35.

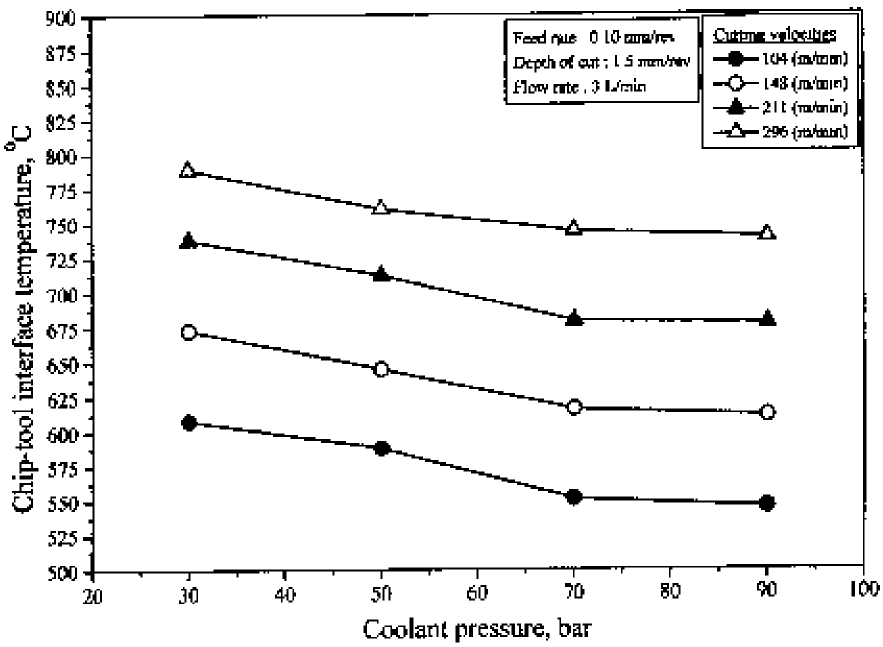


Fig. 3.20 Variation in chip-tool interface temperature under variable P and V_c at Q=3 L/min, S_o=0.10 mm/rev

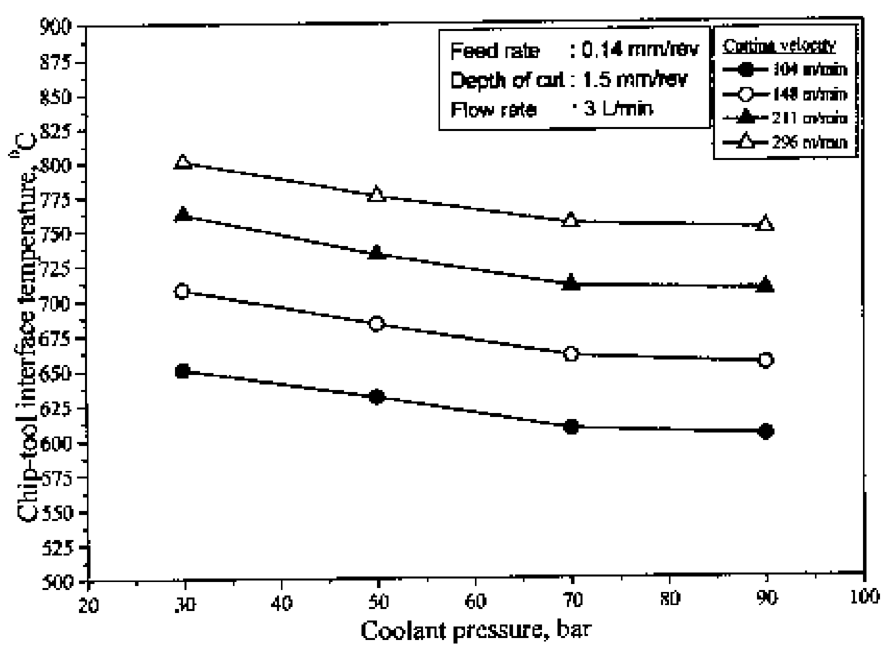


Fig. 3.21 Variation in chip-tool interface temperature under variable P and V_c at Q=3 L/min, S_o=0.14 mm/rev

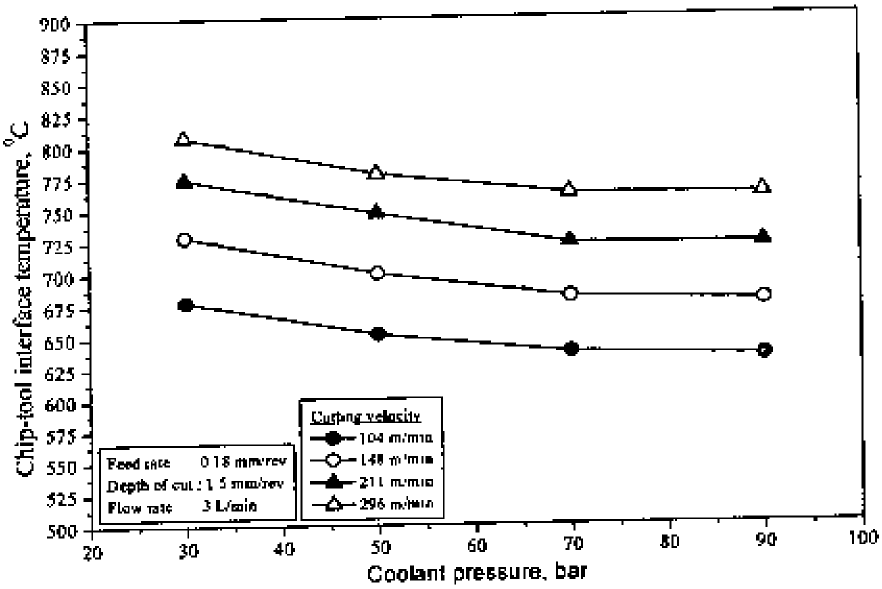


Fig. 3.22 Variation in chip-tool interface temperature under variable P and V_c at Q=3 L/min, S_o=0.18 mm/rev

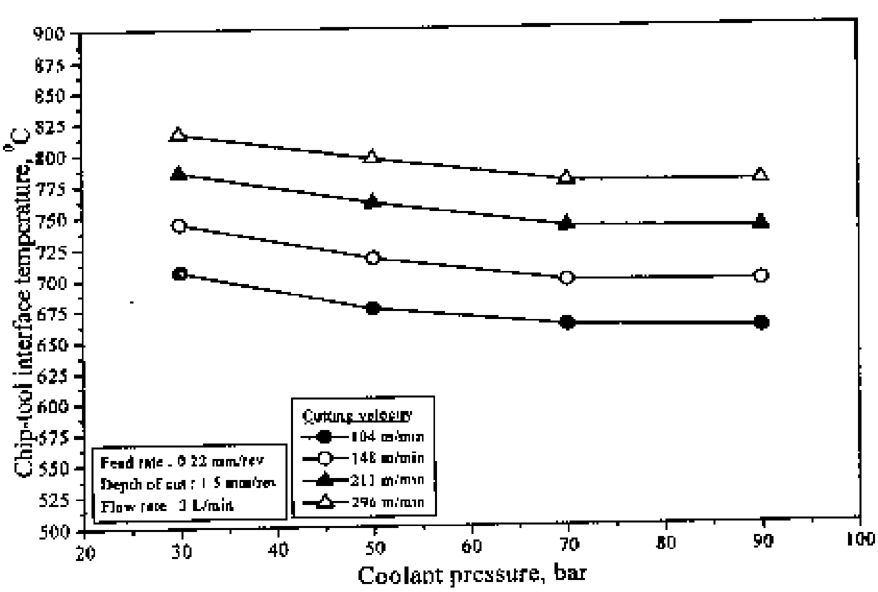


Fig. 3.23 Variation in chip-tool interface temperature under variable P and V_c at Q=3 L/min, S_o=0.22 mm/rev

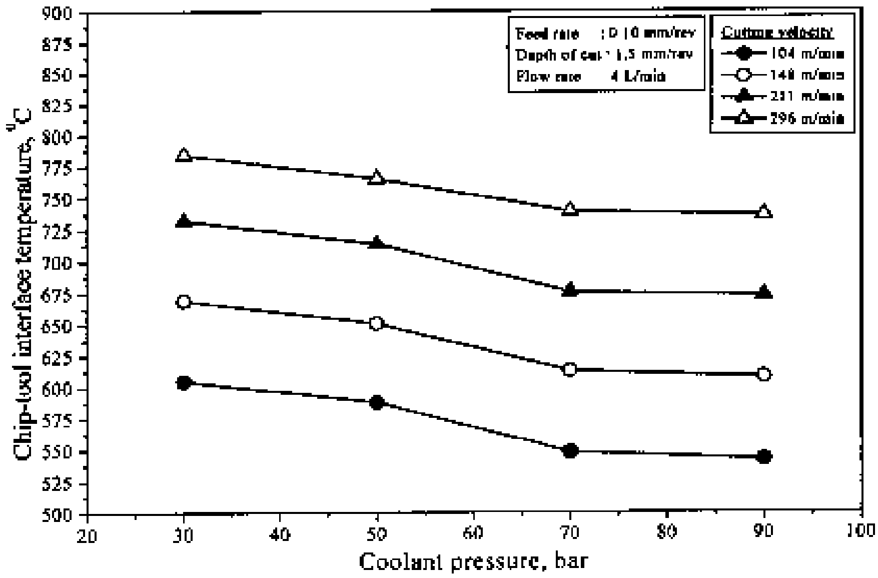


Fig. 3.24 Variation in chip-tool interface temperature under variable P and V_c at Q=4 L/min, S_0=0.10 mm/rev

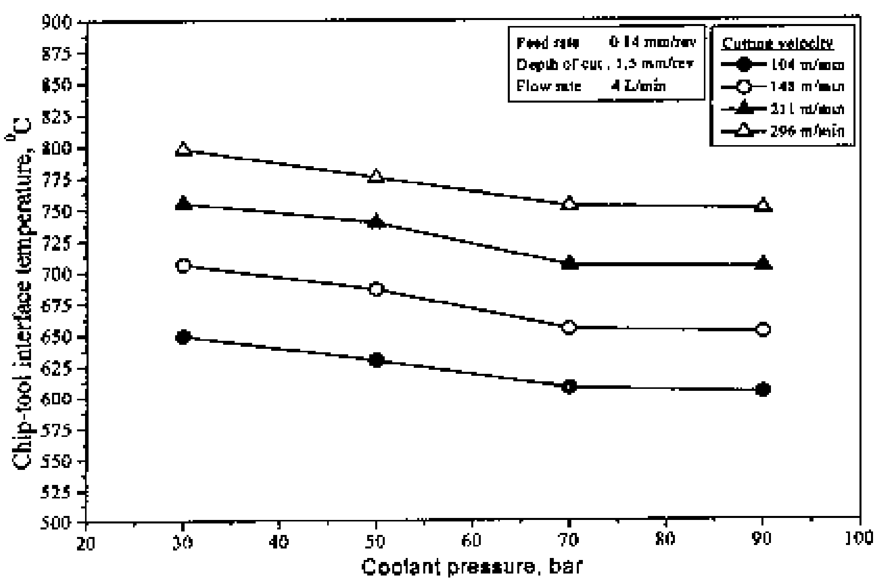


Fig. 3.25 Variation in chip-tool interface temperature under variable P and V_c at Q=4 L/min, S_0=0.14 mm/rev

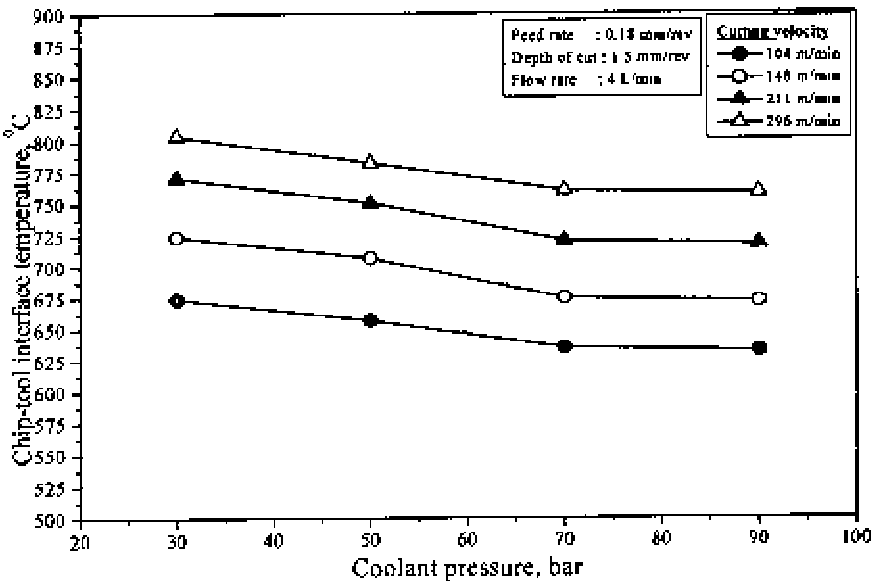


Fig. 3.26 Variation in chip-tool interface temperature under variable P and V_c at Q=4 L/min, S_o=0.18 mm/rev

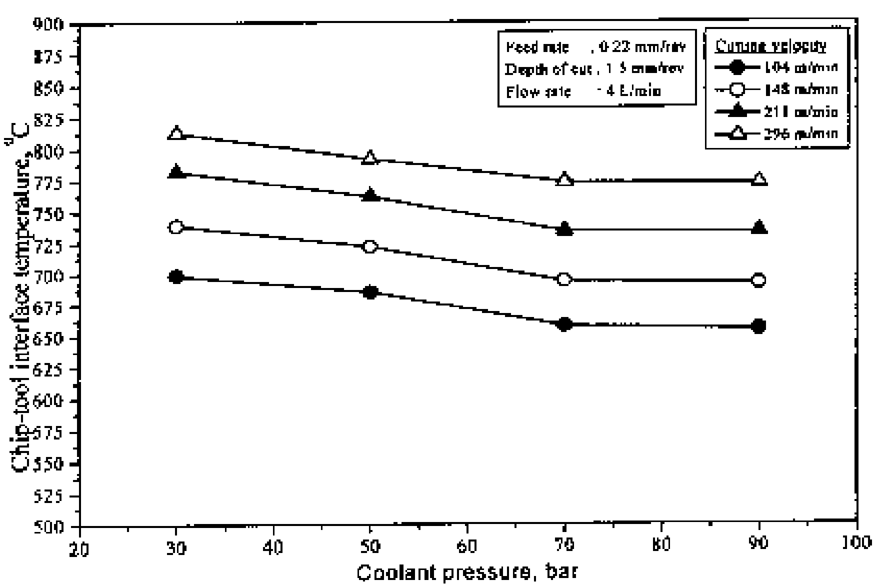


Fig. 3.27 Variation in chip-tool interface temperature under variable P and V_c at Q=4 L/min, S_o=0.22 mm/rev

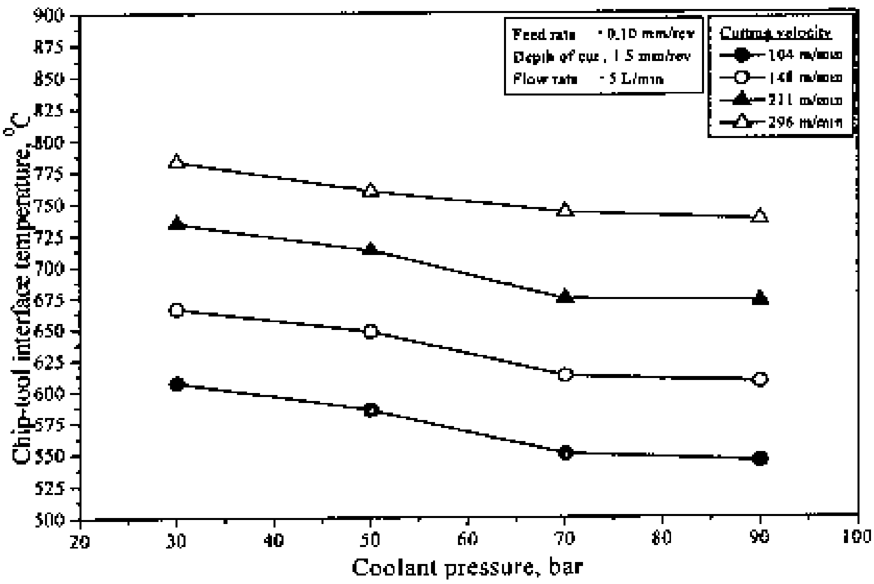


Fig. 3.28 Variation in chip-tool interface temperature under variable P and V_c at Q=5 L/min, S_o=0.10 mm/rev

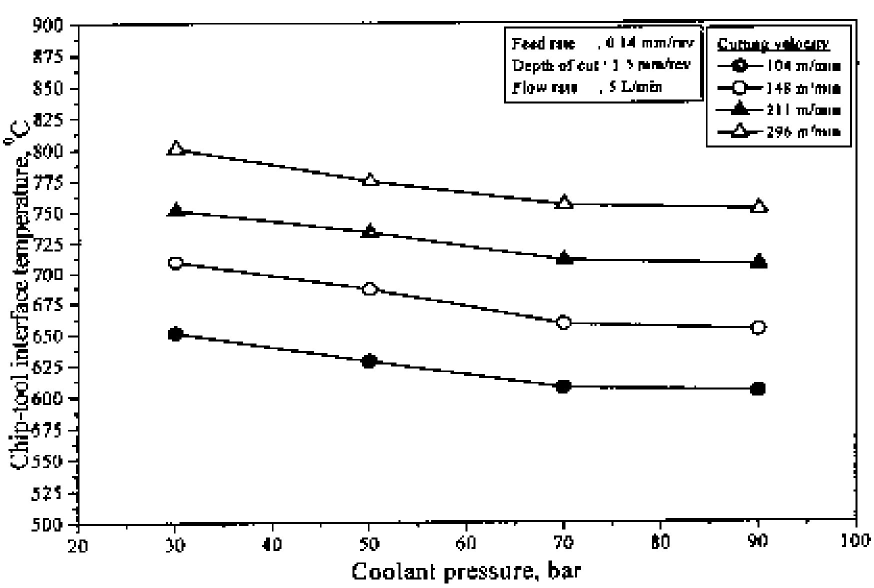


Fig. 3.29 Variation in chip-tool interface temperature under variable P and V_c at Q=5 L/min, S_o=0.14 mm/rev

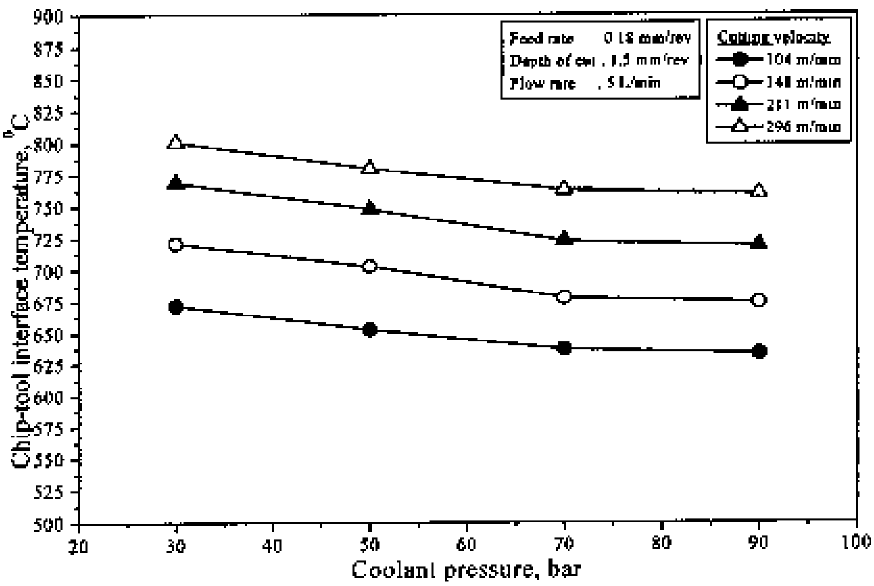


Fig. 3.30 Variation in chip-tool interface temperature under variable P and V_c at Q=5 L/min, S_o=0.18 mm/rev

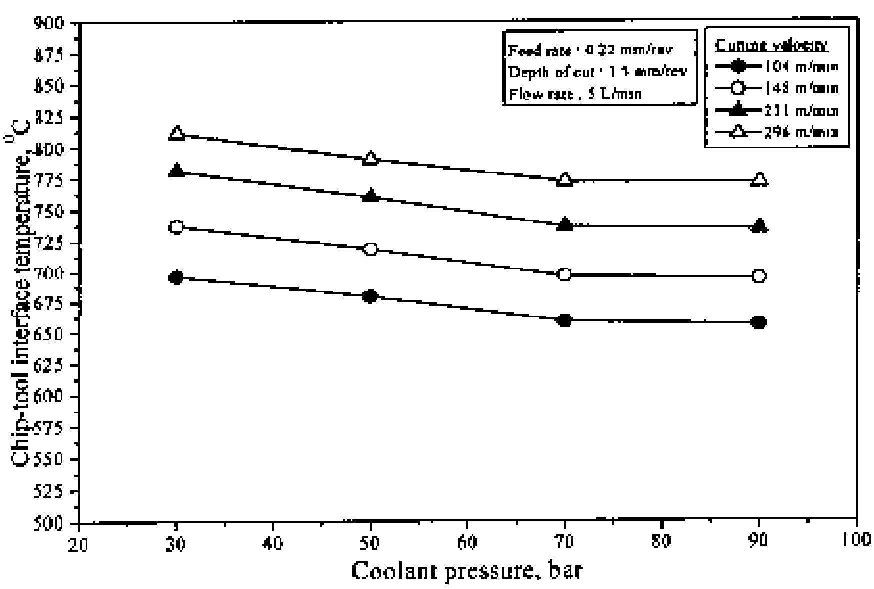


Fig. 3.31 Variation in chip-tool interface temperature under variable P and V_c at Q=5 L/min, S_o=0.22 mm/rev

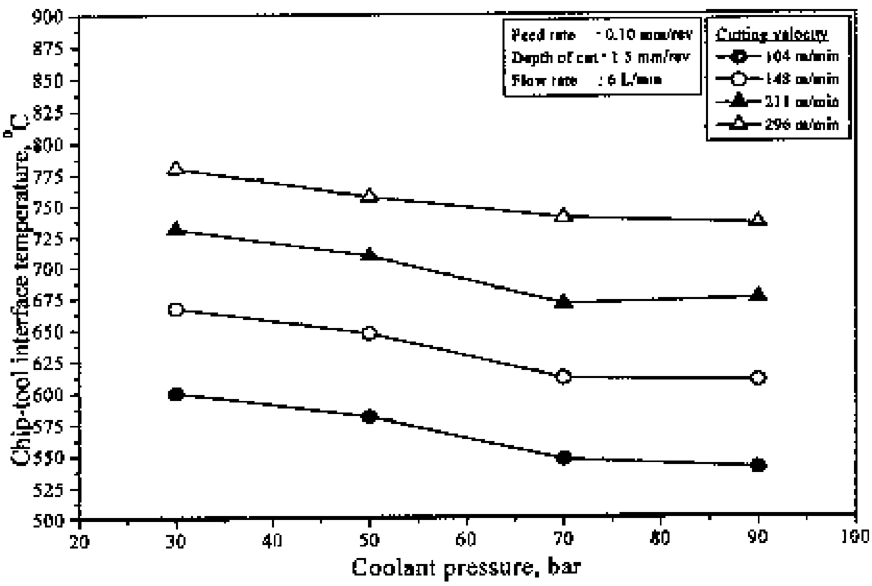


Fig. 3.32 Variation in chip-tool interface temperature under variable P and V_c at Q=6 L/min, S_o=0.10 mm/rev

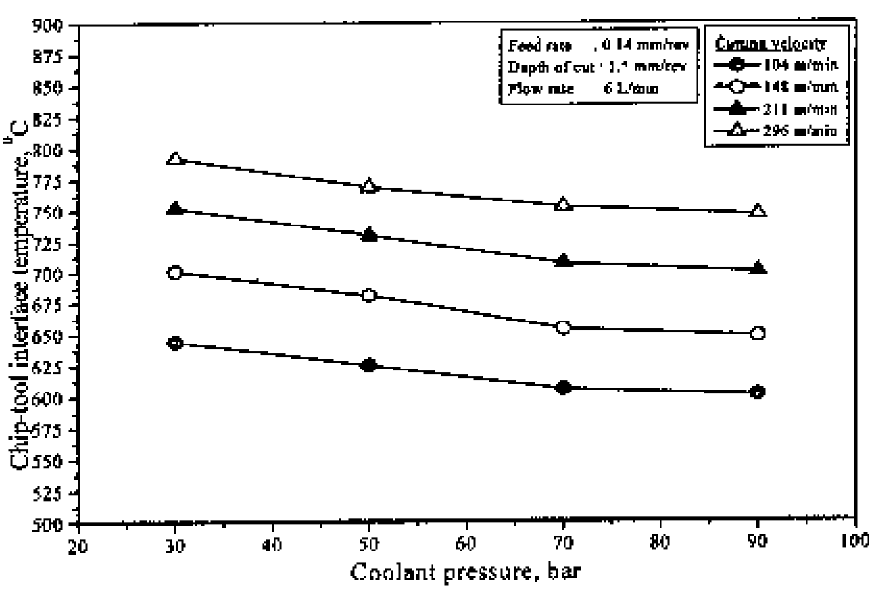


Fig. 3.33 Variation in chip-tool interface temperature under variable P and V_c at Q=6 L/min, S_o=0.14 mm/rev

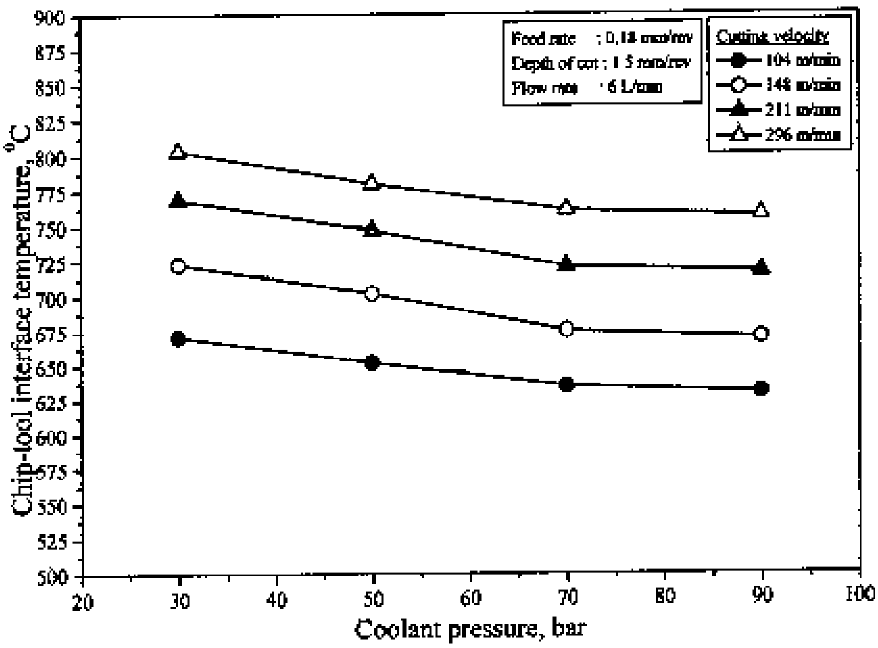


Fig. 3.34 Variation in chip-tool interface temperature under variable P and V_c at Q=6 L/min, S_0=0.18 mm/rev

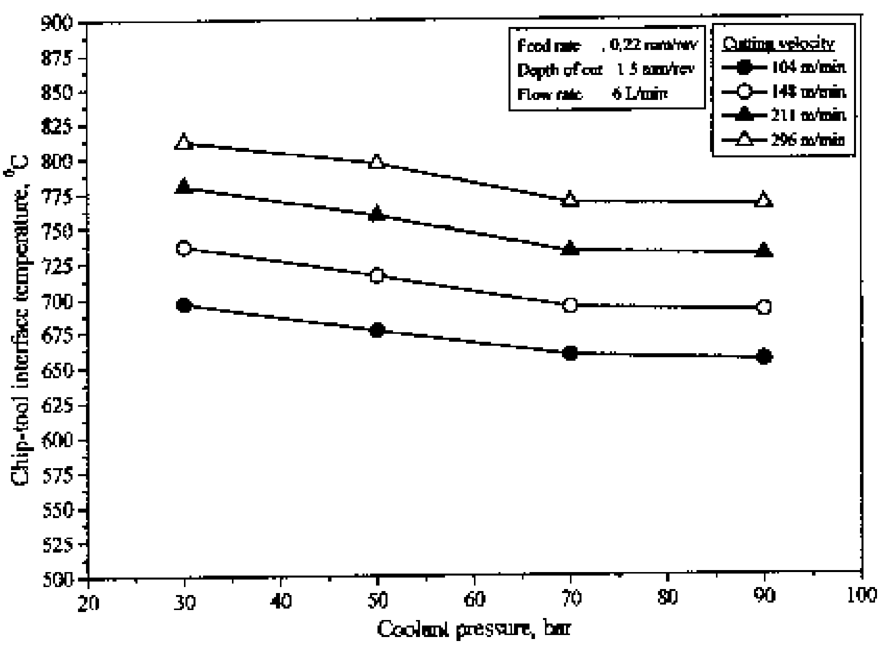


Fig. 3.35 Variation in chip-tool interface temperature under variable P and V_c at Q=6 L/min, S_0=0.22 mm/rev

Flow rate, Q is another important parameter of HPC condition. In the present investigation, four level of flow rate were used to see the variation in responses with the change in flow rate. By increasing the flow rate, it is expected to improve npon the aforesaid machinability characteristics that play vital role on productivity, product quality. Fig. 3.36 to 3.51 show the variation in temperature with variable flow rate and variable cutting velocities in turning AISI 4320 steel by SNMG inserts.

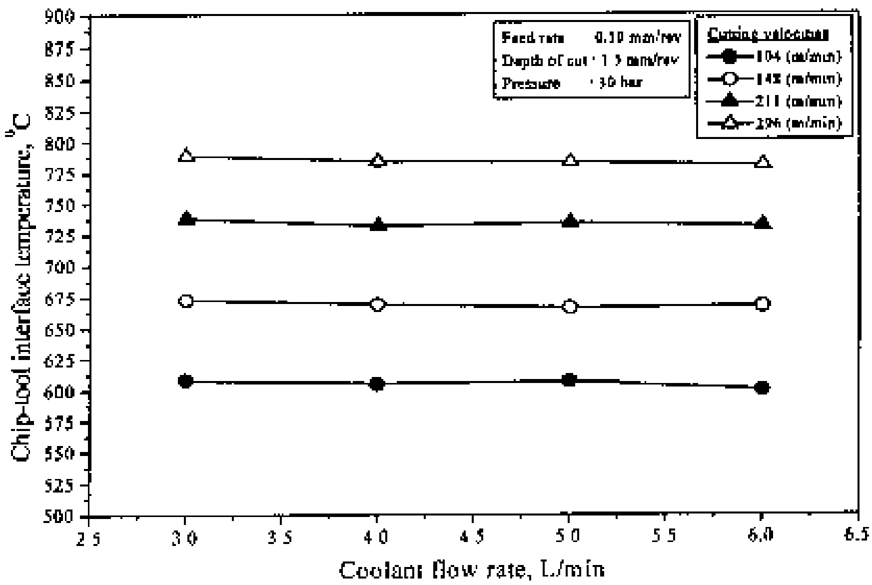


Fig. 3.36 Variation in chip-tool interface temperature under variable Q and V_c at P= 30 bar, S_o=0.10 mm/rev

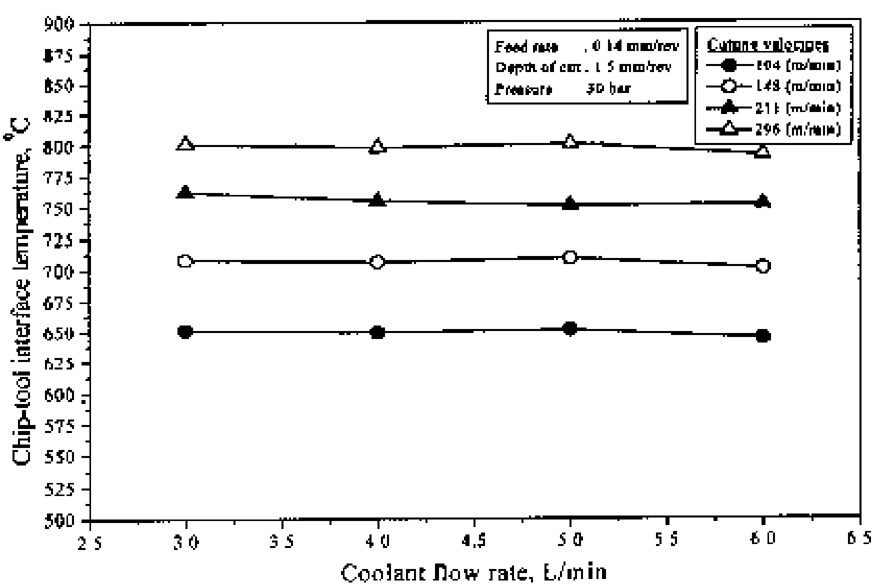


Fig. 3.37 Variation in chip-tool interface temperature under variable Q and V_c at P= 30 bar, S_o=0.14 mm/rev

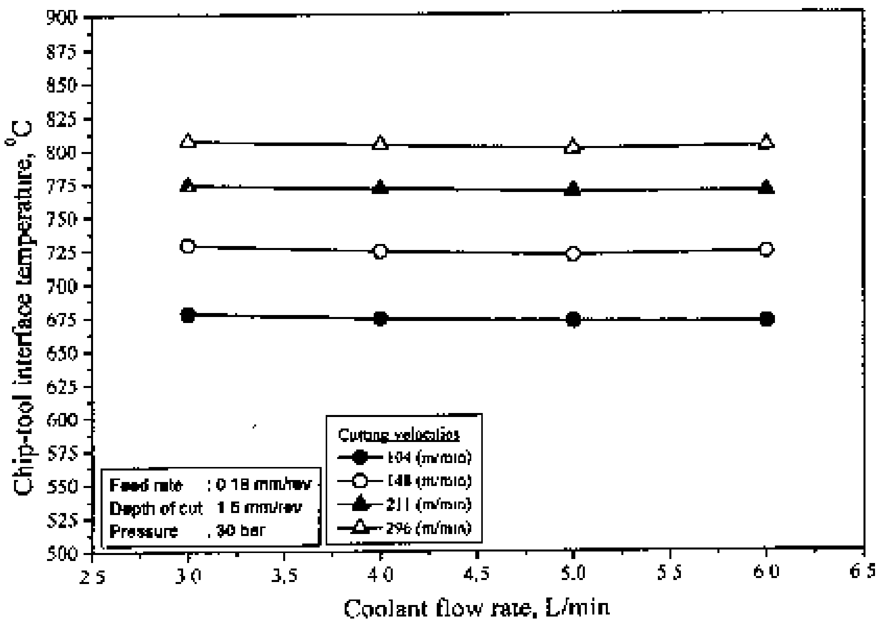


Fig. 3.38 Variation in chip-tool interface temperature under variable Q and V_c at P= 30 bar, S_0=0.18 mm/rev

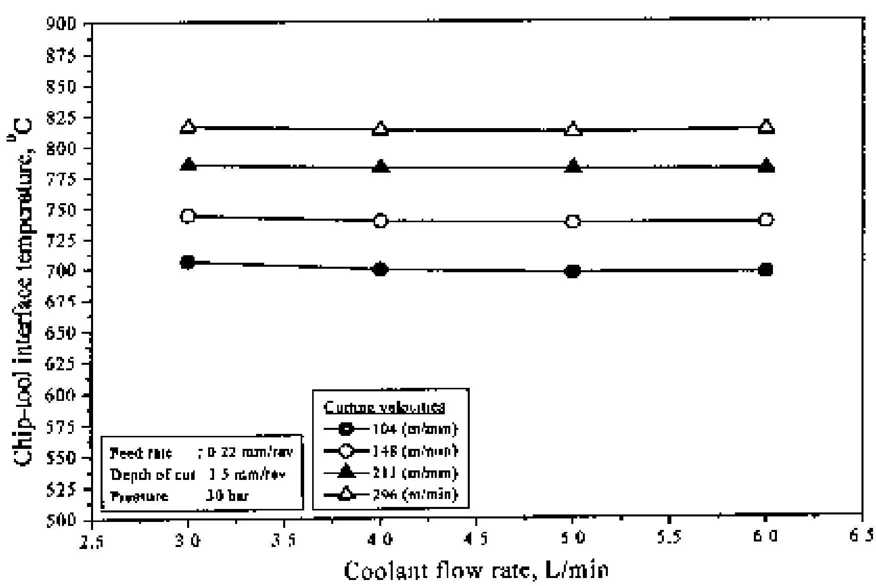


Fig. 3.39 Variation in chip-tool interface temperature under variable Q and V_c at P= 30 bar, S_0=0.22 mm/rev

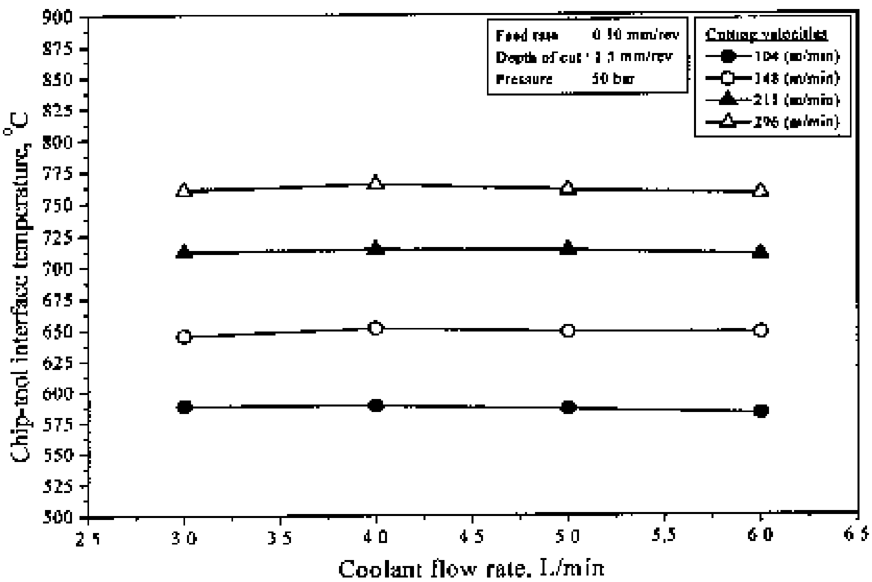


Fig. 3.40 Variation in chip-tool interface temperature under variable Q and V_c at P= 50 bar, S_0=0.10 mm/rev

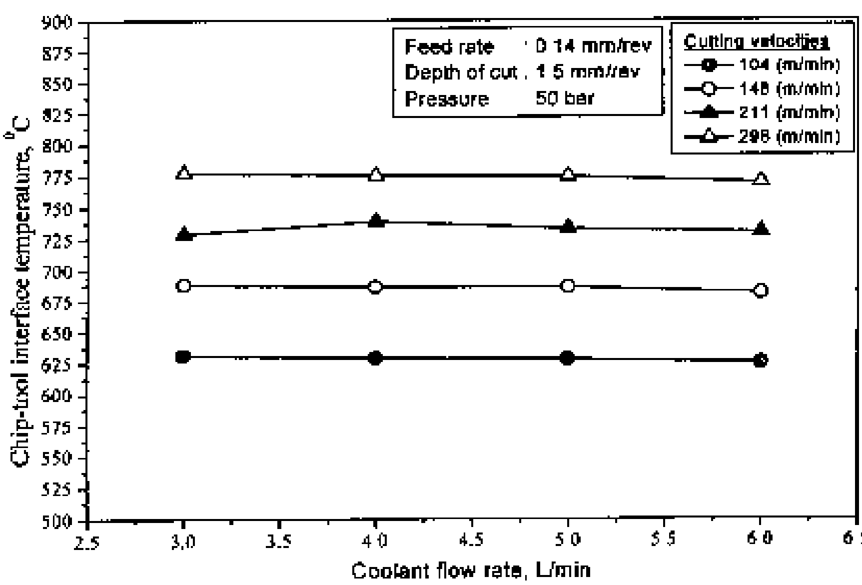


Fig. 3.41 Variation in chip-tool interface temperature under variable Q and V_c at P= 50 bar, S_0=0.14 mm/rev

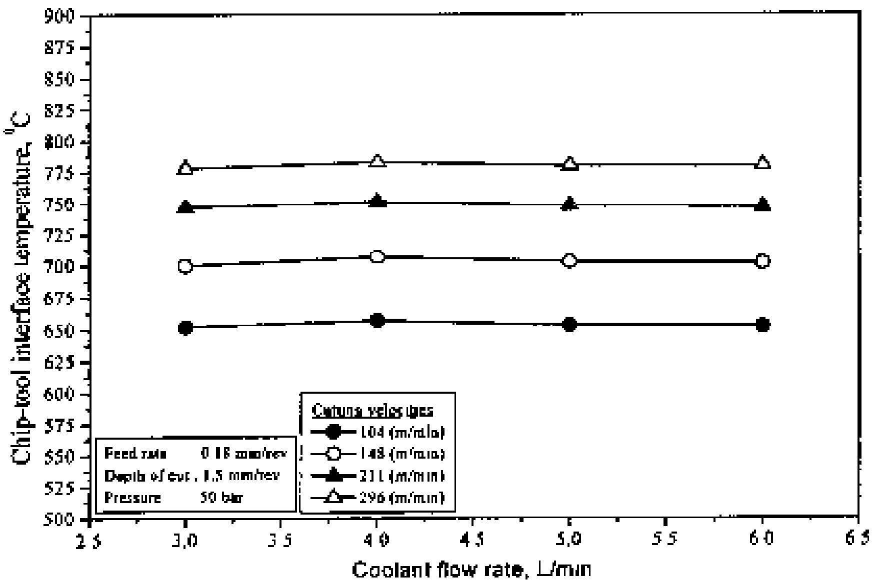


Fig. 3.42 Variation in chip-tool interface temperature under variable Q and V_c at P= 50 bar, S_0=0.18 mm/rev

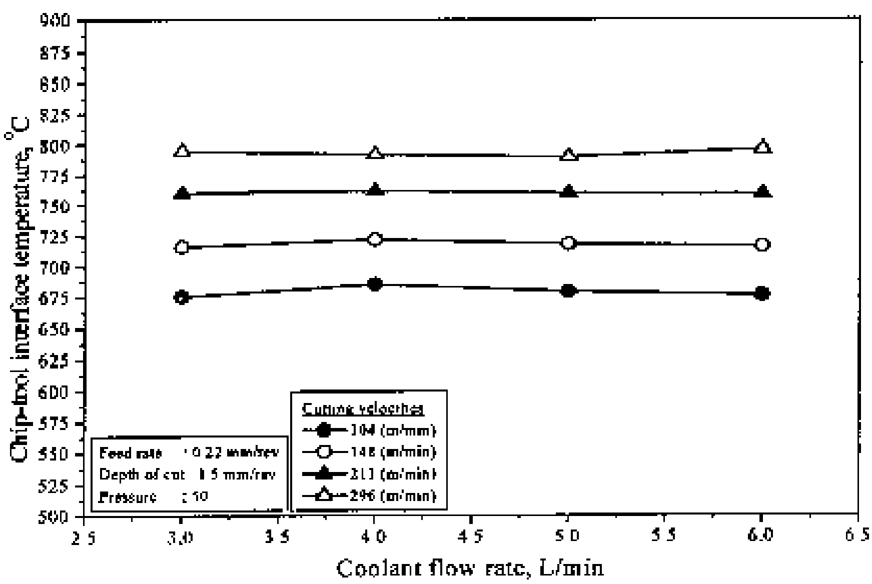


Fig. 3.43 Variation in chip-tool interface temperature under variable Q and V_c at P= 50 bar, S_0=0.22 mm/rev

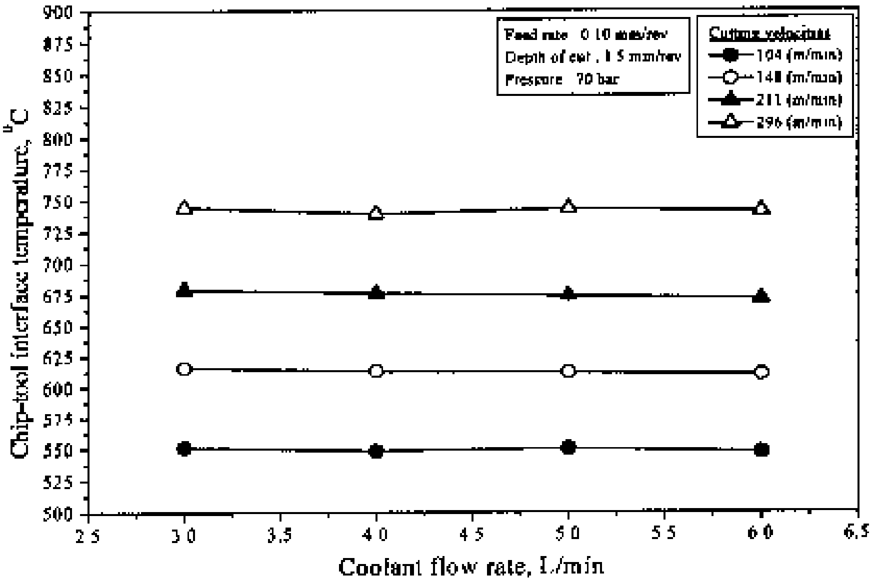


Fig. 3.44 Variation in chip-tool interface temperature under variable Q and V_c at P= 70 bar, S_o=0.10 mm/rev

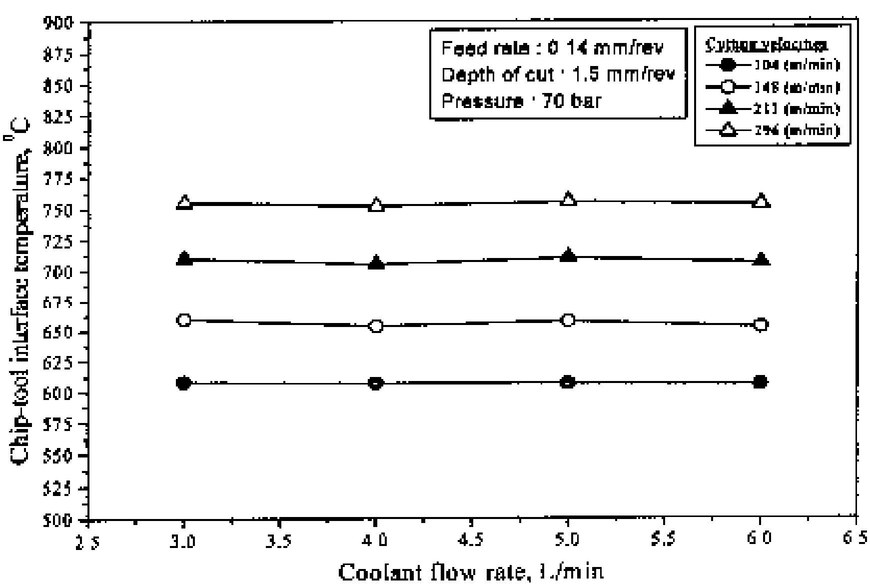


Fig. 3.45 Variation in chip-tool interface temperature under variable Q and V_c at P= 70 bar, S_o=0.14 mm/rev

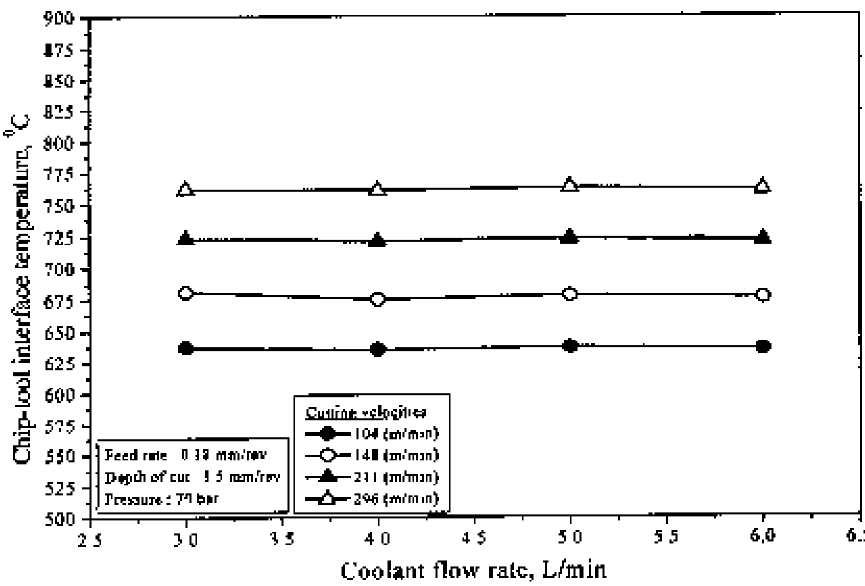


Fig. 3.46 Variation in chip-tool interface temperature under variable Q and V_c at P= 70 bar, S_o=0.18 mm/rev

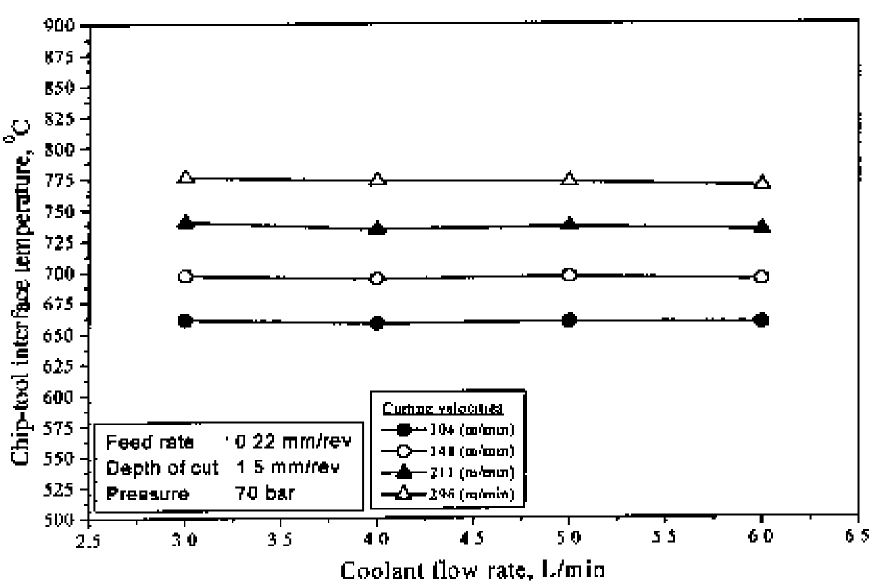


Fig. 3.47 Variation in chip-tool interface temperature under variable Q and V_c at P= 70 bar, S_o=0.22 mm/rev

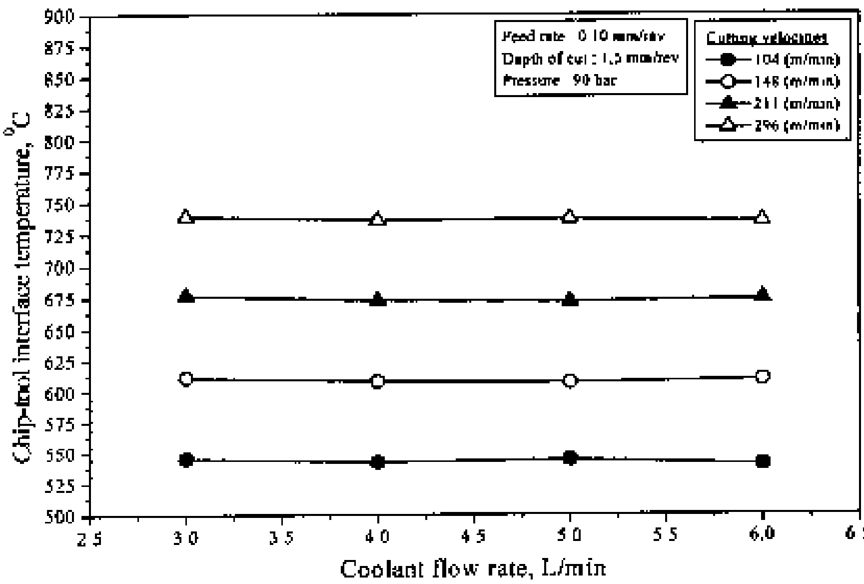


Fig. 3.48 Variation in chip-tool interface temperature under variable Q and V_c at P= 90 bar, S_o=0.10 mm/rev

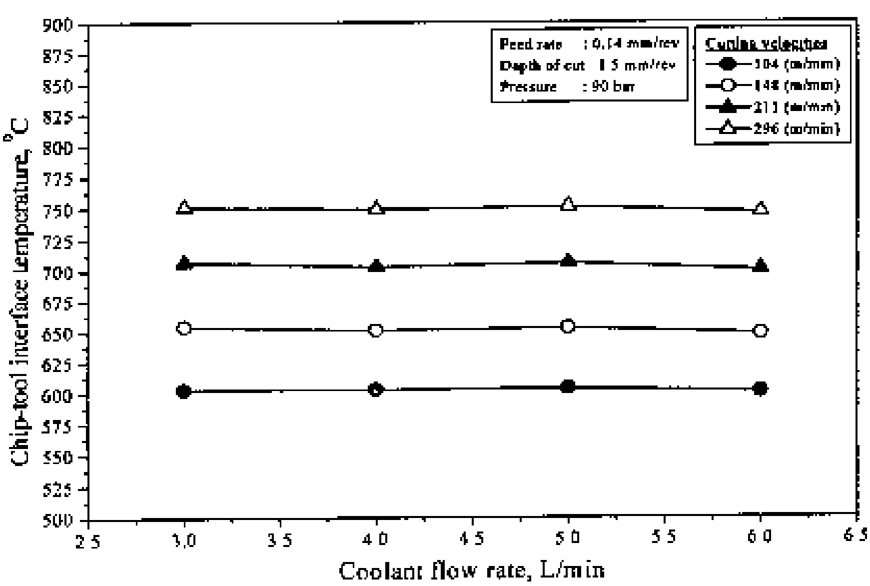


Fig. 3.49 Variation in chip-tool interface temperature under variable Q and V_c at P= 90 bar, S_o=0.14 mm/rev

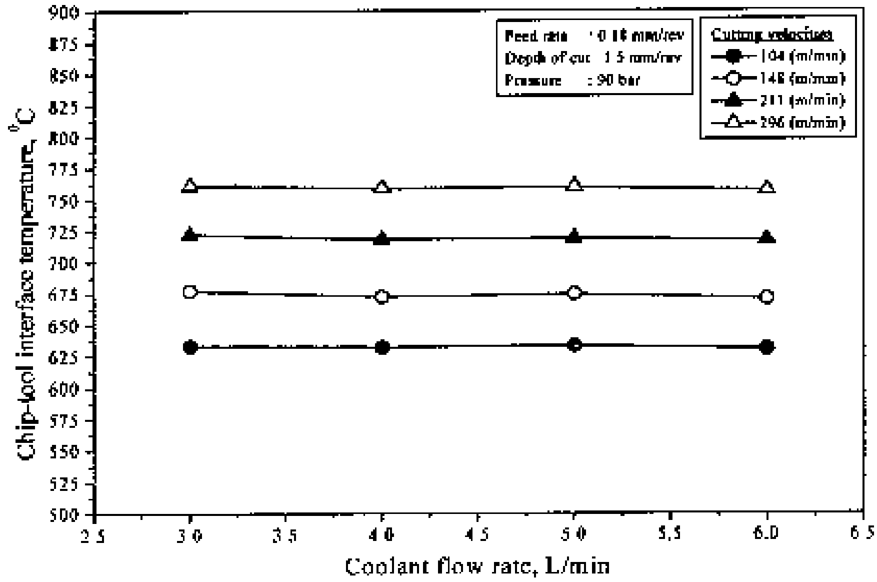


Fig. 3.50 Variation in chip-tool interface temperature under variable Q and V_c at P= 90 bar, S_o=0.18 mm/rev

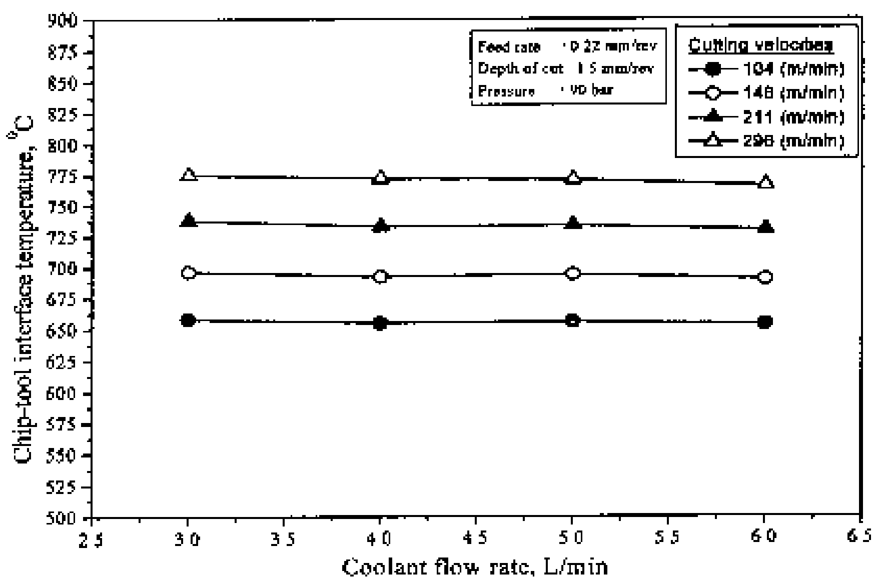


Fig. 3.51 Variation in chip-tool interface temperature under variable Q and V_c at P= 90 bar, S_o=0.22 mm/rev

3.4.2 Study of Chip Morphology

The high-pressure coolant stream helps to break up chips and remove them from the cutting area more efficiently, which means the cutting tool spends less time re-cutting metal chips. It has the benefit of a powerful stream that can reach onto the cutting area, provides strong chip removal and in some cases, enough pressure to deburr [**Aronson 2004**].This high speed coolant easily penetrates the vapor barrier at chip-tool interface to effectively lubricate and cool the tool The combination of reduced heat and more efficient evacuation of chips prolongs tool life and makes replacement more predictable because the cutting tool wears out naturally, rather than failing prematurely because of excessive heat or chip damage. In fact, when users apply high pressure coolant to a longstanding process, which has always produced dark blue chips, they are often amazed that the same or even higher speeds and feeds produce shiny, silver or metallic chips that are cool to the touch. So benefits of high pressure coolant involves faster cycle time, better chip control, improved surface finish, and multiplied tool life.

Machining is a process of shaping by the removal of material which results in chips and the geometrical and metallurgical characteristics of these chips are very representative of the performances of the process because the form (shape and color) and thickness of the chips directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The research aiming at building up a system for chip formation and classifying chip forms in metal cutting, particularly in turning and drilling, have been studied extensively [**Nakayama et al. 1978 and 1992, Shaw 1986, Venkatesh et al 1993, Jawahir et al. 1993,2000 , Batzer et al. 1998 ,Trent and Wright 2001**]. In general, chip formation in machining can be categorized as forming continuous, discontinuous, or serrated chips **[Komanduri and brown 1981, Komanduri and von Turkovich 1981]**.

In the present work, the chip samples collected while turning the AISI 4320 steel by SNMG insert at different V_C-S_0 combinations under HPC condition by the cutting oil (HC straight run, VG 68) have been visually examined and categorized with respect to their shape and color. The form and color of all those chips were noted down based on ISO 3685-1977 (E) standard chip forms. The results of such categorization of the chips produced at different pressure and flow rate have been shown in Table 3.2 to 3.5. The actual color and shape of the chips have been shown from Fig. 3.52 to 3.67.

Table 3.2 Comparison of chip shape and colour at different V_C and S_O under HPC conditions while turning by SNMG carbide insert at pressure 30 bar with various flow rate

S_o mm/rev	V_c mm/min	Pressure, P = 30 bar							
		Q = 3 L/min		Q = 4 L/min		Q = 5 L/min		Q = 6 L/min	
		Shape	**Color**	**Shape**	**Color**	**Shape**	**Color**	**Shape**	**Color**
0.1	104	Connected	Metallic	Connected	Metallic	Loose arc	Metallic	Connected	Metallic
	148	Connected	Metallic	Snarled ribbon	Metallic	Loose arc	Metallic	Connected	Metallic
	211	Snarled tubular	Metallic	Snarled ribbon	Metallic	Snarled tubular	Metallic	Snarled tubular	Metallic
	296	Snarled ribbon	Metallic	Snarled tubular	Metallic	Snarled ribbon	Metallic	Snarled ribbon	Metallic
0.14	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
0.18	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
0.22	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Golden	Loose arc	Metallic	Loose arc	Golden	Loose arc	Metallic

Table 3.3 Comparison of chip shape and colour at different V_C and S_O under HPC conditions while turning by SNMG carbide insert at pressure 50 bar with various flow rate

S_o mm/rev	V_c mm/min	Pressure, P = 50 bar							
		Q = 3 L/min		Q = 4 L/min		Q = 5 L/min		Q = 6 L/min	
		Shape	Color	Shape	Color	Shape	Color	Shape	Color
0.1	104	Connected	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Connected	Metallic	Snarled ribbon	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Snarled ribbon	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Snarled ribbon	Metallic	Snarled ribbon	Metallic	Snarled ribbon	Metallic	Connected	Metallic
0.14	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Metallic	Snarled ribbon	Metallic	Loose arc	Metallic	Loose arc	Metallic
0.18	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Golden
	211	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden
	296	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden
0.22	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Golden	Loose arc	Metallic	Loose arc	Golden
	211	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden
	296	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden	Loose arc	Golden

Table 3.4 Comparison of chip shape and colour at different V_C and S_O under HPC conditions while turning by SNMG carbide insert at pressure 70 bar with various flow rate

S_o mm/rev	V_c mm/min	Pressure, P = 70 bar							
		Q = 3 L/min		Q = 4 L/min		Q = 5 L/min		Q = 6 L/min	
		Shape	Color	Shape	Color	Shape	Color	Shape	Color
0.1	104	Loose arc	Metallic	Connected	Metallic	Connected	Metallic	Connected	Metallic
	148	Loose arc	Metallic	Connected	Metallic	Connected	Metallic	Connected	Metallic
	211	Snarled ribbon	Metallic	Snarled ribbon	Metallic	Snarled ribbon	Metallic	Snarled Tubular	Metallic
	296	Snarled ribbon	Metallic	Snarled ribbon	Metallic	Snarled ribbon	Metallic	Snarled ribbon	Metallic
0.14	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
0.18	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Golden
	296	Loose arc	Golden	Loose arc	Metallic	Loose arc	Golden	Loose arc	Golden
0.22	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Golden	Loose arc	Metallic	Loose arc	Golden	Loose arc	Golden

Table 3.5 Comparison of chip shape and colour at different V_C and S_0 under HPC conditions while turning by SNMG carbide insert at pressure 90 bar with various flow rate

S_0 mm/rev	V_c mm/min	Pressure, P = 90 bar							
		Q = 3 L/min		Q = 4 L/min		Q = 5 L/min		Q = 6 L/min	
		Shape	Color	Shape	Colour	Shape	Color	Shape	Color
0.1	104	Loose arc	Metallic	Loose arc	Metallic	Connected	Metallic	Connected	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Connected	Metallic	Connected	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Snarled ribbon	Metallic	Snarled Tubular	Metallic
	296	Connected	Metallic	Connected	Metallic	Snarled ribbon	Metallic	Snarled ribbon	Metallic
0.14	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
0.18	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Metallic	Loose arc	Golden	Loose arc	Metallic	Loose arc	Metallic
0.22	104	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	148	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	211	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic	Loose arc	Metallic
	296	Loose arc	Golden	Loose arc	Golden	Loose arc	Metallic	Loose arc	Metallic

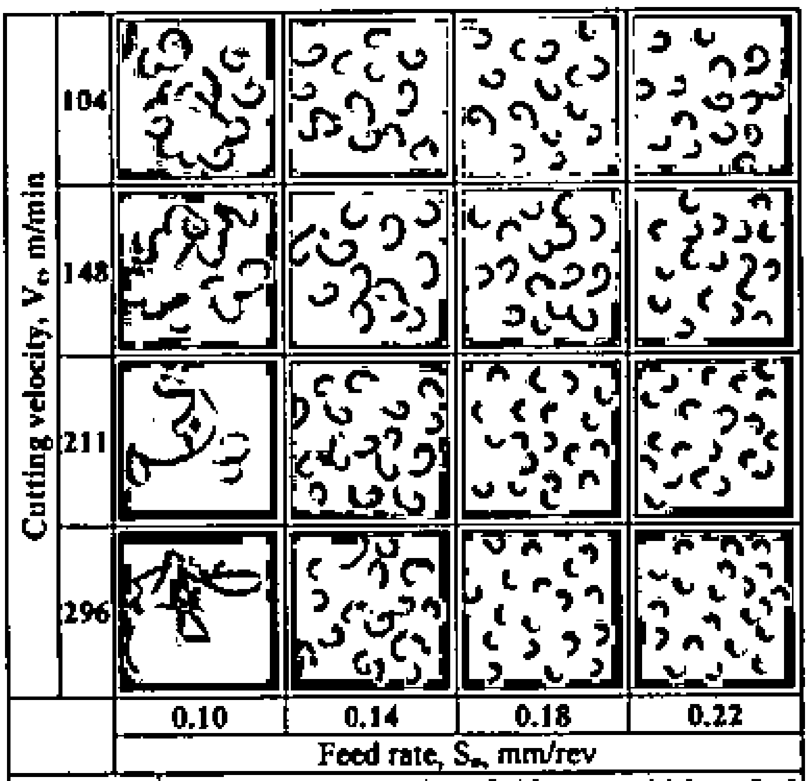


Fig. 3.52 Actual shape and color of chip at P= 30 bar, Q=3 L/ min.

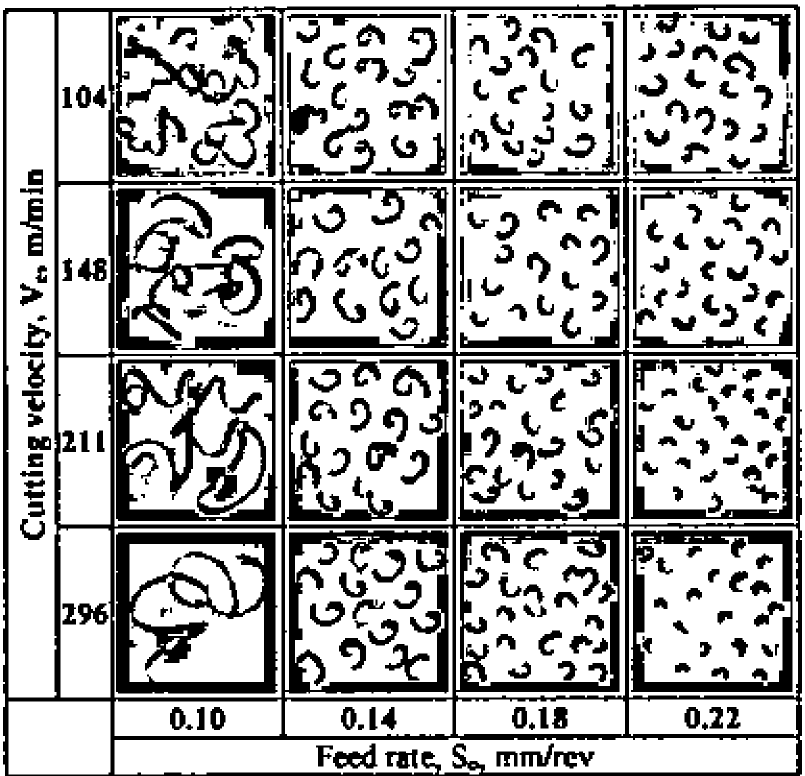


Fig. 3.53 Actual shape and color of chip at P= 30 bar, Q=4 L/ min.

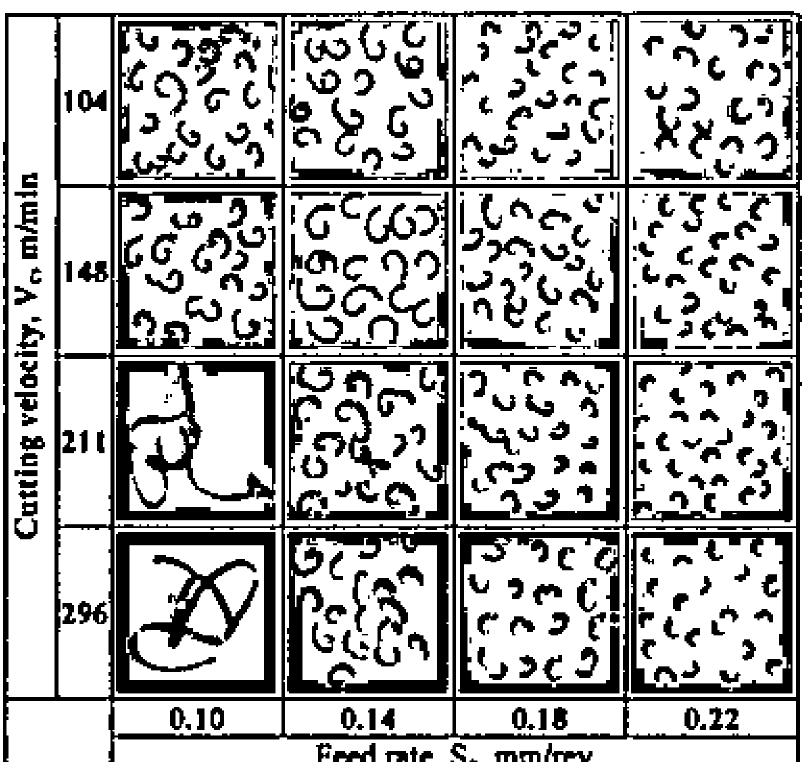


Fig. 3.54 Actual shape and color of chip at P= 30 bar, Q=5 L/ min.

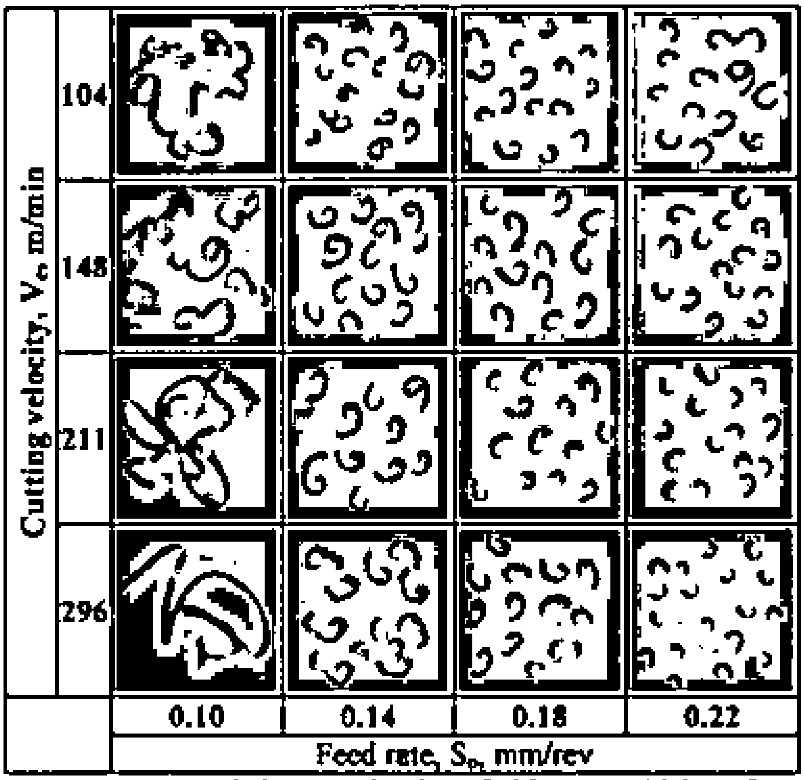


Fig. 3.55 Actual shape and color of chip at P= 30 bar, Q=6 L/ min.

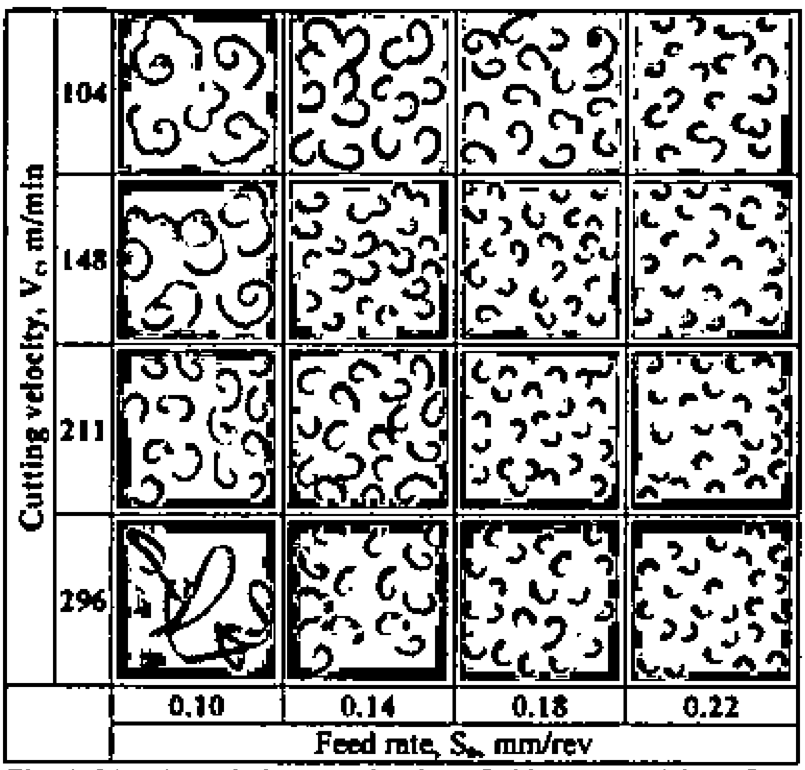


Fig. 3.56 Actual shape and color of chip at P= 50 bar, Q=3 L/ min.

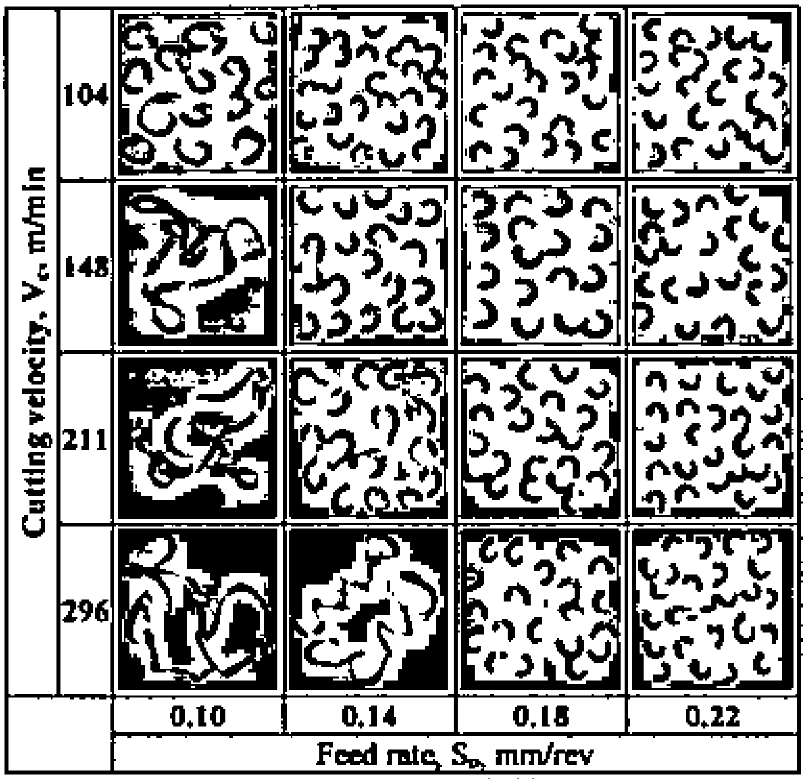


Fig. 3.57 Actual shape and color of chip at P= 50 bar, Q=4 L/ min..

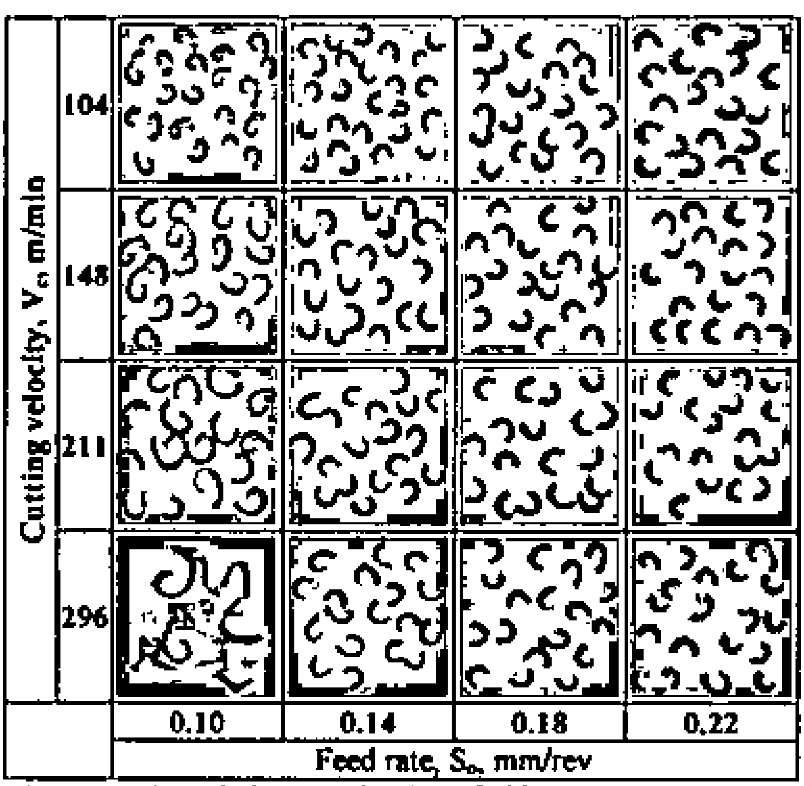


Fig. 3.58 Actual shape and color of chip at P= 50 bar, Q=5 L/ min.

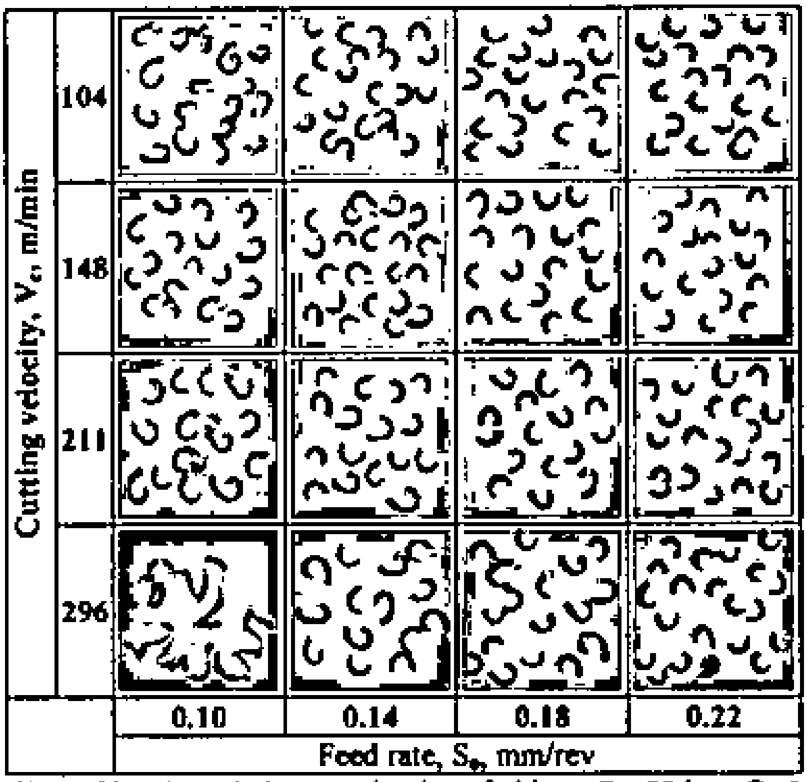


Fig. 3.59 Actual shape and color of chip at P= 50 bar, Q=6 L/ min.

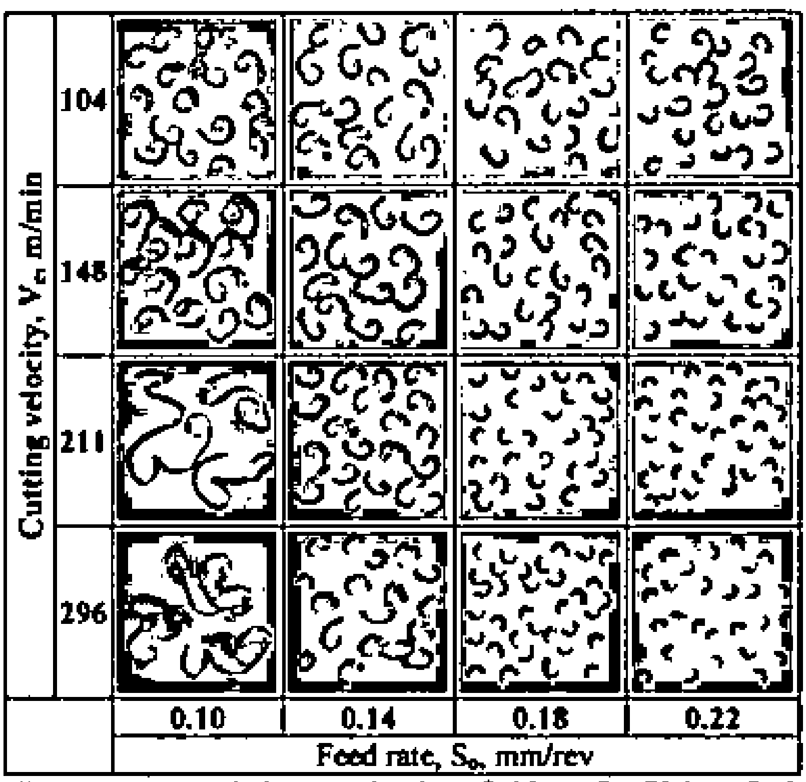


Fig. 3.60 Actual shape and color of chip at P= 70 bar, Q=3 L/ min.

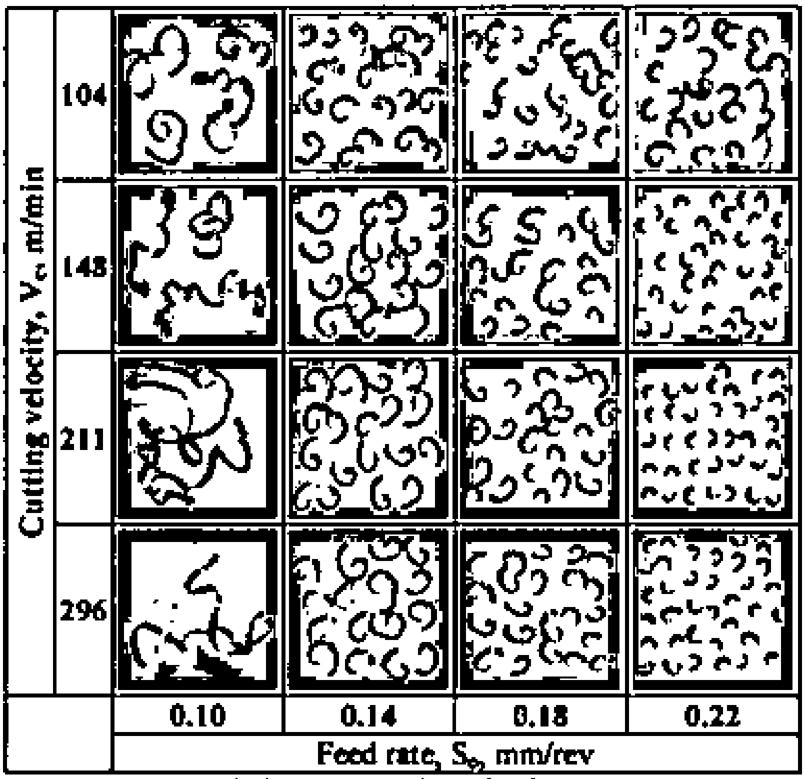


Fig. 3.61 Actual shape and color of chip at P= 70 bar, Q=4 L/ min

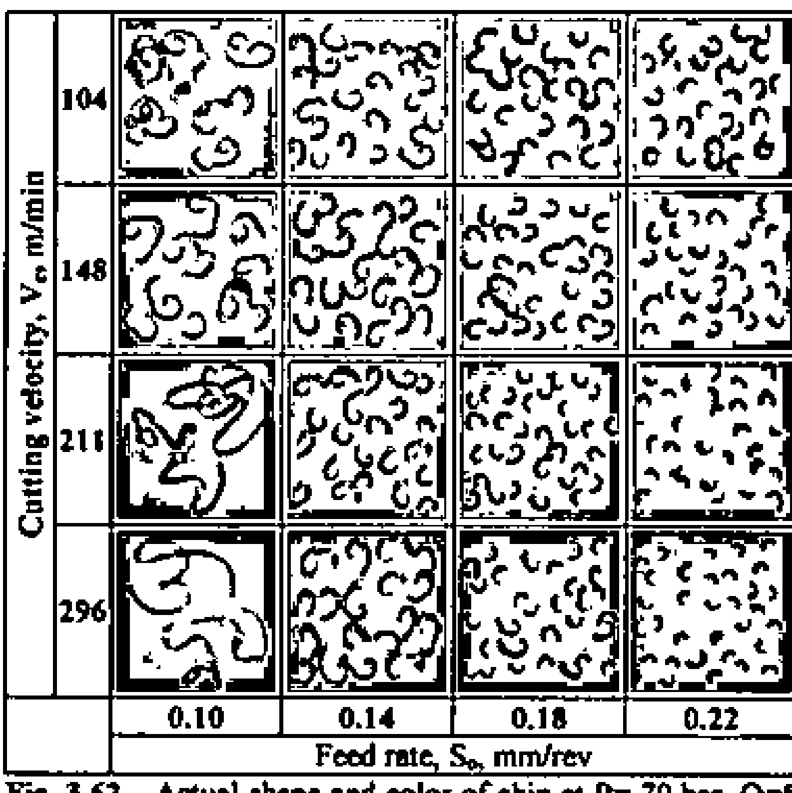


Fig. 3.62 Actual shape and color of chip at P= 70 bar, Q=5 L/ min

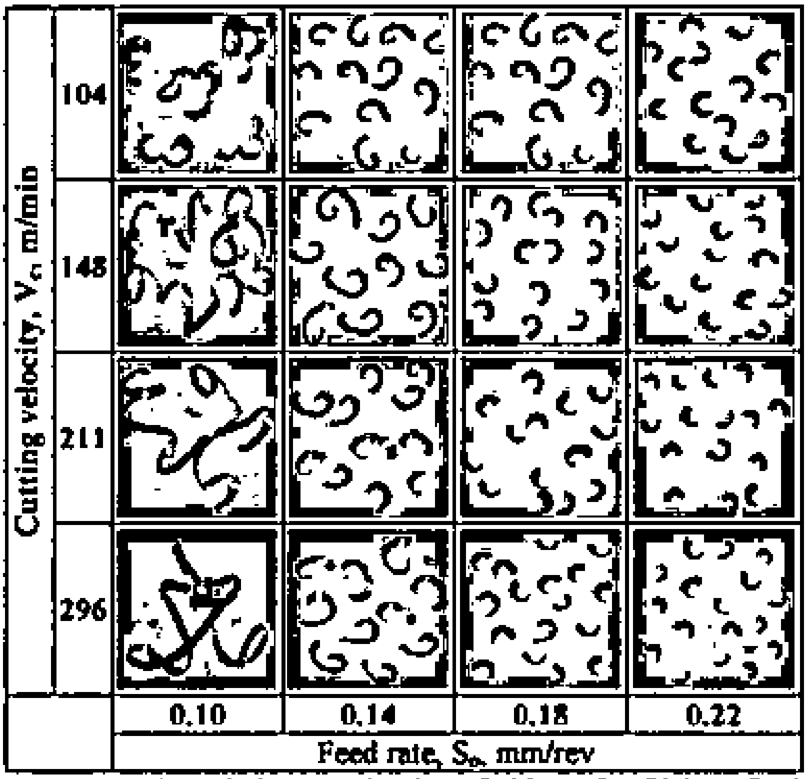


Fig. 3.63 Actual shape and color of chip at P= 70 bar, Q=6 L/ min

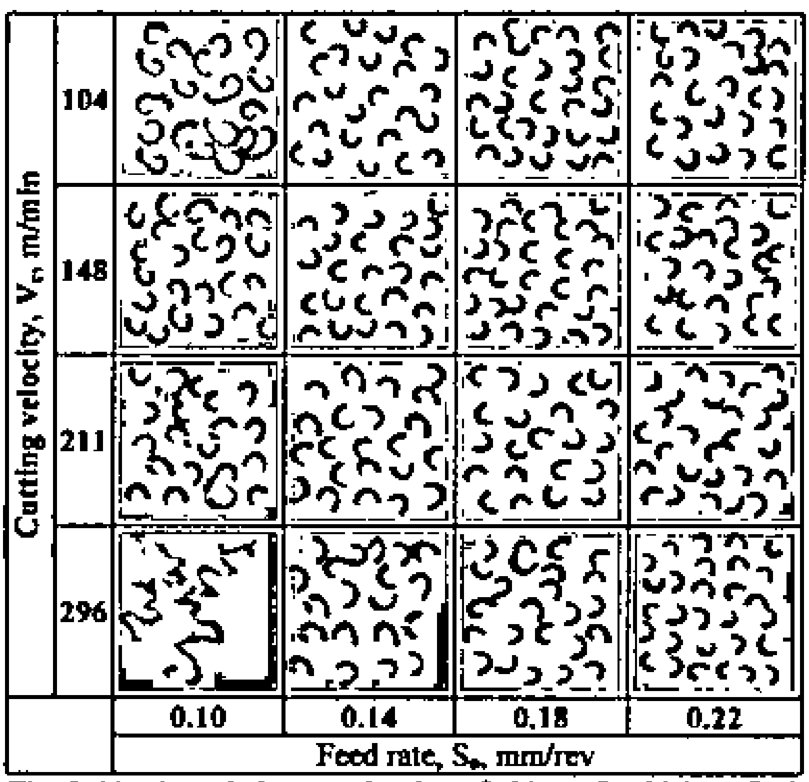


Fig. 3.64 Actual shape and color of chip at P= 90 bar, Q=3 L/ min

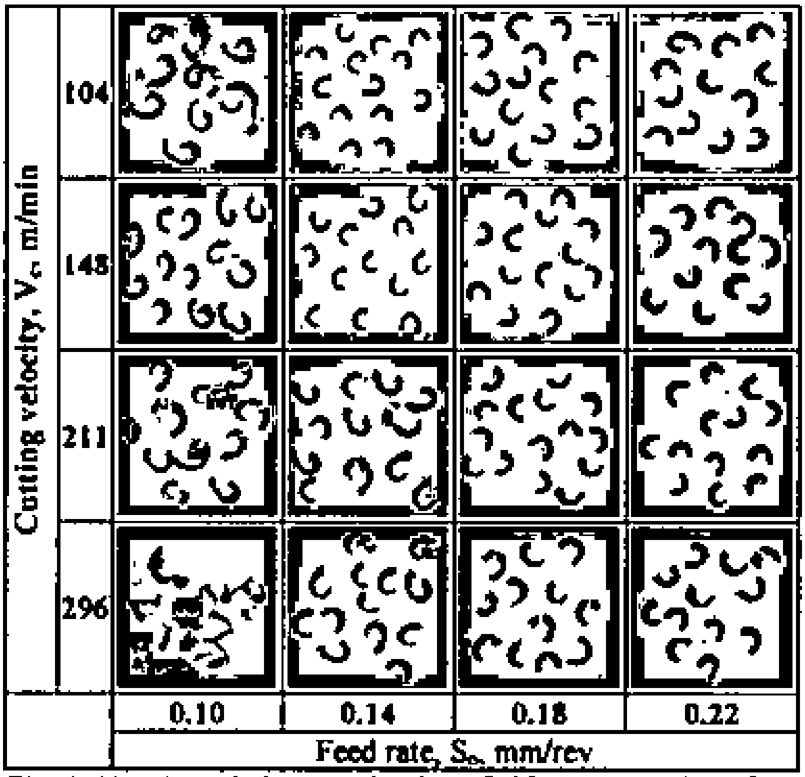


Fig. 3.65 Actual shape and color of chip at P= 90 bar, Q=4 L/ min

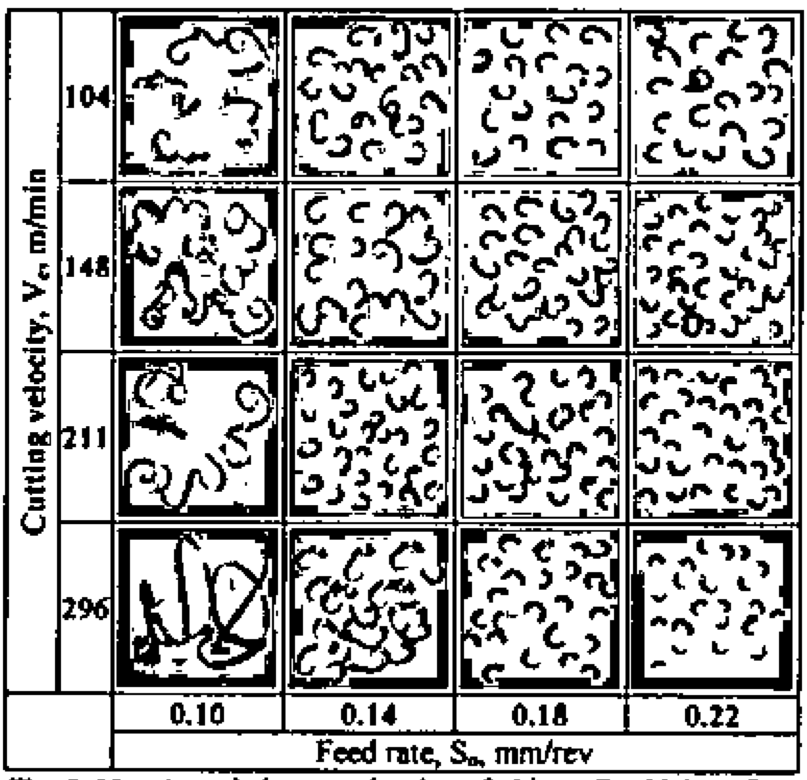


Fig. 3.66 Actual shape and color of chip at P= 90 bar, Q=5 L/ min

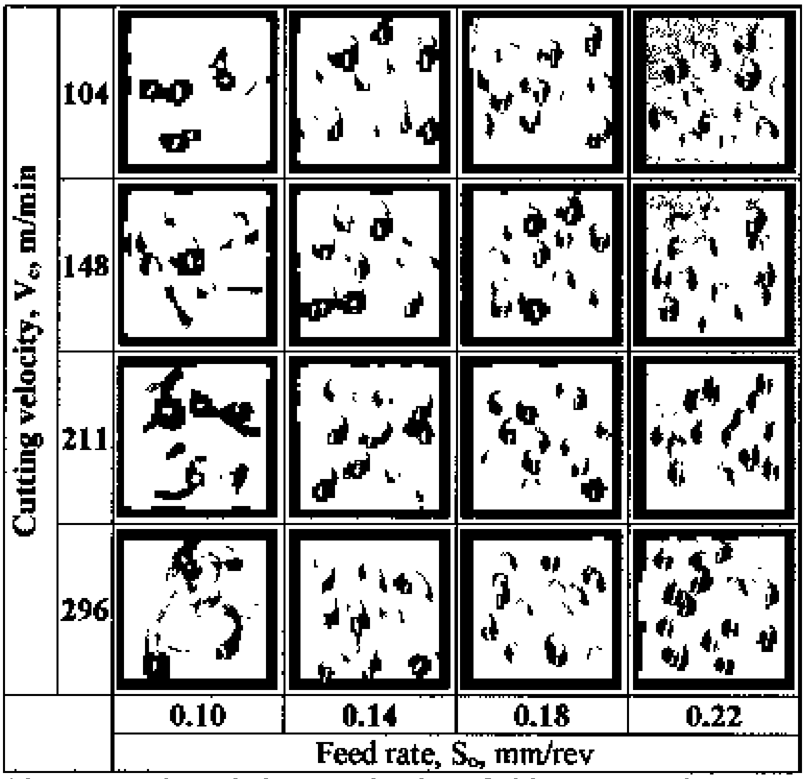


Fig. 3.67 Actual shape and color of chip at P= 90 bar, Q=6 L/ min

In machining, another important machinability index is chip reduction coefficient, ξ (ratio of chip thickness after and before cut). For a given tool geometry and cutting conditions, the value of ξ depends upon the nature of chip-tool interaction, chip contact length and chip form all of which are expected to be influenced by HPC jet in addition to the levels of V_C and S_0. The thickness of the chips was repeatedly measured by a digital slide caliper to determine the value of chip reduction coefficient, ξ (ratio of chip thickness after and before cut. The variation in value of ξ with V_C and S_0 at various pressure and flow rate has been plotted which are shown from Fig. 3.68 to Fig. 3.83 respectively.

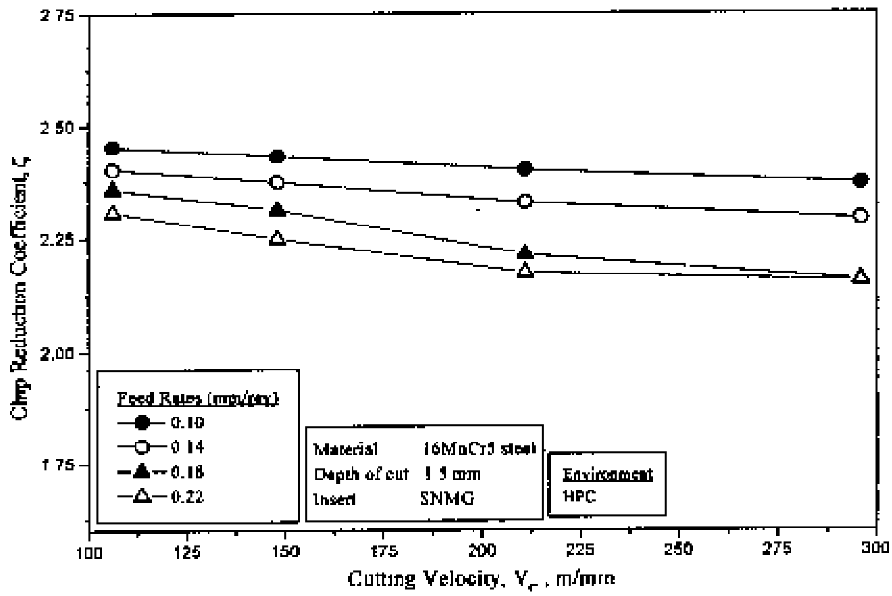


Fig. 3.68 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=30 bar and Q=3 L/min

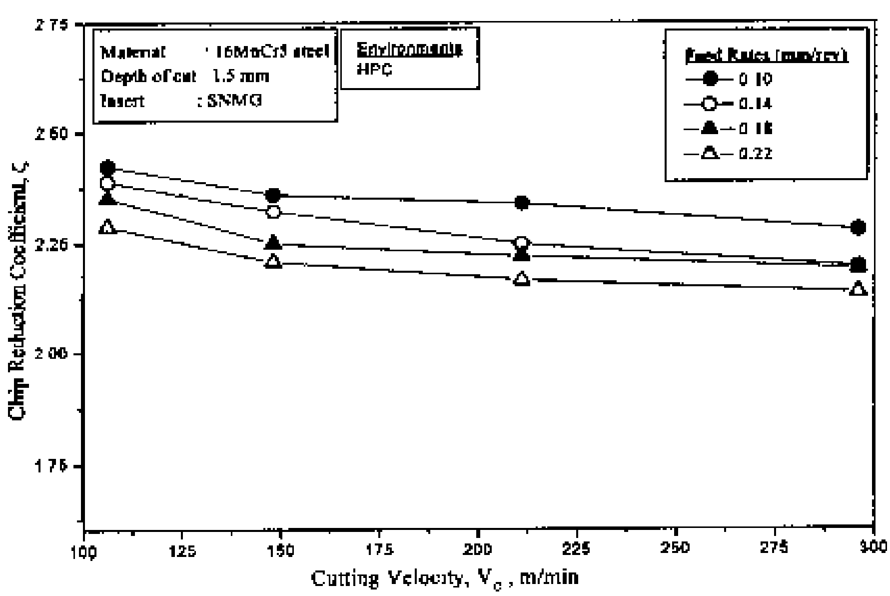


Fig. 3.69 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=30 bar and Q=4 L/min

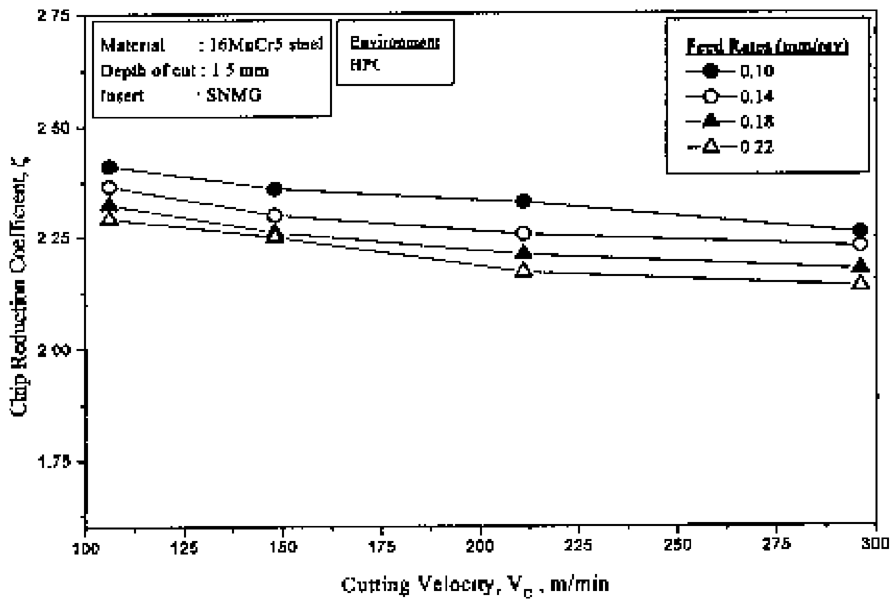


Fig. 3.70 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=30 bar and Q=5 L/min

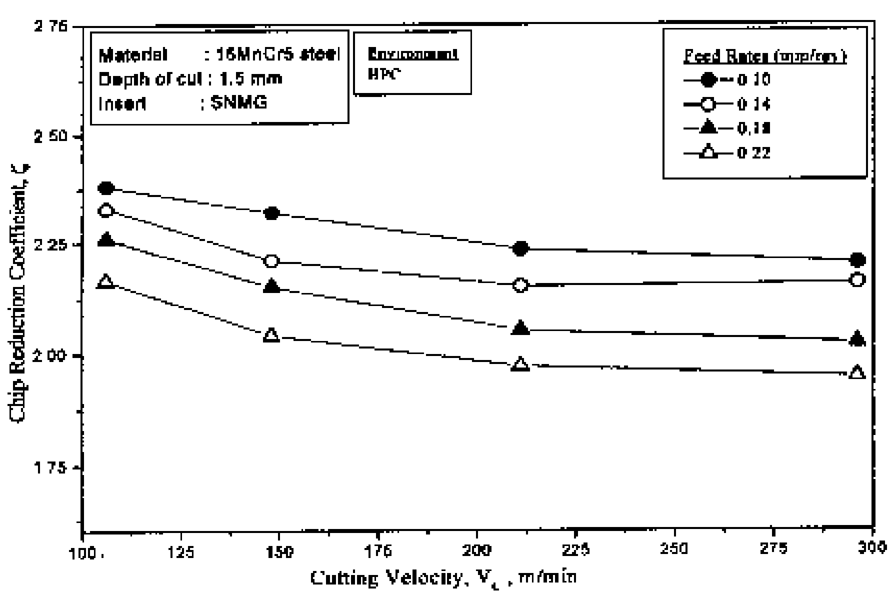


Fig. 3.71 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=30 bar and Q=6 L/min

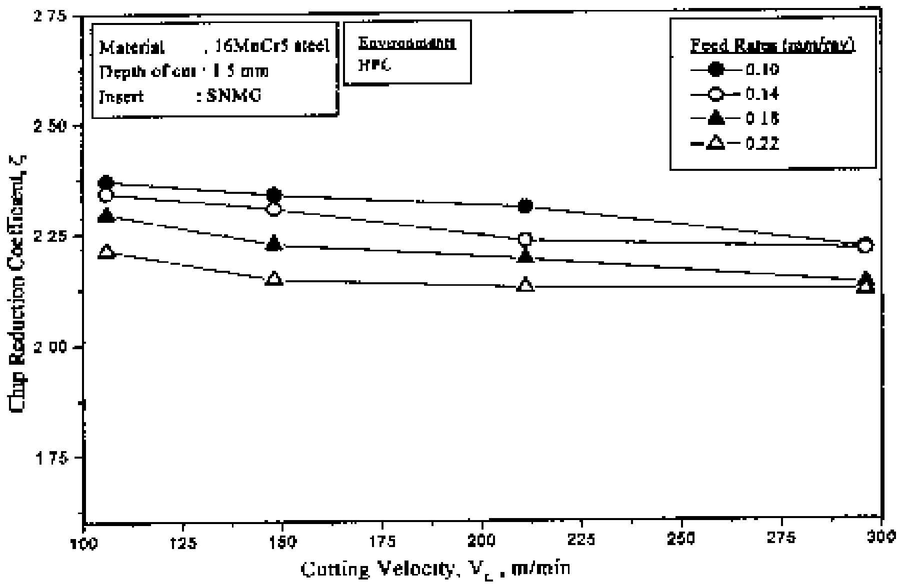


Fig. 3.72 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=50 bar and Q=3 L/min

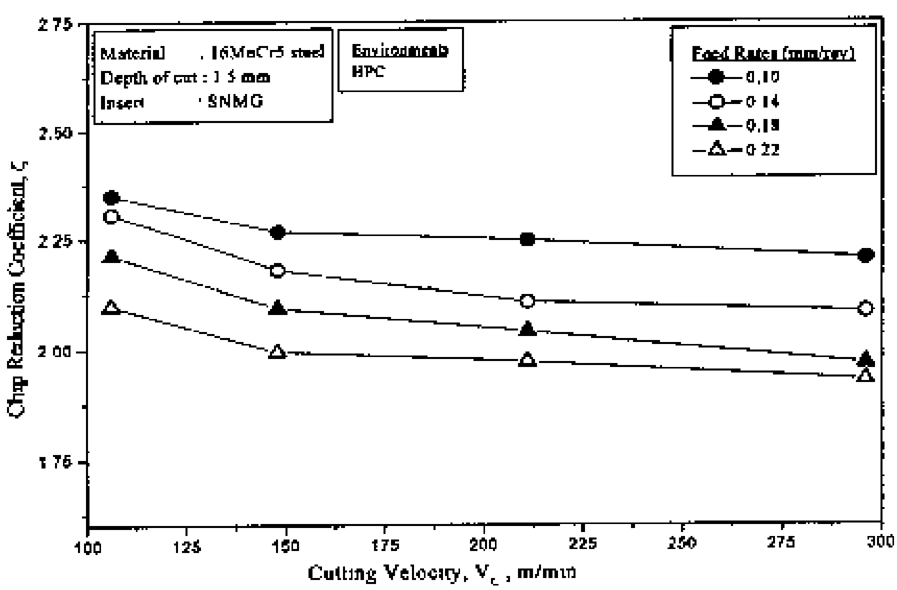


Fig. 3.73 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=50 bar and Q=4 L/min

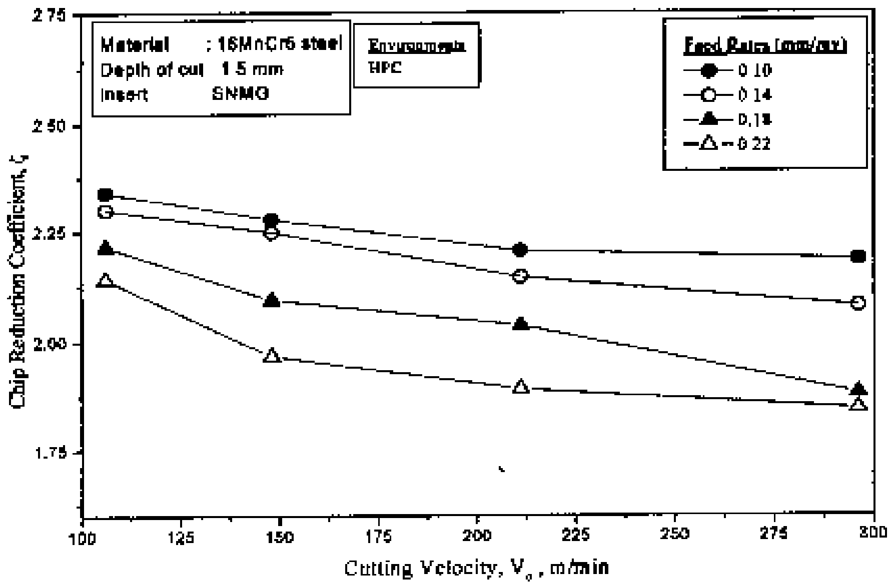


Fig. 3.74 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=50 bar and Q=5 L/min

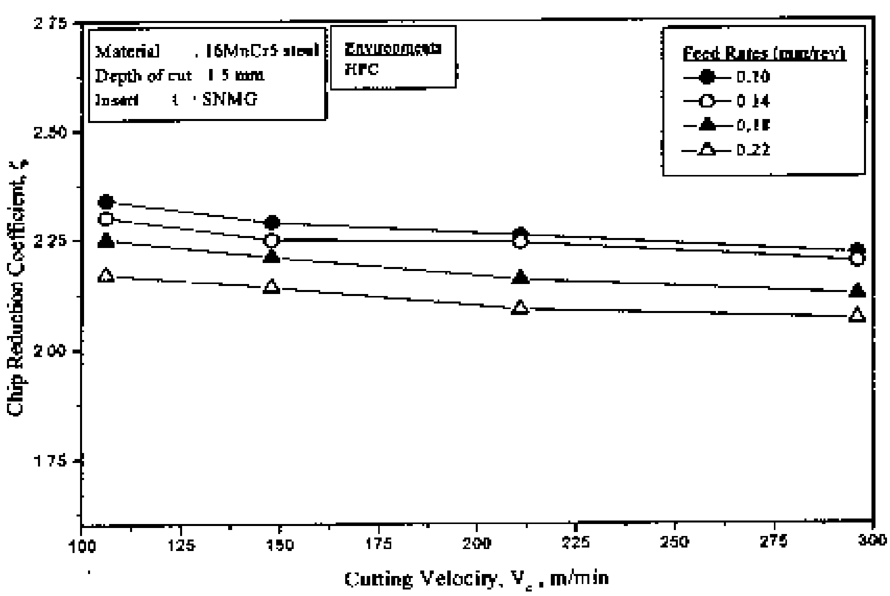


Fig. 3.75 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=50 bar and Q=6 L/min

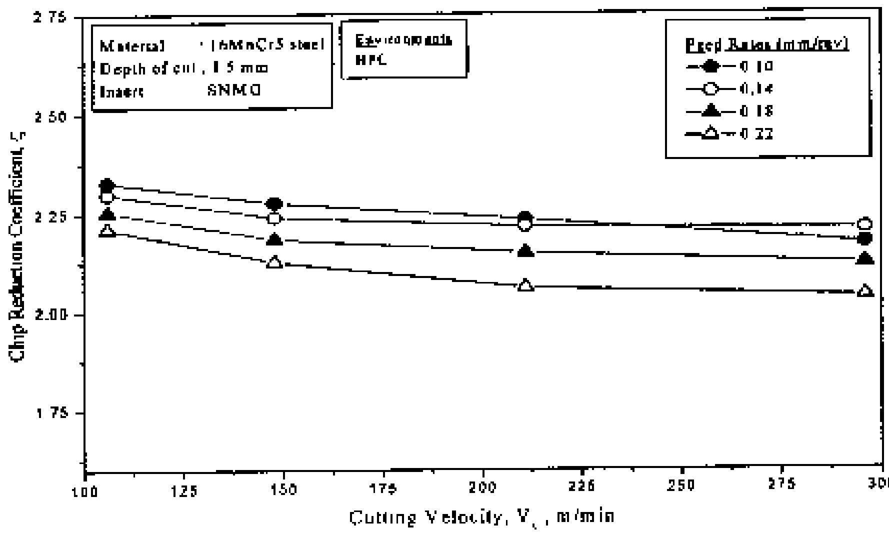


Fig. 3.76 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=70 bar and Q=3 L/min

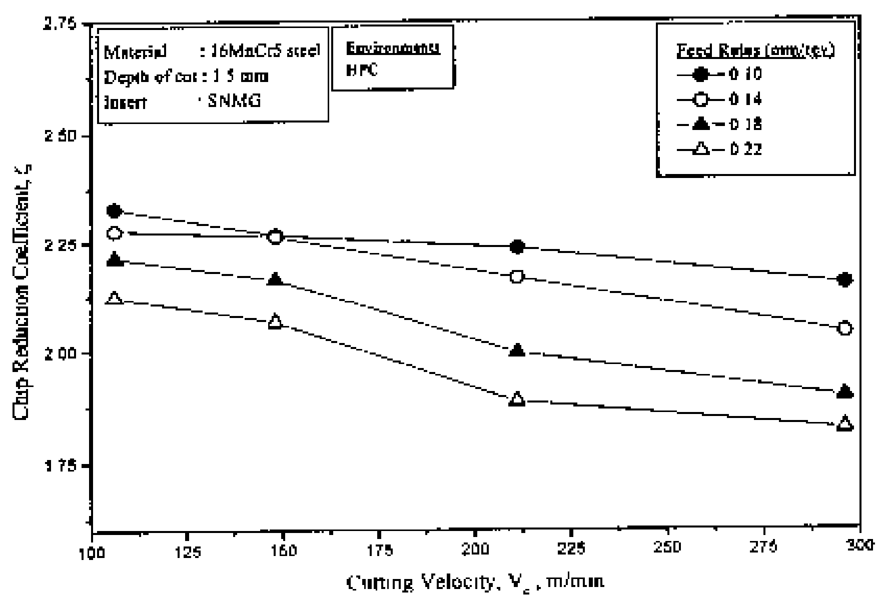


Fig. 3.77 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=70 bar and Q=4 L/min

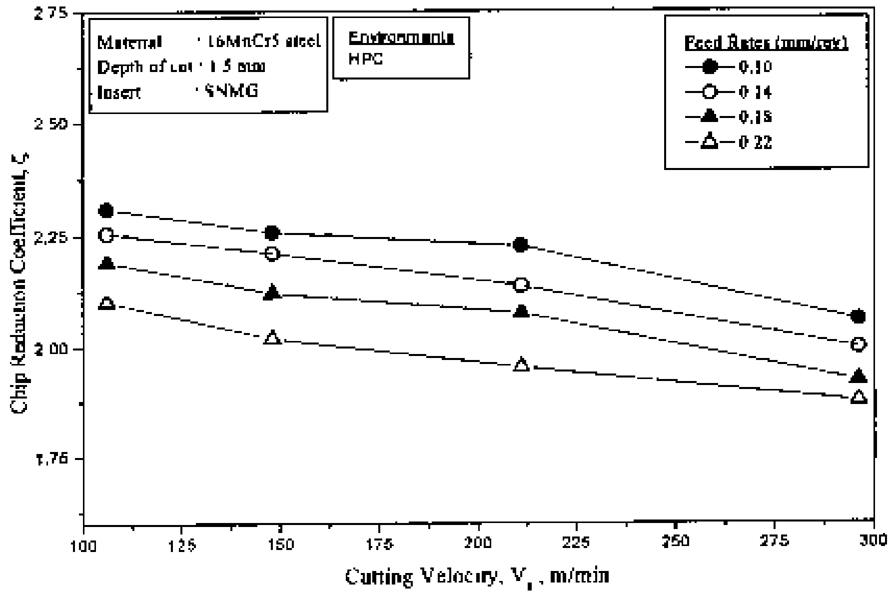


Fig. 3.78 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=70 bar and Q=5 L/min

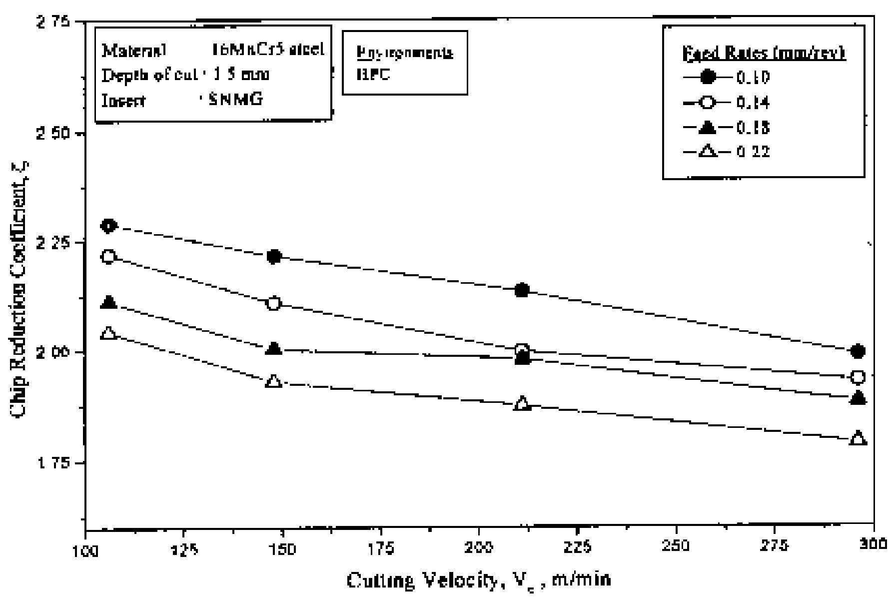


Fig. 3.79 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=70 bar and Q=6 L/min

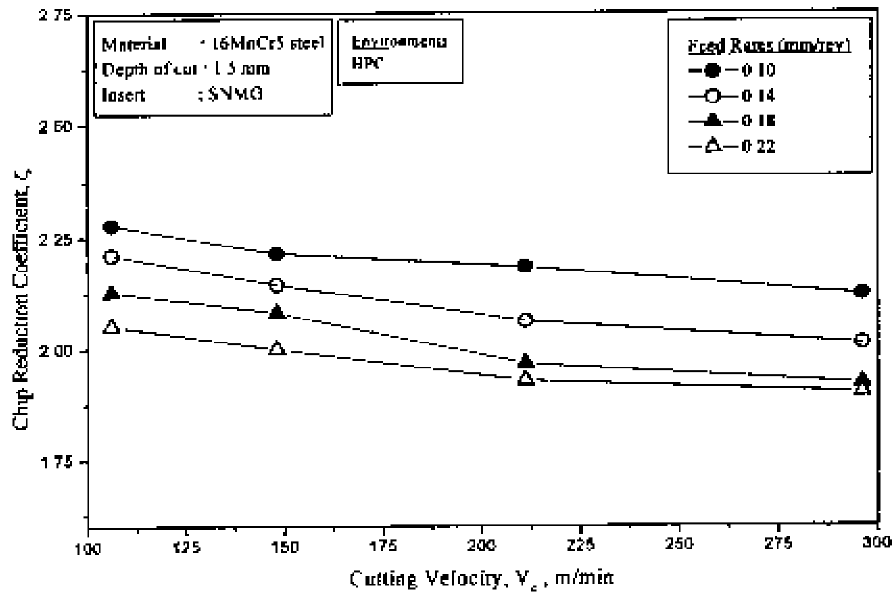


Fig. 3.80 Variation of chip reduction coefficient with V_c at different S_0 under HPC condition at P=90 bar and Q=3 L/min

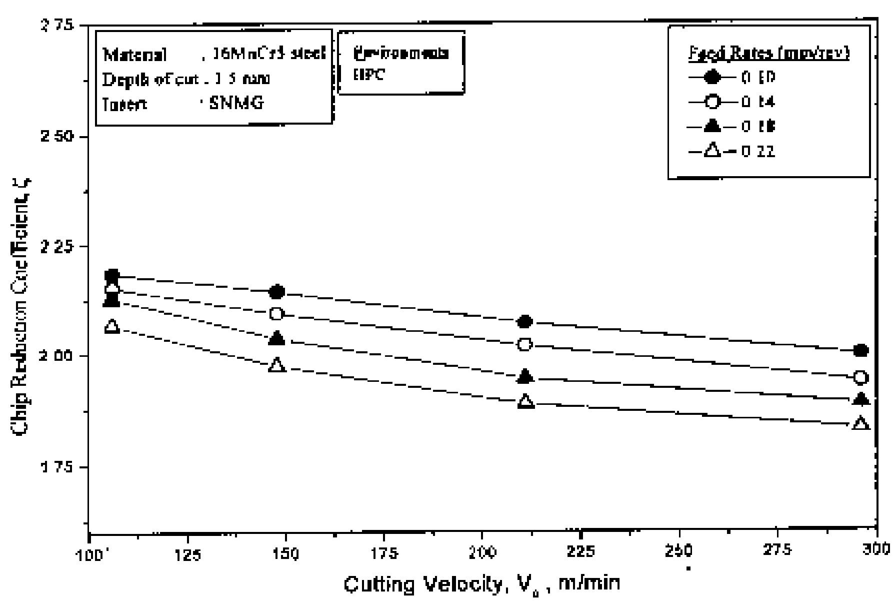


Fig. 3.81 Variation of chip reduction coefficient with V_c at different S_0 under HPC condition at P=90 bar and Q=4 L/min

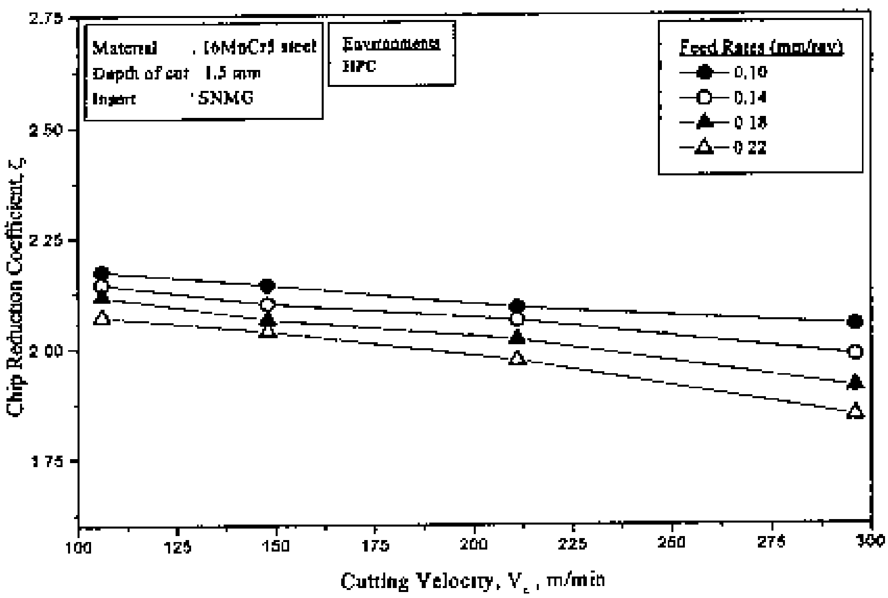


Fig. 3.82 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=90 bar and Q=5 L/min

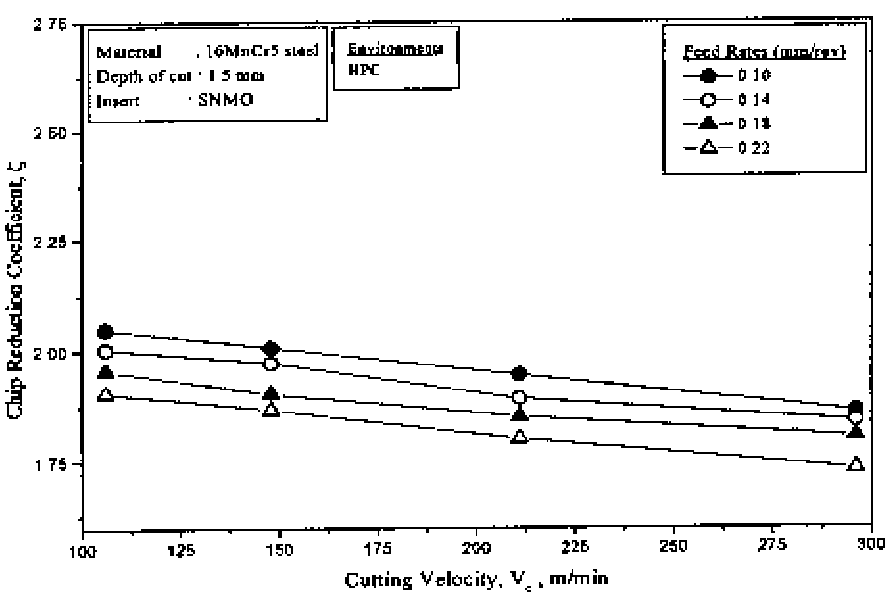


Fig. 3.83 Variation of chip reduction coefficient with V_c at different S_o under HPC condition at P=90 bar and Q=6 L/min

3.4.3 Surface roughness

Surface roughness is predominantly considered as the most important feature of practical engineering surfaces due to its crucial influence on the mechanical and physical properties of machined parts. So, characterization of surface topography is essential in applications involving friction, lubrication, and wear, contact resistance etc. [**Thomas 1999**]. Surface finish is also an important index of machinability or grindability because performance and service life of the machined/ground component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface microcracks, if any, particularly when that component is to be used under dynamic loading or in conjunction with some other mating part(s). Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining. Even if it is to be finally finished by grinding, machining prior to that needs to be done with surface roughness as low as possible to facilitate and economize the grinding operation and reduce initial surface defects as far as possible.

Although ronghness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of a surface will usually increase its manufacturing costs. This often results in a trade-off between the manufacturing cost of a component and its performance in application. Several factors will influence the final surface roughness in a machining operation. The final surface roughness might be considered as the sum of two independent effects: 1) the ideal surface roughness is a result of the geometry of tool and feed rate and 2) the natural surface roughness is a result of the irregularities iu the cutting operation [**Boothroyd**

& Knight, 1989]. Factors such as spindle speed, feed rate, and depth of cut that control the cutting operation can be setup in advance and factors such as tool geometry, tool wear, chip loads and chip formations, or the material properties of both tool and workpiece are uncontrolled **[Huynh & Fan, 1992]** . Even in the occurrence of chatter or vibrations of the machine tool, defects in the structure of the work material, wear of tool, or irregularities of chip formation contribute to the surface damage in practice during machining [**Boothroyd & Knight, 1989**].

From the previous research, the major causes behind development of surface roughness in continuous machining processes like turning, particularly of ductile metals are: (1) regular feed marks left by the tool tip on the finished surface, (2) irregular deformation of the auxiliary cutting edge at the tool-tip due to chipping, fracturing and wear, (3) vibration in the machining system and (4) built-up edge formation, if any. Roughness may be measured using contact or non-contact methods. Contact methods involve dragging a measurement stylus across the surface; these instruments include profilometers. Non-contact methods include interferometry, confocal microscopy, electrical capacitance and electron microscopy.

After machining AISI 4320 steel bar by the uncoated SNMG insert, at different V_C-S_0 combinations under HPC conditions, the surface finish was measured by a Talysurf (Surtronic 3+ Roughness Checker, Taylor Hobson, UK) using sampling length of 0.8 mm . The variation in surface roughness observed with advancement of machining steel by the uncoated carbide insert at a particular set of cutting velocity, feed rate and depth of cut , under HPC conditions having various pressure (P) and flow rate (Q) which have been shown from Fig. 3.84 to 3.99.

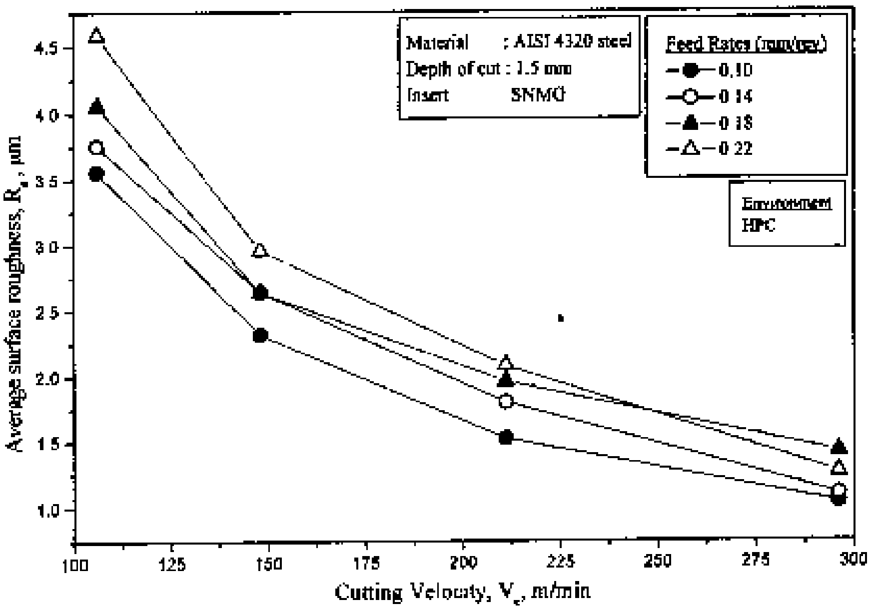


Fig. 3.84 Variation in R_a with V_c and S_o under HPC conditions at P=30 bar and Q=3 L/min

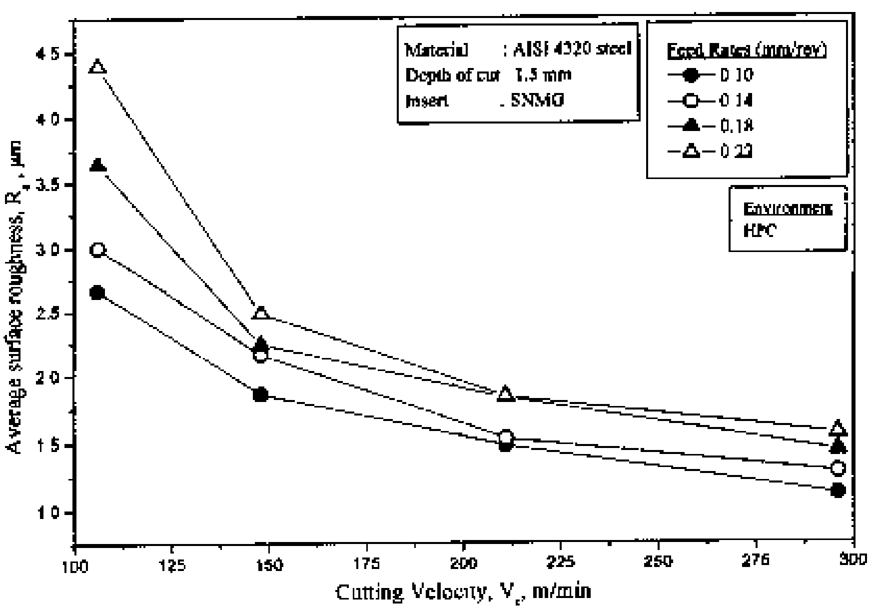


Fig. 3.85 Variation in R_a with V_c and S_o under HPC conditions at P=30 bar and Q=4 L/min

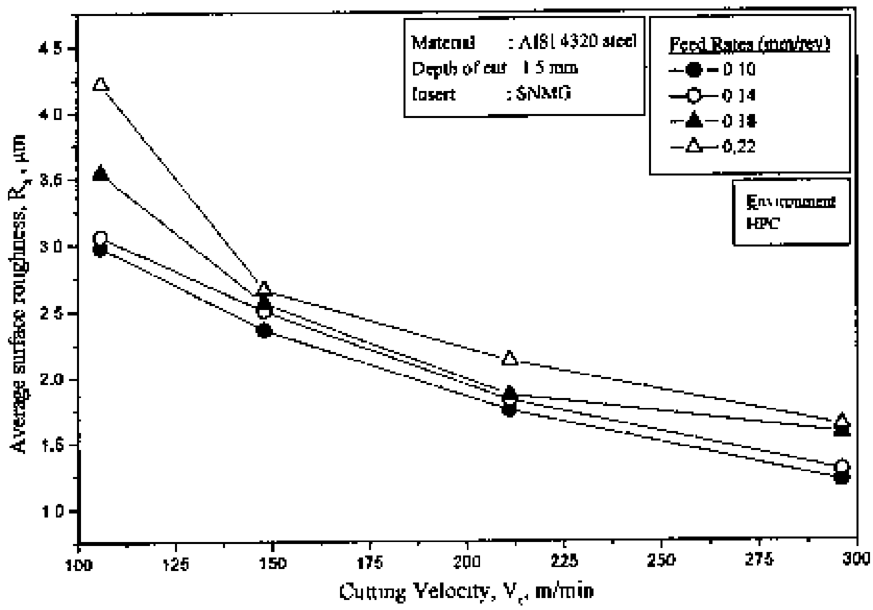


Fig. 3.86 Variation in R_a with V_c and S_o under HPC conditions at P=30 bar and Q=5 L/min

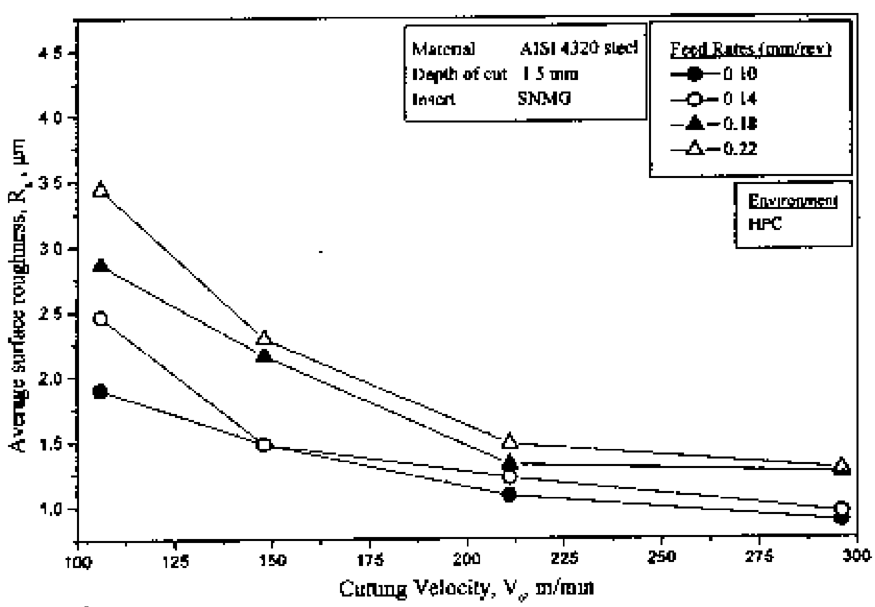


Fig. 3.87 Variation in R_a with V_c and S_o under HPC conditions at P=30 bar and Q=6 L/min

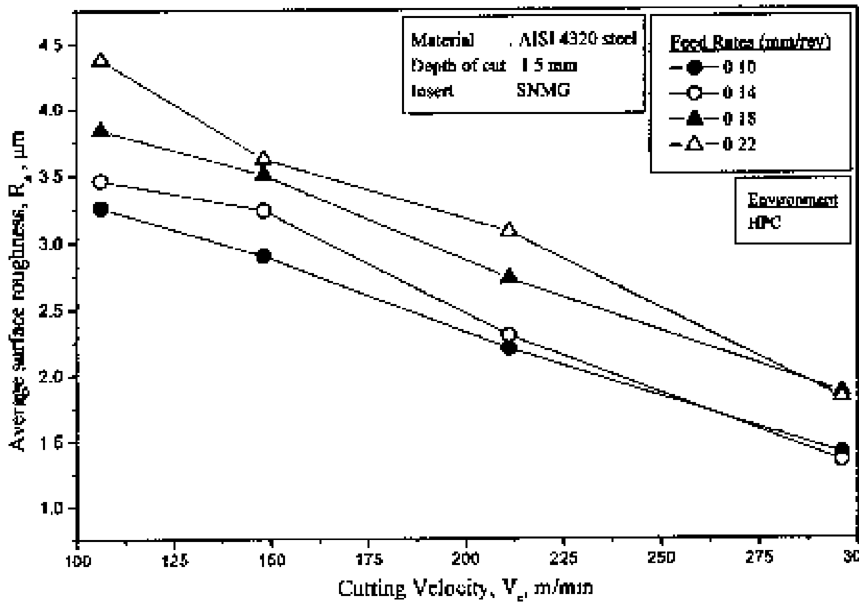


Fig. 3.88 Variation in R_a with V_c and S_0 under HPC conditions at P=50 bar and Q=3 L/min

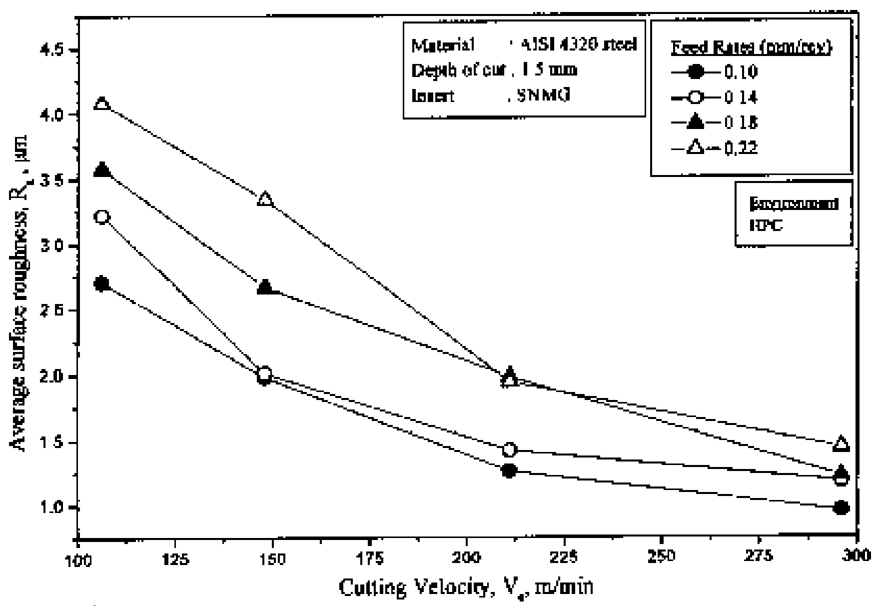


Fig. 3.89 Variation in R_a with V_c and S_0 under HPC conditions at P=50 bar and Q=4 L/min

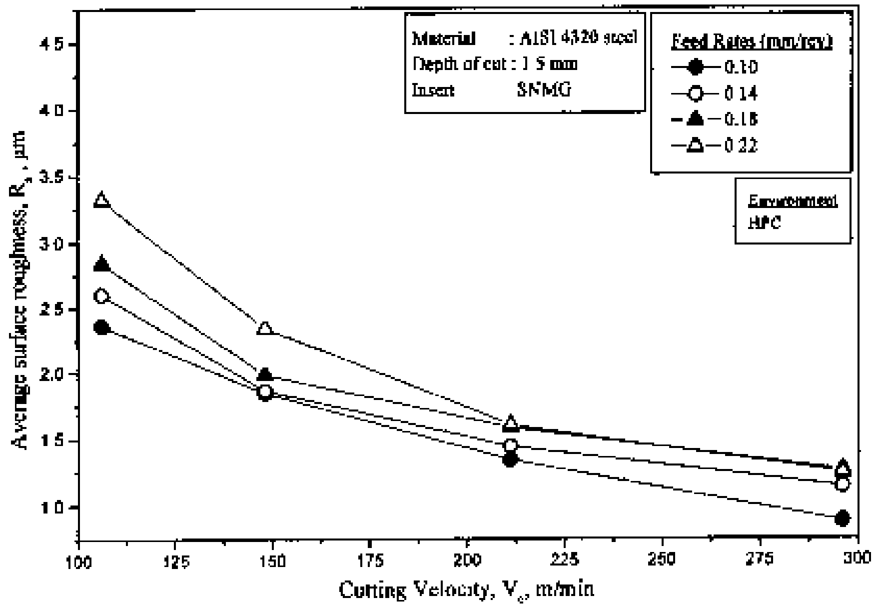


Fig. 3.90 Variation in R_a with V_c and S_o under HPC conditions at P=50 bar and Q=5 L/min

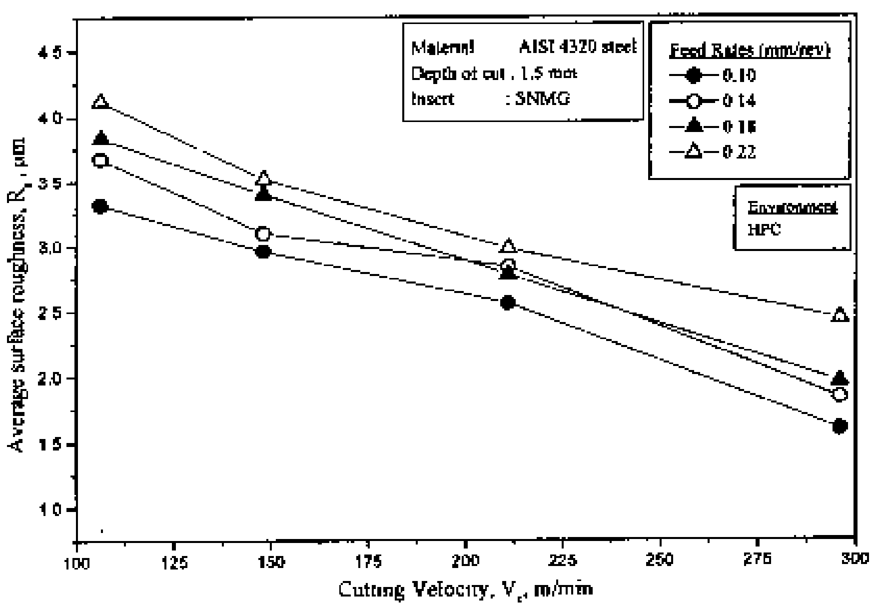


Fig. 3.91 Variation in R_a with V_c and S_o under HPC conditions at P=50 bar and Q=6 L/min

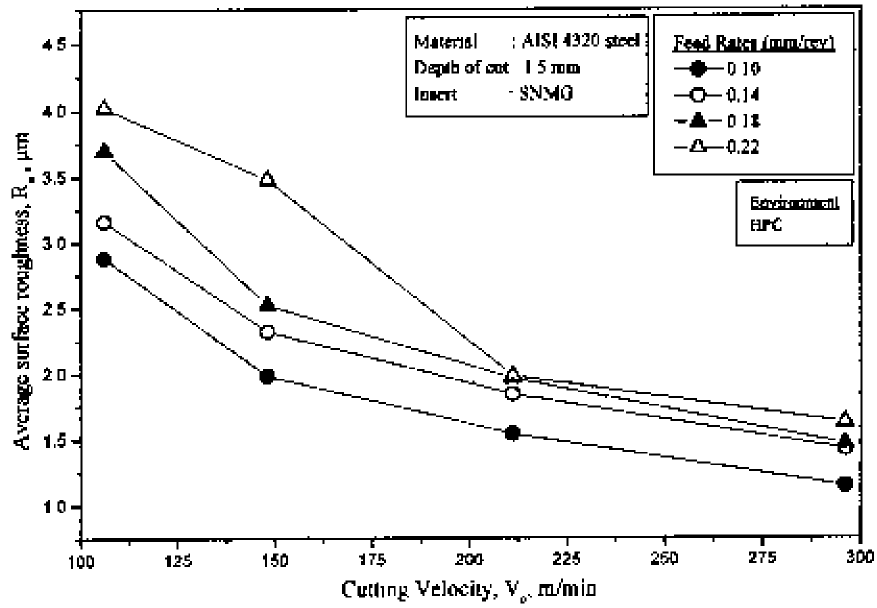


Fig. 3.92 Variation in R_a with V_c and S_o under HPC conditions at P=70 bar and Q=3 L/min

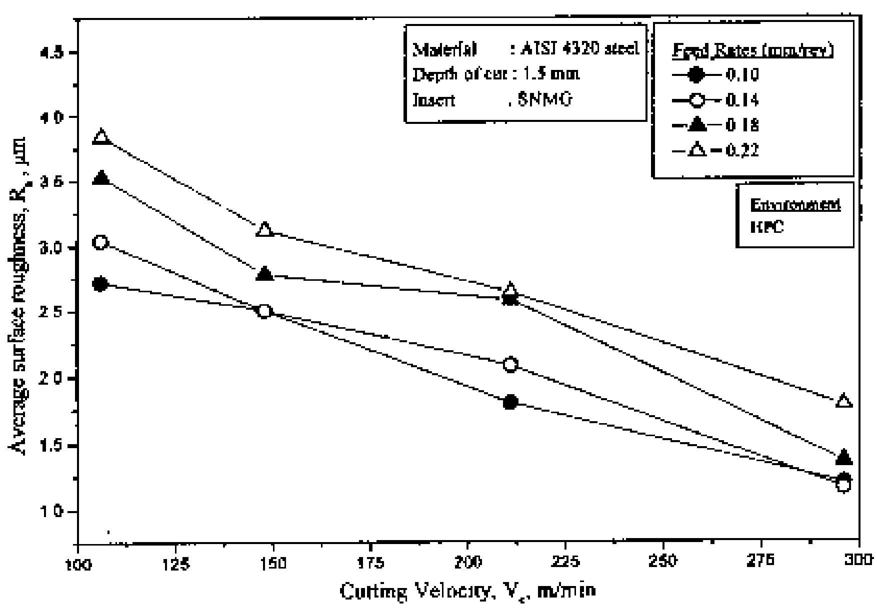


Fig. 3.93 Variation in R_a with V_c and S_o under HPC conditions at P=70 bar and Q=4 L/min

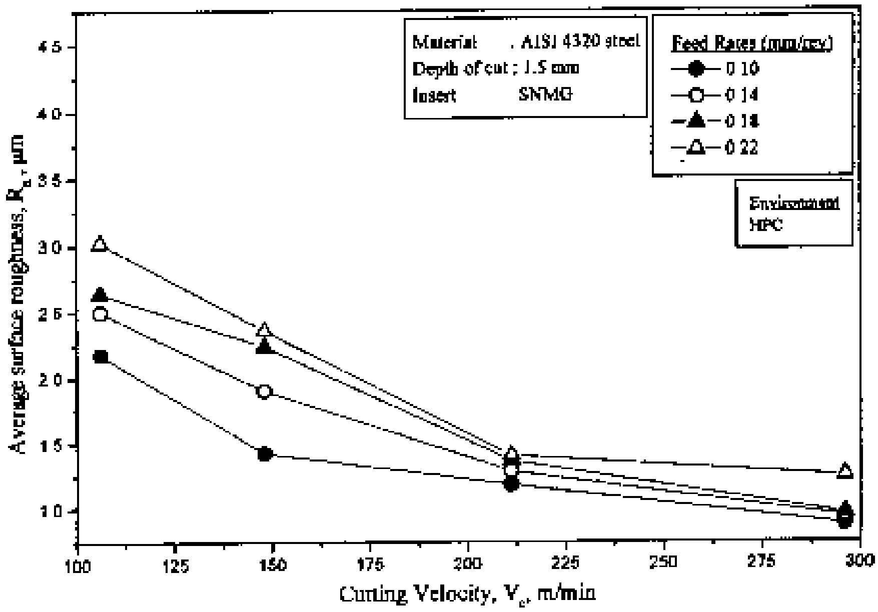


Fig. 3.94 Variation in R_a with V_c and S_o under HPC conditions at P=70 bar and Q=5 L/min

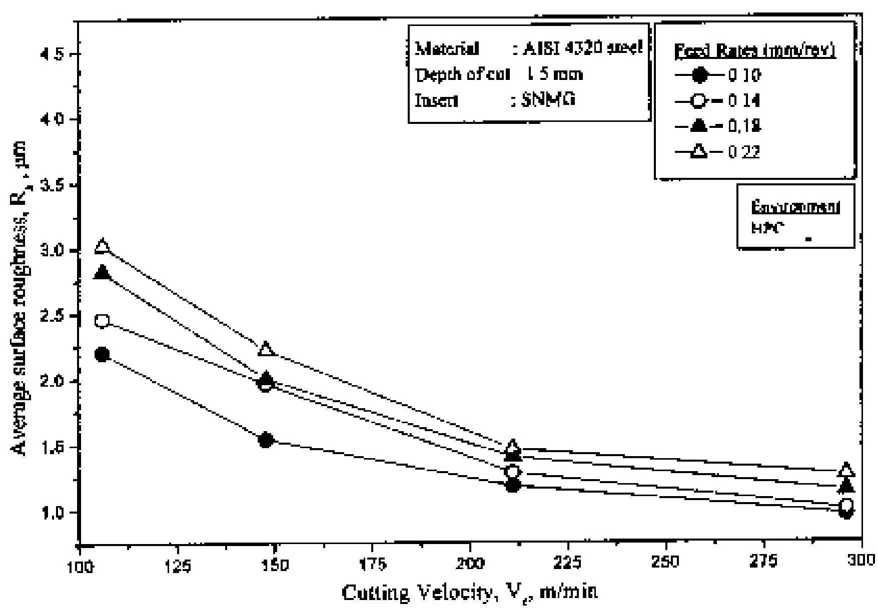


Fig. 3.95 Variation in R_a with V_c and S_o under HPC conditions at P=70 bar and Q=6 L/min

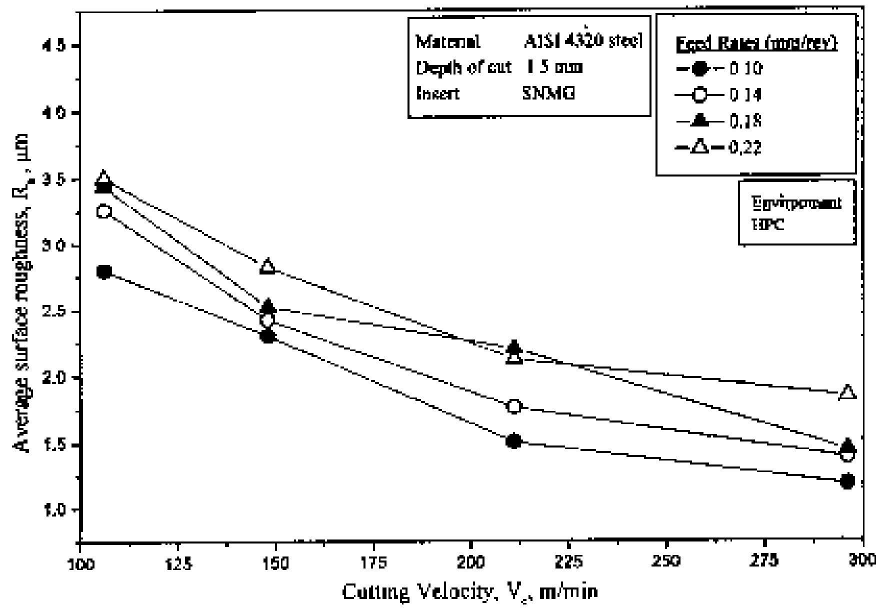


Fig. 3.96 Variation in R_a with V_c and S_o under HPC conditions at P=90 bar and Q=3 L/min

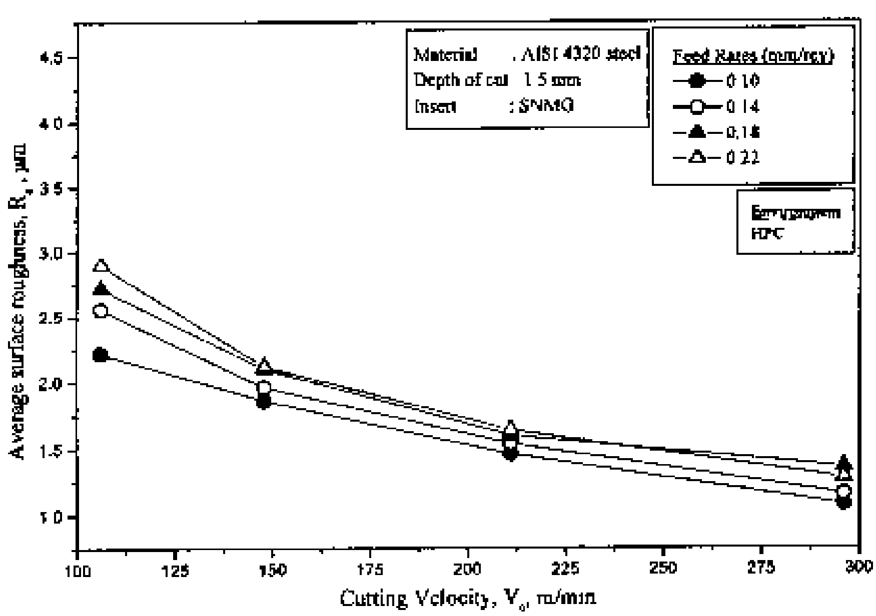


Fig. 3.97 Variation in R_a with V_c and S_o under HPC conditions at P=90 bar and Q=4 L/min

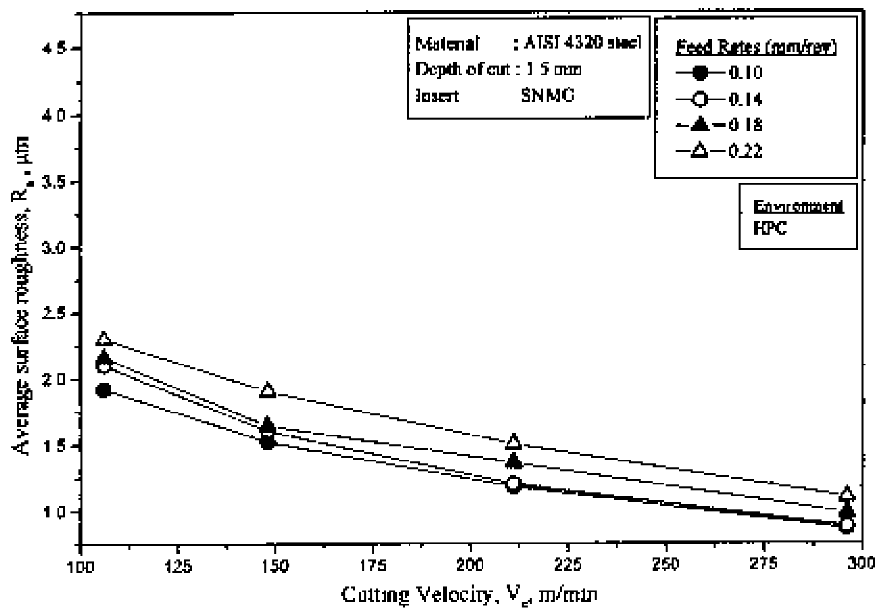


Fig. 3.98 Variation in R_a with V_c and S_o under HPC conditions at P=90 bar and Q=5 L/min

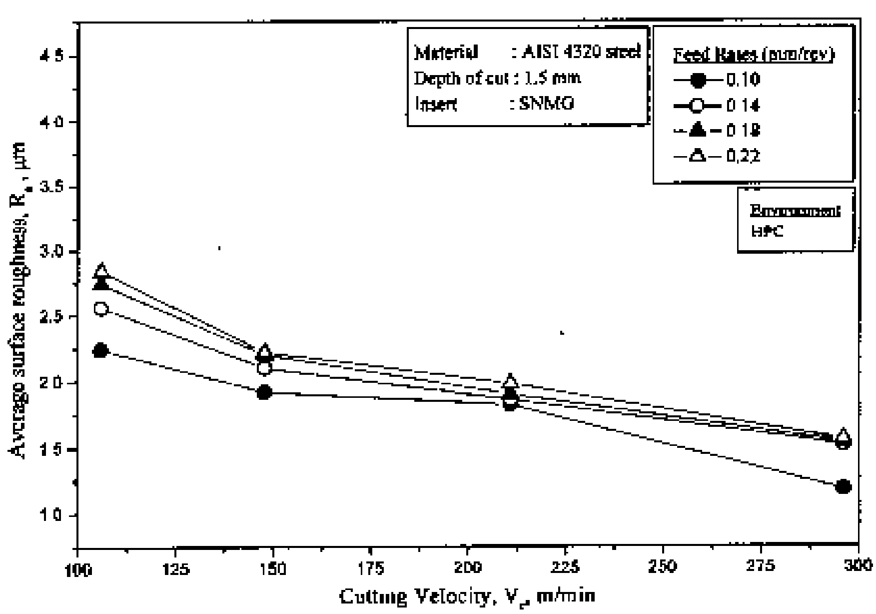


Fig. 3.99 Variation in R_a with V_c and S_o under HPC conditions at P=90 bar and Q=6 L/min

Chapter-4

Optimization of Pressure and Flow Rate

4.1 Introduction

Optimization in metal cutting processes is carried out since many days in order to optimize the cutting or process parameters to achieve cost effective machining. In the manufacturing sector, it is very important to optimize process parameters for improving product quality, shortening processing time, reducing production cost and increasing product competitiveness. Multiple attribute decision making (MADM) involves making preference decision (such as evaluation, prioritization, selection) over the available alternatives that are characterized by multiple, usually conflicting attributes [**Hwang and Yoon 1981**]. In general, the intention of solving the MADM problem is to obtain the best of the available alternatives - those that give the highest degree of satisfaction with respect to all criteria or goals. Once the aggregated scores are determined, the ranking order of alternatives can be automatically decided. Therefore, MADM models can be ideally applied in selecting the optimized process parameters with multiple performance criteria.

In this study, a detailed experimental investigation has been carried out based on design of experiment to examine the effect of HPC as well as to find out the most influential factors affecting machining response in turning AISI 4320 steel with carbide tool. The process attributes, θ, ξ, R_a are then analyzed by implementing multiple attribute decision making method and then extending it by graphical method to find out the optimized values of pressure and flow rate.

4.2 Design of Experiment

Design of experiment (DOE) is a very effective statistical method by which it is possible to determine the most influential factors affecting the output among many factors. DOE deals with determined process variable or design variables and response variables. This response variable is a function of design factors. As mentioned earlier, under this research work θ, ξ, and R_a are measured at different values of V_c , S_o , P and Q. Hence, there are three responses θ, ξ, and R_a controlled by four design factors, V_c , S_o , P and Q. Among many other methods of DOE, 2^k factorial design method has been conducted here where K signifies the four design factors having two levels each. Therefore, 16 experiments have been carried out under 2^4 factorial design. Table 4.1 presents the 4 design factors with their 2 levels (maximum and minimum).

Table 4.1 Factors and levels selected for the Design of Experiment (DOE)

Level	V_c (m/min)	S_o (mm/rev)	P (bar)	Q (liter/min)
minimum	104	0. 10	30	3
maximum	296	0. 22	90	6

Table 4.2 represents the design matrix containing observations of the 16 trial experiments. Here, A, B, C, D denote feed rate, cutting velocity, pressure and flow rate respectively. Again, AB or ACD etc. indicate the interaction effect of feed and velocity and feed, pressure and flow rate respectively.

Table 4.2 Design matrix containing observations of the 16 trial experiments.

Trials	Main Effects				Interaction Factors											Output		
	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	ABCD	θ	ξ	R_a
1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1	608	2.454	3.56
2	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	706	2.306	4.58
3	-1	1	-1	-1	-1	1	1	-1	-1	1	1	1	-1	1	-1	789	2.371	1.04
4	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1	815	2.155	1.26
5	-1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	1	-1	545	2.381	2.80
6	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1	658	2.165	3.50
7	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1	738	2.205	1.18
8	1	1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1	775	1.948	1.84
9	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1	1	-1	600	2.278	1.90
10	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1	696	2.052	3.44
11	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	780	2.122	0.88
12	1	1	-1	1	1	-1	1	-1	1	-1	-1	1	-1	-1	-1	813	1.901	1.28
13	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	1	541	2.050	2.24
14	1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	1	-1	-1	654	1.906	2.84
15	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	1	-1	736	1.863	1.18
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	765	1.732	1.56
rank	**2**	**1**	**3**	**5**	**4**													
θ	545	1203	395	49	295	39	3	29	2.99	8.99	25	1.01	13	11	17			
rank	**2**	**4**	**3**	**1**									**5**					
ξ	1.6	1.3	1.4	2.1	0.1	0.06	0.12	0.2	0	0.2	0.03	0.13	0.28	0.1	0			
rank	**2**	**1**		**3**				**5**	**4**									
R_a	5.52	15	0.8	4.4	2.2	0.8	0.32	3.4	3.6	1.44	1.68	0.5	1.1	1.7	0.16			

From this table it is clear that the most influential factors are different for different responses. It can be concluded from the table that

i. The most influential factors affecting θ are V_c, S_o, P, interactions effect of V_c and S_o and Q which are ranked from 1 to 5 in the table. This suggests that optimizing V_c can contribute upto 46% to achieve desired θ values. Accordingly, S_0, P interactions effect of V_c and S_o and Q are able to contribute approximately 21%, 15%, 11.3%, 1.8% respectively. It can be seen that flow rate has a minor effect on θ compared to others. Fig 4.1 makes this result more distinct by plotting the main effects of 4 design factors. Fig. 4.2 also shows the interaction effects of the factors which clearly indicate interaction effects are not dominant to affect θ.

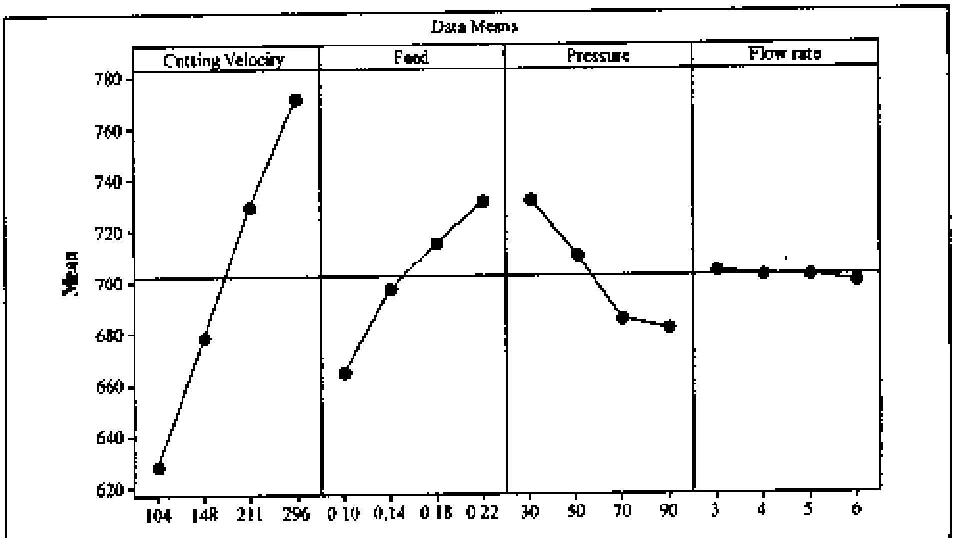


Fig. 4.1 Main effects on average chip-tool interface temperature..

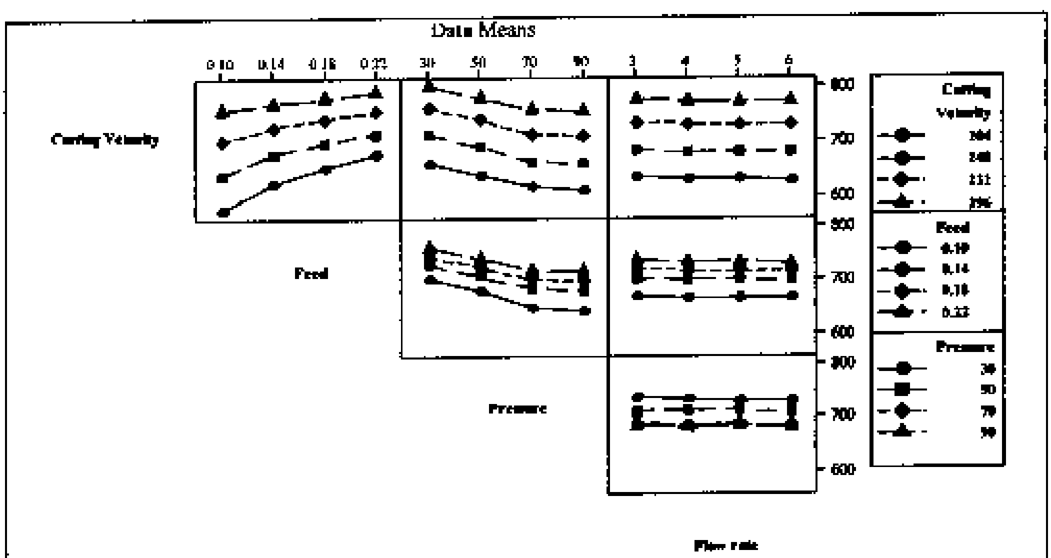


Fig. 4.2 Interaction plot of average chip-tool interface temperature

ii. Interestingly, in case of chip reduction co-efficient, the most influential factor is Q. again, three factor interaction effects (V_c, Q and P) has come into consideration to effect ξ. Fig. 4.3 and 4.4 show the main effects and interaction effect plots which clearly help to visualize the contributing factors, Q, S_o, P, V_c, interactions among V_c, Q and P which are of 27.5%, 21%, 18.4%, 17%, 3.67% respectively.

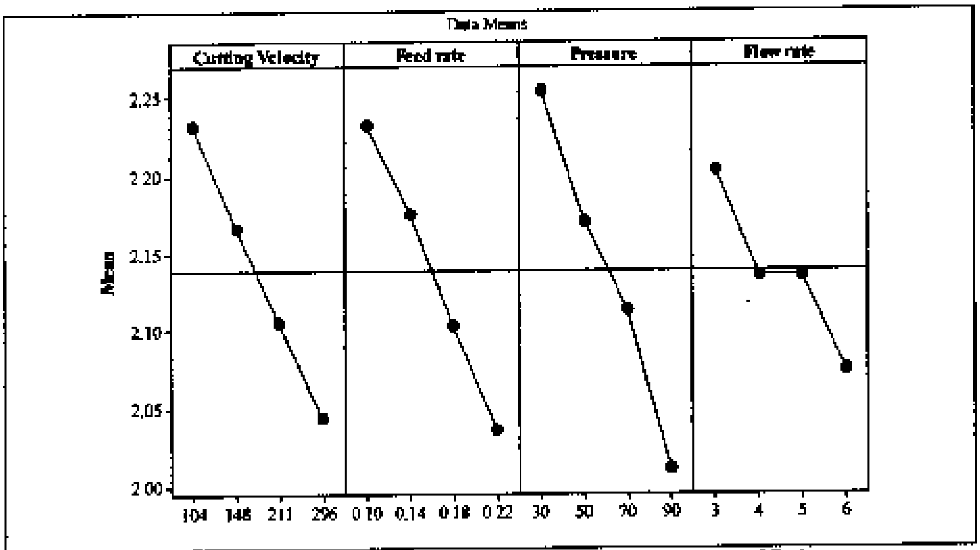


Fig. 4.3 Main effects plot of chip reduction co-efficient

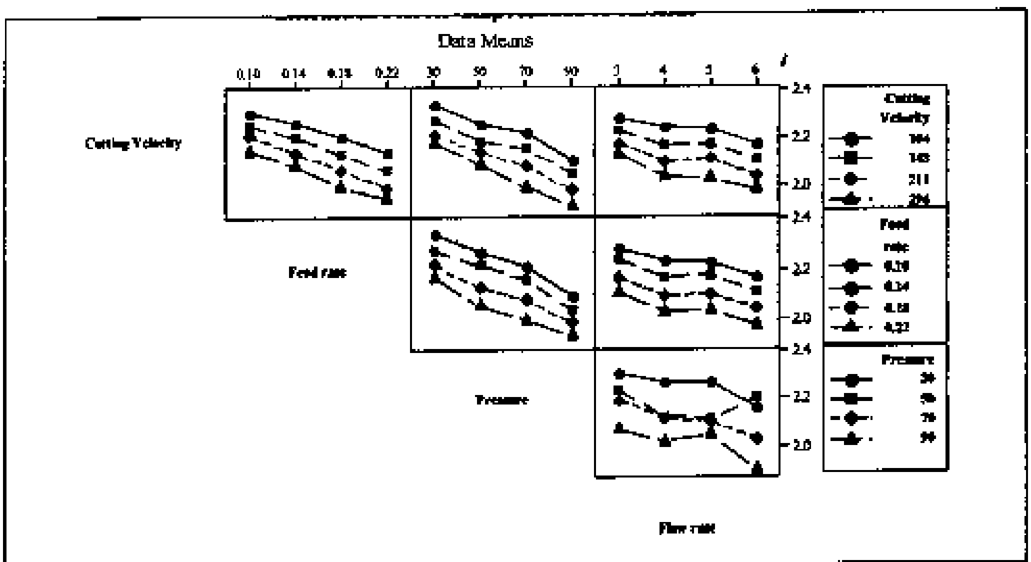


Fig. 4.4 Interactions plot of chip reduction co-efficient

iii. Alike cutting temperature scenarios, V_c and S_0 are the two influential factors to affect R_a. They are able to change R_a approx. 35.2% and 13 % respectively. The other three factors are Q, interaction of V_c and P as well as P and Q having 10.3%, 8.4%, and 7.9% effects on R_a respectively. Fig. 4.5 and Fig. 4.6 shows the main effect and interaction effects on R_a and it can be concluded that in case of R_a, V_c itself is the most consideration factor compared to other fours.

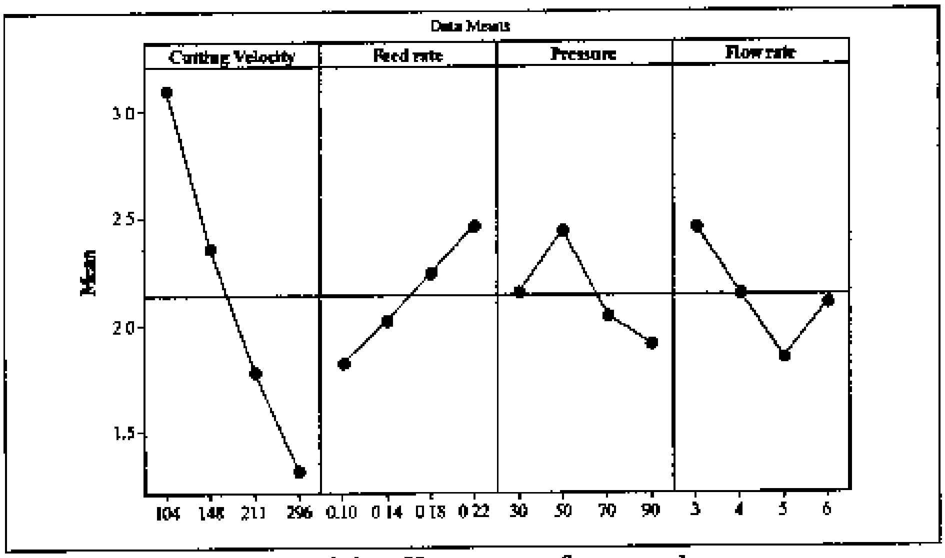


Fig. 4.5 Main effects on surface roughness

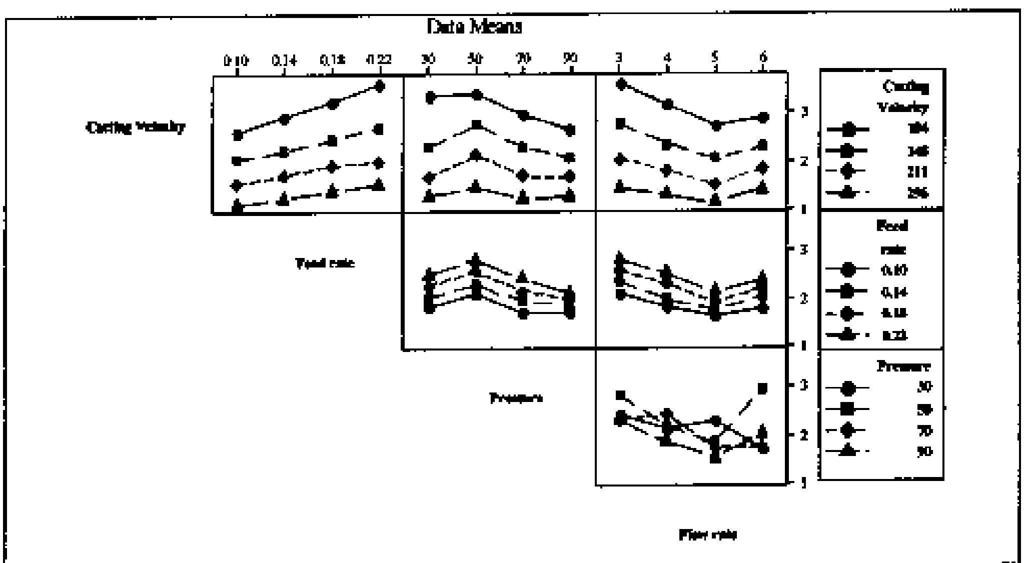


Fig. 4.6 Interaction plot of surface roughness

Overall one decision is certain from the DOE that interaction effects are not dominant here for any machining response. Therefore, optimizing main effects should be given higher priority.

4.3 Multiple Attribute Decision Making Method

The present research work deals with the three machining attributes: average chip-tool interface temperature, chip reduction co-efficient and surface roughness and four process parameters, V_c, S_o, P and Q. Design of Experiment is conducted to find out the primary influential factors of a particular attribute. The primary influential factors for one attribute are not same for all the machining attributes. From the previous section of DOE, it is very much distinct that top influential factors that affect θ do not affect ξ or R_a to the same extent. For θ and R_a, V_c is the most influential factor where as for ξ, flow rate plays the major role.

But, metal cutting efficiency or manufacturing efficiency does not depend on any single attribute or response. For example, minimizing cutting temperature at the chip-tool interface does not assure good or smooth machining. It requires the inclusion of other attributes such as tool wear, chip formation mode, chips morphology, cutting forces, dimensional deviation, surface finish and surface integrity etc. A machining process will be highly efficient if the positive effects of all of the considered attributes can be accumulated at an optimum level. On the other hand, these attributes mutually are of conflicting characters. Increasing V_C reduces chip reduction co-efficient but it also increases average cutting temperature. Therefore, it is necessary to find an optimum value of the process parameters (V_c, S_o, P and Q) at which the combinational effect of the three attributes, θ, ξ and R_a is satisfactory.

Design of Experiment of this present research work contains 16 runs in order to find out the influencing or dominant design factors. These 16 combinations of the fonr process parameters and each combination provide an alternative for decision making. The three responses, θ, ξ and R_a are regarded as the three attributes of the attributive matrix under the Simple Additive Weighting (SAW) method [**Fishburn 1967**]. Different weights are assigned to θ, ξ and R_a according to different machining requirement. Hence, in this research paper, a complete spectrum of weights are presented [**SUN et al. 2005**] .The optimal solutions of the process parameters can be obtained with specific weight of each criterion which can be provided by the industry according to the actual machining requirement. SAW (Simple Additive Weighting) has been carried out for the attribute matrix where the sensitivity study of the model is done by assigning a series of weights to the attributes. Table 4.3 lists the optimized solutions under different weight scenarios. It can be found that

i. When higher weightage is given to θ (50%~100%), 13 no run under DOE becomes almost invariant as an optimal solution where reduced cutting velocity and feed rate are desired along with increased level of P and Q. Now, the question arises regarding the extent of the increased level of P and Q. This permits to conduct MODM (Multiple Object Decision Making) method to find out the optimized value of Pand Q which have been shown in the next article.

ii. When chip reduction co-efficient is given higher weightage, optimal solution set becomes a set of 15 and 16 no trial runs and they become invariant. In these cases, changing feed rate does not affect combined machining efficiency. Additionally, high level of V_c, P and Q are desired for optimum output. In order to determine the limiting value of V_c, more experiments need to be carried out under DOE to enable

MADM selection process to select optimum set of V_c. Increased level of P and Q can be determined as discussed in previous point.

Table 4.3 Shows the weight used to observe optimal set of solutions in 16 trials.

Weight allotted to θ	Weight allotted to ξ	Weight allotted to R_a	Optimal set of solutions
33.33%	33.33%	33.34%	{15},{16, 13}
25%	25%	50%	{15}, {11}
25%	50%	25%	{15, 16}
50%	25%	25%	{13},{9}
75%	12.5%	12.5%	{13}
100%	0%	0%	{13}
12.5%	75%	12.5%	{16}, {15}
12.5%	12.5%	75%	{11}, {15}
0%	100%	0%	{16}
0%	0%	100%	{11},{15}
0%	50%	50%	{15, 16}
25%	75%	0%	{16}, {14}

iii. When, R_a is of higher importance, optimal solution goes to 15 and 11 no experimental runs. All the solutions in this set have reduced level of V_c and increased level of S_0 as well as Q. Changing P does not signify any major change in total output.

iv. In brief, for maximum weight range, the optimized solution set contains 13, 15, 16 trial runs. This indicates that this three solution set are robust against the weight change of θ, ξ and R_a. This also indicates that the increased level of P and Q from 30 bar and 3 liter/min respectively will provide effective machining.

4.4 Optimization of Pressure (P) and Flow Rate (Q)

In conventional machine tools, changing the values of V_c and S_0 is limited to manufacturers' specifications. On the other hand, changing the lubrication process parameters is free from this limitation and almost any required values of P and Q can be provided. Multiple Object Decision Making method can be used to optimize the pressure and flow rate. In this research paper, optimization is carried out by plotting the normalized weightage matrix done under SAW along with the findings of DOE.

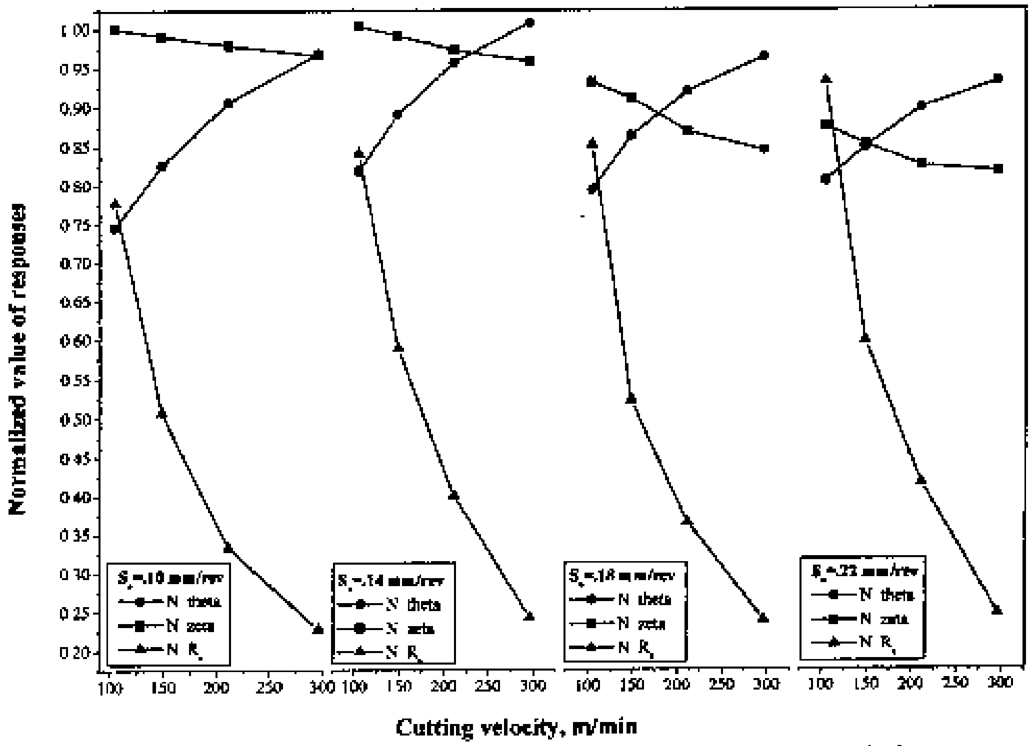


Fig.4.7 Optimization of V_c and S_o at P=30 bar and Q= 3 L/min

It is distinct from the DOE table that V_c and S_o are the common dominant factors in all the three responses and optimizing V_c and S_o definitely return much better output than optimization of pressure and flow rate alone. Therefore, graphs of weighted normalized attributes at different V_c and S_o are plotted first to get the optimum values.

After that, based on the optimal set of {V_c, S_o}, another set of graphs are plotted containing weighted normalized attribute variables. The intersection or the minimum points of these graphs will return the optimized P and Q values. Fig. 4.7

and 4.8 presents a graph of equally weighted normalized θ, ξ and R_a with respect to V_c and S_0. It is clear from the graph that the intersection point returns the optimal set of {V_c, S_o} which are {149, 0.22} and {185, 0. 18}.But we have available nearest V_c are 148 m/min and 211 m/min. Finally, we choose 211 m/min as V_c for high MRR.

Next, normalized θ, ξ, and R_a values are plotted again with respect to different flow rate for any one of the optimal sets of V_c and S_0. Fig. 4.9 shows the trends of θ, ξ, and R_a with respect to different flow rate at 30, 50, 70, 90 bars respectively. It is distinct from the graph that the minimum normalized value is found in the third panel at 70 bar and 6 liter/min.

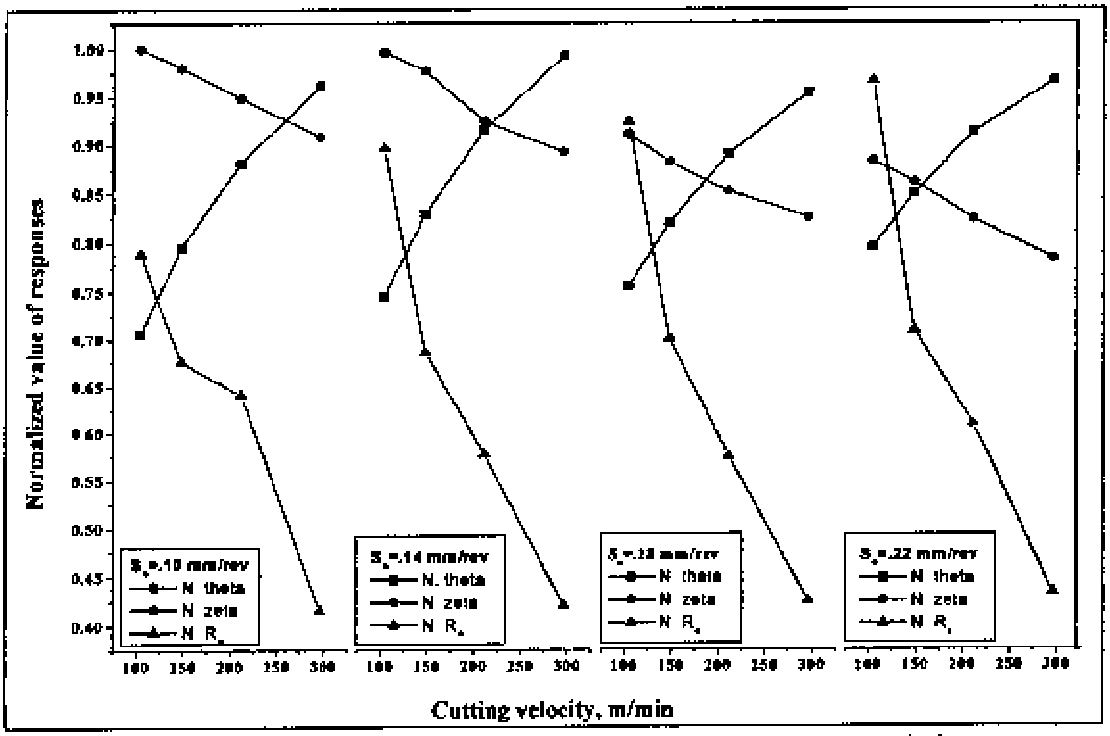


Fig. 4.8 Optimization of V_c and S_o at P=90 bar and Q= 6 L/min

The entire problem is a minimization problem where all the three attributes are non-beneficial. Hence, the minimum normalized value derived from the function:

(1/3) θ + (1/3) ξ + (1/3) R_a is the clear indication of the effective combinational effect of the three responses.

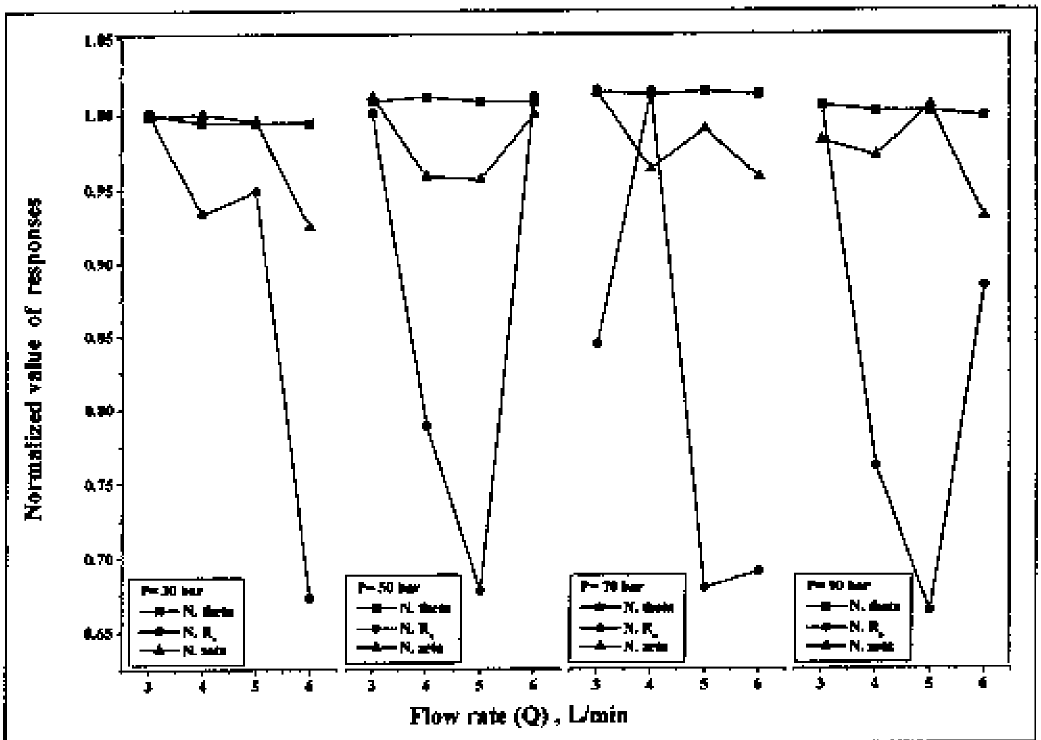


Fig. 4.9 Optimization of pressure and flow rate (V_C = 211 m/min)

4.5 Cutting Forces

The deformation of a work material means that enough force has been exerted by the tool to permanently reshape or fracture the work material. Cutting forces are generally resolved into components in mutual perpendicular directions for convenience of measurements, analysis, and estimation of power consumption and for design of Machine-Fixture-Tool-Work systems. When a solid bar is turned by single point cutting tool like insert, there are three forces acting on the cutting tool namely as; tangential force or main cutting force (P_Z), axial force or feed force (P_X), and radial force (P_Y) as indicated in Fig. 4.10.

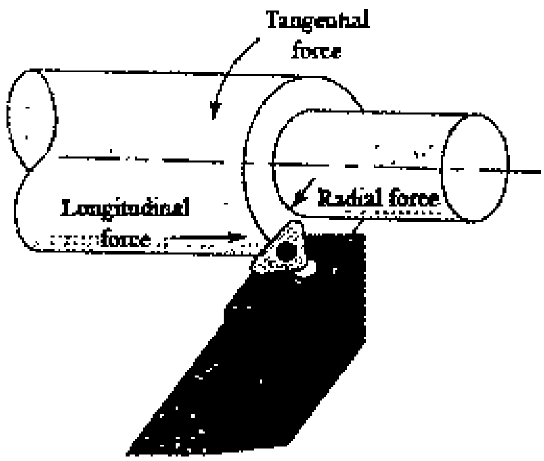


Fig. 4.10 Typical turning operation showing the forces.

The tangential force acts in a direction tangential to the revolving work piece and represents the resistance to the rotation of the work piece. In a normal operation, tangential force is the highest of the three forces and accounts for maximum portion of the total power required by the operation. Longitudinal force acts in the direction parallel to the axis of the work and represents the resistance to the longitudinal feed of the tool. Radial force acts in a radial direction from the center line of the work piece. The radial force is generally the smallest of the three. Its effect on power requirements is very small because velocity in the radial direction is negligible.

The volume of material deposited as well as tool wear interfere with the cutting processs and affect both the cutting forces (main cutting force and feed force), Longitudinal turning tests have been studied in depth by a large number of research workers all over the world. Effects of independent parameters (Viz, Cutting Speed, feed rate, depth of cut, tool angles, etc.) on dependent machining parameters (Viz, shear angle, cutting forces, shear flow stress, tool chip interface temperature) have been studied during longitudinal turning and also during accelerated cutting

[**Venkatesh et al. 1982**]. 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. Huang and Liang [**2003**] also stated that the tool material composition and properties are also crucial to the behavior of machining forces, which in turn affect tool life and surface roughness.

Heat influence on the cutting forces is mainly because the friction co-efficient is tightly dependent upon temperature and the properties of cut material also depend on temperature. When cutting speed increases both, radial and feed forces tend to decrease, for most of the metallic parts cut with carbide tools. Trent [**1991**] attributes such behavior partly to the softening effect of the workpiece material, due to temperature increase, and partly to the decreasing of the chip-tool contact length. Additionally, the depth of cnt (doc) apparently has an influence larger than the cutting speed, and feed rate has a moderate effect on forces. However, Mazurkiewicz [**1989**] successfully showed 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 rednce cutting forces and increase tool life to some extent.

Before taking force reading, optimization has been carried out with the help of Design of Experiment along with Multiple Attribute Decision Making method and multiple graphical plots based on three responses such as temperature, chip reduction coefficient and surface roughness. After optimization of pressure and flow rate, the magnitude of main cutting force (P_Z) have been monitored by dynamometer and feed force (P_X) have been calculated for all combinations of cutting velocities and feed rates under both dry and HPC environments .The effect of high pressure coolant jet on P_Z and P_X at different V_C and S_0 under both dry and high-pressure coolant conditions have been graphically shown in Fig 4.11 and Fig 4.12.

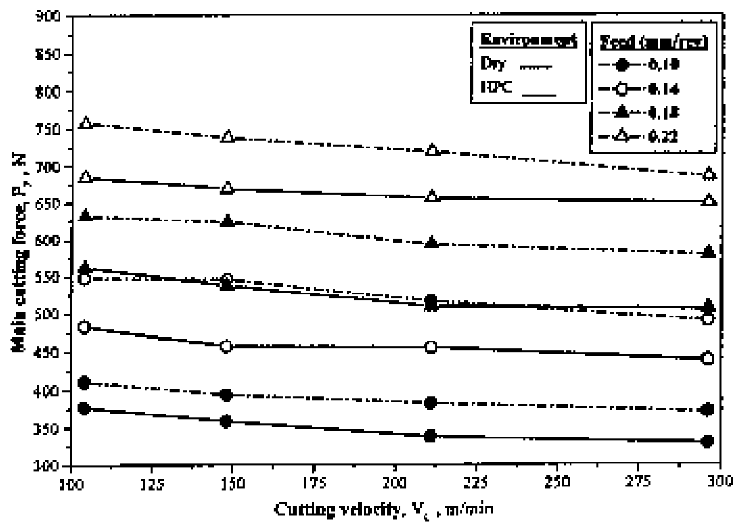


Fig. 4.11 Variation in main cutting force, P_Z with different V_c and S_o under Dry and HPC (P= 70 bar, Q=6 l/min) environment

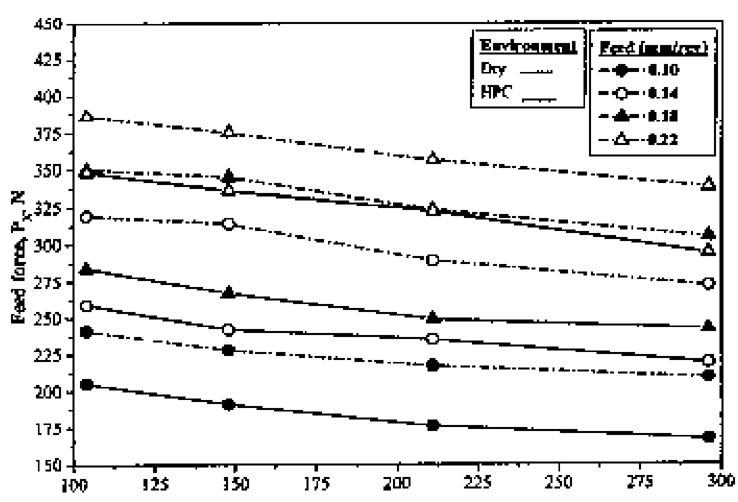


Fig 4.12 Variation in feed force, P_X with different V_c and S_o under Dry and HPC (P= 70 bar, Q=6 l/min) environment

4.6 Dimensional deviation

Possibility of controlling high cutting temperature in high production machining by high-pressure coolant injection technique not only provided reduction in cutting forces and temperature but also induced good dimensional accuracy and surface finish[**Dhar et al. 2006**]. Since, application of coolant 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 [**Mazurkiewicz et al. 1989**], HPC technique can results in good dimensional accuracy due to reduced force causes by machining and less tool wear because excessive force causes chatter and vibration and excess heat increases tool wear.

During straight turning in a centre lathe, the diameter of the machined part is gradually found to (1) increase along length of cut due to gradual wear of the tool tip (2) decrease due to thermal expansion and subsequent cooling of the job if the job temperature rises significantly during machining and (3) increase due to system compliance of the machine-fixture-tool-work 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 machine-fixture-tool-work piece system were calculated for the steel specimens being machined under the present conditions and the values appear to be extremely small 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.

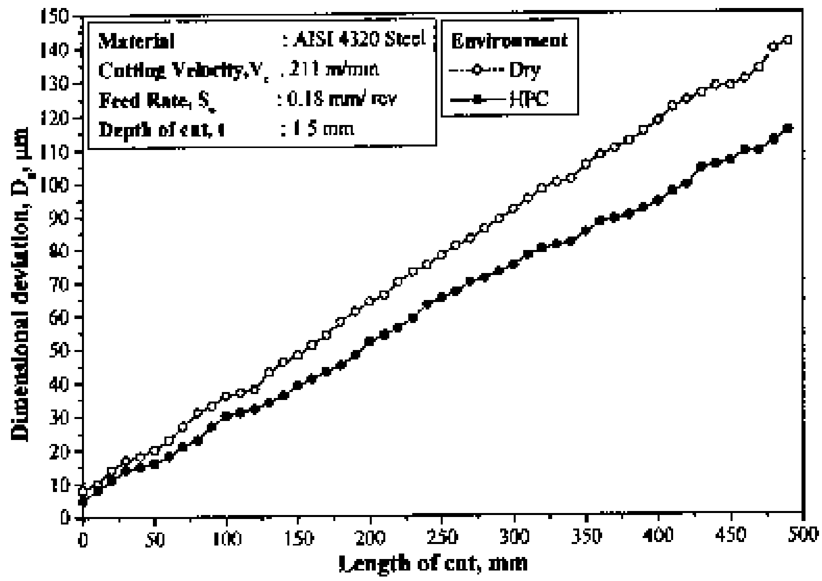


Fig 4.13 Variation in deviation of dimension with length of cut under Dry and HPC (P= 70 bar, Q=6 l/min) conditions.

The variation in diameter of the job was precisely measured along its axis after one full pass of the machining over 500 mm length with full depth, at reasonably high S_o and V_c suitable for the tool-work-environment combination undertaken keeping the initial diameter and the length of the AISI 4320 steel bar same and uniform as far as possible. The gradual increase in dimensional deviations one full pass of machining at cutting velocity 211 m/min, 0.18 mm/rev feed and 1.5 mm depth of cut under dry and HPC cooling condition is shown in Fig. 4.13 .

Chapter-5

Results and Discussion

5.1 Cutting Temperature

Although MRR increases with increase in velocities and feed rates but it raises temperature significantly and such detrimental cutting temperature adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products. So the machining temperature at the cutting zone is an important index of machinability and needs to be controlled as far as possible. By directing the coolant stream more precisely and with the optimum amount of pressure and flow rate, noticeably more heat can be removed from the cutting zone. This degree of cooling also enables the cutting tool to remove greater amounts of metal, thus improving productivity. Additionally, the high-pressure coolant stream helps break up chips and remove them from the cutting area more efficiently, which means the cutting tool spends less time re-cutting metal chips. The combination of reduced heat and more efficient evacuation of chips prolong tool life and makes replacement more predictable because the cutting tool wears out naturally, rather than failing prematurely because of excessive heat or chip damage. Thus, the application of HPC at chip tool interface, having optimum pressure and flow rate, 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 at the cutting zone is very high.

The average chip-tool interface temperature (θ_{avg}) has been determined using the tool work thermocouple technique and plotted against cutting velocity for different feeds under HPC conditions having various pressure and flow rate. From Fig. 3.4 to 3.19, the effect of HPC jet pressure and flow rate on average chip-tool interface temperature (θ_{avg}) under different cutting velocity, V_c and feed rate, S_o is showing as compared to each other. However, it is clear from the aforementioned figures that with the increase in V_c and S_o, average chip-tool interface temperature, (θ_{avg}) increased as usual under HPC condition, due to increase in energy input. It is also observed that Temperature at the tool-workpiece is surprisingly reduced with increase in pressure at various speeds and feed rates but the impact of flow rates is ambiguous.

However, during machining at lower 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 or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip-tool interface. From Fig.3.4 to 3.19, it is distinct that HPC cooling provided more improvement 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 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. 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, V_c and S_o with increasing pressure and flow rate. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

To investigate the effect of pressure and flow rate on machining temperature, temperature versus pressure (θ_{avg} Vs P) and temperature versus flow rate (θ_{avg} Vs Q) graphs are plotted which are shown from Fig 3.20 to 3.35 (P Vs θ_{avg}) and 3.36 to 3.51 (Q Vs θ_{avg}) respectively. It is evident from those graph that the effect of pressure on machining temperature is more significant than that of flow rate and temperature is reduced with increasing pressure at a decreasing rate because at a high pressure coolant easily can enter at the chip-tool interface by creating a hydraulic wedge between chip-tool interface and thus resulting a reduced curl radius and reduced friction but after certain pressure the cooling tendency decreases with increasing pressure.

5.2 Chip Morphology

The geometrical and metallurgical characteristics of chips are very representative of the performances of the machining process. Indeed, they bear witness to most of the physical and thermal phenomena occurring during the machining, . This explains the large number of works made on chips **[Komanduri et al. 1981, Hastings et al. 1980, Lee 1980, Sutter et al. 1997, Radwan 1985, Komanduri et al. 1982]**. When machining ductile metals, the pattern of chips are found to depend upon the mechanical properties of the work material, tool geometry particularly rake angle, levels of V_c and S_o and cutting environment. If there is no chip breaker, length and uniformity of chips increases 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.

Excellent chip breakability has been reported when machining AISI 4320 steels with high pressure coolant supply. This is attributed to a coolant wedge which forms between the chip and tool, forcing the chip to bend upwards giving it the desirable upward curl required for segmentation. An increase in feed rate in excess of 0.10 mm/rev also causes improved chip breakability. The geometry of the SNMG insert is such that the chips first came out continuously got curled along normal plane and then hitting at the principal flank of this insert broke into pieces with regular size and shape .When AISI 4320 steel is machined by the uncoated SNMG insert under HPC condition , snarled tubular or ribbon type continuous chips are produced at lower feed rates and more or less loose arc or connected arc type discontinuous chips are produced at higher feed rates which are revealed from Table 3.2 to Table 3.5. Application of HPC coolant uplifts chips due to formation of cushion layer thereby decreasing frictional force and curl radius .Thus increasing chip breakability.

The form of these ductile chips change noticeably and their back surface appeared much brighter and smoother during the HPC jet assisted turning of AISI 4320 steel. 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 because HPC jet creates a cushion layer which prevents intimate contact at the tool-chip interface, consequently leading to bending and self-breakage of chips. Thus results in a reduced frictional force at the tool-chip interface. The colour of the chips have also become much lighter i.e. metallic or golden (Table 3.2 to 3.5) depending upon cutting velocity, V_c and feed rates, S_o due to reduction in cutting temperature by High pressure coolant.

Chip-reduction coefficient, ξ (ratio of chip thickness after and before cut) is also an important machinability index .The degree of chip thickness ratio plays vital role on cutting forces and hence on cutting energy requirements and cutting temperature. Almost all the parameters involved in machining have direct and indirect influence on the thickness of the chips during deformation. It was found that there is a reduced chip thickness (after cut) with the increase in pressure which indicates positive effects of pressure on cooling and lubrication during machining under HPC environment.

By HPC applications, chip thickness ratio, ξ 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.From Fig. 4.69 to 4.84, it is apparent that the value of chip thickness ratio, ξ gradually decreased with the increase in cutting speed, V_c though in different degree under HPC conditions having various pressure and flow rate by straight cutting oil. The value of chip thickness ratio, ξ 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 AISI 4320 steel by uncoated 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_0 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.

From Table 3.2 to 3.5 it can be notified that the role of HPC jet has been more effective in respect of form and colour of the chips when machined by the groove type SNMG insert (the groove of SNMG insert helps easy coolant flow towards the cutting zone). Such improvement can be attributed to effectively larger positive rake of the tool and better cooling by the jet coming along the groove parallel to the cutting edges. Besides high-pressure coolant jet reduce tool-chip contact area due to the fragmentation of the chip by the impinging jet at the chip-tool interface. So mostly arc chips are produced under high-pressure condition and thus a manageable chip can be produced or maintained (this is another important function of HPC system). Due to effective cooling and lubrication with appropriate pressure and flow rate makes possible reduction of curl radius to increase chip breakability because this high speed coolant easily penetrates the vapor barrier to effectively lubricate and cool the tool .Again, the direction from which the cutting fluid is applied can be used to change the direction of chip flow in case of continuous chip to prevent wrapping of this chips around the tool or workpiece. Because there are some chips which cannot be broken, but they can often still be controlled through effective nozzling. Thus difficult, stringy chips directed down into the chip pan to prevent wrapping around the tool or workpiece and make the operation easy and uninterrupted.

5.3 Surface Roughness

Surface roughness is an important design consideration as it impacts many part characteristics such as fatigue strength, cleanability, assembly tolerances, coefficient of friction, wear rate, corrosion resistance, and aesthetics **[Feng et al. 2002]**.Tsai et al. **[1999]** stated that the possible factors affecting surface finish were feed rate, cutting speed, depth of cut, cutter geometry, cutter runout, tool wear, and the cutter force and vibration under dynamic cutting conditions. It was found that there are two main effects that lead to the degradation of surface roughness – adhesion and ploughing. The frictional interaction between the tool and workpiece has a significant impact on surface quality [**Grzesik 1996**]. At low velocities, friction is largely due to local adhesion and shearing at contact surfaces **[Moore 1975]**. In the case of turning, this friction is at the tool-chip interface. Thus, at lower velocities, the chip hits the tool on a secondary cutting surface where there is significant friction. As the adhesion is increased, the tool's effect on the workpiece is converted from shearing to ploughing. The divergence from theoretical surface roughness at low feeds can be attributed to this increased adhesion and ploughing [**Grzesik 1996**].

Groover [**1996**] and Boothroyd & knight[**1989**] considers the impact of three factors, namely, the feed, nose radius, and cutting edge angles, on surface roughness and developed the following equations to estimate the ideal roughness value

$R_a = S_o/32r$ [For non zero cutter radius (r)] ... ... (5.1)

$R_a = S_o/4(\text{Cot}\alpha + \text{cot}\beta)$ [For zero cutter radius (r)] ... ... (5.2)

Where, R_a= ideal arithmetic average() surface roughness (mm), S_o=feed (mm/rev), r= cutter nose radius, α and β are the major cutting edge angle (MCEA) and end cutting edge angle (ECEA) ,respectively. Both equation clearly implies that the ideal roughness of the surface is a function of only feed rate and tool geometry and best possible finish can be obtained for a given tool shape and feed. However, these eqnations hold true only if built up edge, chatter, inaccuracies in the machine tool movement and other factors are eliminated completely.

Fig. 3.84 to 3.99 clearly shows that surface roughness increases with the increase in feed, S_o and decreased with the increase in V_c. Increase in S_o raised R_a mainly according to the equation 5.1. Reduction in R_a with the increase in V_c may be attributed to smoother chip-tool interface with lesser chance of built-up edge formation in addition to possible truncation of the feed marks and slight flattening of the tool-tip. Increase in V_c may also cause slight smoothing of the abraded auxiliary cutting edge by adhesion and diffusion type wear and thus reduced surface roughness.

It is evideut in Fig. 3.84 to 3.99 that HPC jet assisted cooling could provide marginal improvement in surface finish at the beginning of machining with the fresh cutting edges. The slight improvement in surface finish by HPC jet assisted cooling might be due to reduction in break-in wear and also possibly reduction or prevention of built-up edge formation depending npon the work material and cutting condition. This may reasonably be attributed to more stability of those alloy steel against attrition and built-up edge formation. From Fig. 3.84 to 3.99, it is noticeable that there is some improvement in surface finish with increase in pressure though it is not uniform. It may be due to the controlling of deterioration of the auxiliary cutting edge by abrasive, chipping and built-up-edge.

5.4 Cutting Forces

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 under high-pressure coolant condition. In machining, mechanical and thermal loads, and phase transformation, are main factors that affect the surface integrity of a machined part. Plastic deformation and friction in the contact between the tool and the workpiece generate heat, which raises the temperature of both components. The elevated temperature of the tool reduces its wear resistance and changes both the geometry and the size. This can result in increased cutting forces with larger deflections in the workpiece and may create a chatter condition. The coolant also acts as a lubricant, thus minimizing friction, lowering component forces, and consequently the tool wear rate. Under high speed machining conditions, the coolant has negligible access to the tool-workpiece or the tool-chip interfaces which are under seizure condition. It tends to be vaporized by the high temperature generated close to the tool edge. The effectiveness of coolants is restricted by the fact that they lose their cooling properties upon film boiling at a temperature of about 350^0C for most conventional fluids. The vaporized coolant forms a high temperature blanket that renders the cooling properties of the fluid ineffective.

During machining AISI 4320 steel main cutting forces were recorded at optimum coolant supply pressure and flow rate. This 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 cutting forces observed is also partly due to the chip segmentation when machining with high-pressure coolant supplies. Coolant supply at high-pressure tends to lift up the chip after passing through the deformarion 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 were generated when machining AISI 4320 steel with uncoated 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. The measurement of main cutting force, P_Z components is highly essential to analyses more effectively the machinability factors of AISI 4320 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 AISI 4320 steel. Fig. 4.11 to 4.12 shows the influence of cutting speed on the feed force, P_X and cutting force, P_Z respectively. The turning operations were performed at variable feed and 1.5 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 high cutting speed for both dry and HPC environment. 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 AISI 4320 steel. The feed force, P_X and main cutting force, P_Z are increased by increasing feed and both are low at low feed and high at high feed. The force, P_Z & P_X in HPC condition were reduced upto 16% and 22 % less respectively, than that of turning AISI 4320 steel under dry condition while machining by SNMG insert.

5.5 Dimensional Deviation

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**]. That's why, coolant is delivered to cool and lubricate but it can only perform these functions at the point of chip formation if the coolant actually reaches the cutting zone. When coolant is turned to steam or otherwise fails to reach the target, it does not perform its two essential functions. Besides , poor coolant delivery and low pressure can lead to various adverse effects such as premature tool failure due to abrasion and thermal shock, chipping caused by recutting swarf, dimensional variation due to thermal growth from frictional heat, work hardening of the surface (which can affect secondary operations) and lower levels of surface finish.. The penetration of the high-energy jet into the tool–chip interface reduces the temperature gradient and eliminates the seizure effect, offering adequate lubrication at the tool–chip interface with a significant reduction in friction in addition to alteration of the chip flow conditions resulting in the lowering of component forces and consequently tool wear rate [**Ezugwu et al. 2003**]. This means that temperatures are dramatically lowered due to reduced friction, the tools last longer and higher cutting speeds and feed can be adopted which leads to reduced chip reduction coefficient, lower cutting temperature, lower dimensional deviation and improved surface finish.

It has been mentioned earlier that the diameter in straight turning of long rods may deviate from the theoretically expected valne due to progressive wear of the tool-tip, variation of compliance of the Machine-Fixture-Tool-Work (M-F-T-W) system along the axis of lathe and thermal expansion or distortion of the job, if much heated. The substantial reduction in dimensional deviation observed in the present investigation can be reasonably attributed mainly to reduction in the auxiliary flank wear of the inserts by HPC.

It can be noted that in Fig. 4.13, dimensional deviation increases with the increases of length of the job for both dry and HPC cooling. By applying high pressure cooling it is comparatively less. Fig. 4.13 also shows that for dry and high pressure cooling dimensional deviation increase with the increase of the length of the job. The dimensional deviation is less in high pressure cooling condition compared to dry machining by using SNMG inserts due to much lesser break in wear or initial wear and absence of notching at the auxiliary flank of the insert.

Chapter-6

Conclusions

i. Average cutting temperature at the chip-tool interface is highly influenced by mainly cutting velocity along with feed rate and pressure. In case of chip reduction co-efficient, flow rate plays the key role along with feed rate and pressure. On the other hand, surface roughness is highly influenced by the cutting velocity along with feed rate.

ii. In case of conventional machine tools, where range of cutting velocity and feed rate entirely depends on manufacturers' specification, MADM approach can successfully draw optimal set of solutions of process parameters. It can be concluded by applying SAW method is that changing the weights of θ, ζ, and R_a does not dramatically change the optimal set of process parameters rather in all cases high pressure and flow rate of the HPC jet is desirable to get effective combinational effect.

iii. In this research, it is evident that turning AISI 4320 by uncoated carbide insert is optimized at 211 m/min and 0. 18 mm/rev as well as 148 m/min and 0.22 mm/rev where optimized pressure and flow rate of the HPC jet is 70 bar at 6 liter/min.

iv. High pressure coolant (HPC) jet assisted turning provided significant improvements expectedly, though in varying degree, in respect of chip formation modes, cutting forces, surface finish, and dimensional deviation throughout the V_c-S_o range undertaken mainly due to reduction in the average chip tool interface temperature. The present HPC systems enabled reduction in average chip-tool interface temperature upto 11% by changing pressure and flow rate and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.

v. Due to HPC application, the form and color of the alloy steel chips became favorable for more effective cooling and improvement in nature of interaction at the chip-tool interface.

vi. HPC 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 for adverse chip-tool interaction causing large friction and built-up edge formation at the chip-tool interface. Favourable 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 HPC.

vii. Surface finishes also improved mainly due to reduction of wear and damage at the tool tip as well as friction and increased chip breakability by the application of HPC.

viii. Similarly, the dimensional deviation is less in high pressure cooling condition compared to dry machining by nsing SNMG uncoated carbide inserts due to much lesser break in wear or initial wear and absence of notching at the auxiliary flank of the insert.

Chapter-7

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