Effects of Cryogenic Cooling by Liquid Nitrogen Jet on Machinability of Steel by Coated Carbide Insert

Sumaiya Islam

DEPARTMENT OF INDUSTRIAL & PRODUCTION ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING & TECHNOLOGY
DHAKA, BANGLADESH

DECEMBER 2005

Effects of Cryogenic Cooling by Liquid Nitrogen Jet on Machinability of Steel by Coated Carbide Insert

By

Sumaiya Islam

A Thesis
Submitted to the
Department of Industrial & Production Engineering
in Partial Fulfilment of the
Requirements for the Degree
of
MASTER OF SCIENCE IN INDUSTRIAL & PRODUCTION ENGINEERING

DEPARTMENT OF INDUSTRIAL & PRODUCTION ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING & TECHNOLOGY
DHAKA, BANGLADESH

DECEMBER 2005

The thesis titled **Effects of Cryogenic Cooling by Liquid Nitrogen Jet on Machinability of Steel by Coated Carbide Insert** submitted by Sumaiya Islam, Student No. 040408021F, Session- April 2004, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science In Industrial & Production Engineering on December 20, 2005.

BOARD OF EXAMINERS

1.	Dr. Nikhil Ranjan Dhar Professor & Head Department of Industrial & Production Engineering BUET, Dhaka	Chairman (Supervisor & Ex-officio)
2.	Dr. Mahiuddin Ahmed Professor Department of Industrial & Production Engineering BUET, Dhaka	Member
3.	Dr. Abdullahil Azeem Assistant Professor Department of Industrial & Production Engineering BUET, Dhaka	Member
4.	Dr. Qumrul Ahsan Associate Professor Department of Materials & Metallurgical Engineering BUET, Dhaka	Member (External)

Declaration

It is hereby declare that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Sumaiya.

Sumaiya Islam

This work is dedicated to my loving

Father

Kamrul Islam Khan

&

Mother

Zubbunahar

Contents

List of Figures

List of Tables

Acknowledgements

The author is deeply indebted to Dr. Nikhil Ranjan Dhar, Professor and Head of the Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology for his guidance, help and encouragement throughout the progress of the project work.

The author is grateful to Dr. Qumrul Ahsan, Associate Professor of Materials and Metallurgical Engineering Department, Bangladesh University of Engineering and Technology, Dhaka for his grateful support to use Scanning Electron Microscope.

The author also expressed her gratitude to Md. Kamruzzaman, Assistant Professor of Mechanical Department, Dhaka University of Engineering and Technology, Gazipur and Md. Muhshin Aziz Khan, Assistant Professor of Industrial and Production Engineering Department, ShahJalal University of Science and Technology, Sylhet for their support to continue the project work.

A special word of thanks is due to all staff members of Machine Tools Laboratory of IPE department and SEM laboratory of MME department for their help in conducting the experimental work.

Finally, the author offers her sincere thanks to all those who either directly or indirectly helped her in various ways to complete this project thesis.

Abstract

Cryogenic cooling is a promising new technology in high production machining which economically addressed the current process environmental and health concern. High production and finish machining are inherently associated with generation of intense heat and cutting temperature at the cutting zone. Such high cutting temperature not only reduces tool life but also impairs the surface integrity of the job. So the temperature at the cutting tool interface is one of the important factors influencing the machining process while primarily dependent on the cutting speed and the work piece material properties as well as cutting tool properties. So, the benefits of cryogenic cooling are dependent on the process parameters and the tool geometry.

Beneficial effects of proper cryogenic cooling on machining by uncoated carbide inserts and grinding by conventional wheels in terms of technological benefits and environment friendliness have already been established in number of previous investigations. Substantial cooling and favorable interactions at the chip-tool interface and work-tool interface as well as retention of tools-sharpness were reportedly found to be the main reasons behind these technological benefits of cryogenic machining. The present work deals with experimental investigation in the role of cryogenic cooling by liquid nitrogen jet on cutting temperature, chip formation mode, tool wear, surface finish and dimensional deviation in turning of AISI 8740 steel at industrial speed-feed combination by coated carbide insert which are widely used for high speed turning of plain carbon and low alloy steels.

The results have been compared with dry machining and machining with soluble oil as coolant. The results of the present work indicate substantial benefit of cryogenic cooling on tool life, surface finish and dimensional deviation. This may be attributed to mainly reduction in cutting zone temperature and favorable change in the chip-tool interaction. Further it was evident that machining with soluble oil cooling failed to provide any significant improvement in tool life, rather surface finish deteriorated. Furthermore, it provides environment friendliness (maintaining neat, clean and dry working area, avoiding inconvenience and health hazards due to heat, smoke, fumes, gases etc. and preventing pollution of the surroundings) and improves the machinability characteristics.

Chapter-1

Introduction

1.1 Introduction

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 work piece 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 temperature and severe thermal / frictional conditions at the tool chip interface.

Any manufacturing process for its fruitful implementation essentially needs to be technologically acceptable, technically feasible and economically viable. The fourth dimension that has been a great concern of the modern industries and society is environment-friendliness in and around the manufacturing shops.

The performance and service life of engineering component depends on their material, dimensional and form accuracy and surface quality. The preformed blanks are finished by machining and grinding to attain the desired accuracy and surface integrity.

The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, particularly to meet the challenges thrown by liberalisation 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.

The differences in temperature between the three types of cut are as would be expected, with smaller depth of cut giving significantly lower temperatures. This would validate the use of small depth of cut during the high speed machining of hardened steels in order to minimise cutter wear with the roughing cut there is a large difference between the temperature generated with the new and worn tools, a smaller difference when semi finishing and an even smaller when finishing.

Longer cuts under high cutting temperature cause 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:

- The material and shape of the tool
- The material of the machined parts
- Cutting condition and coolant
- The machining process (turning, milling or drilling, etc)

Tool wear 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 will also detoriate the surface topography. Due to the thermal effect of tool wear, the material in the cutting zone becomes so viscous that it fills the grove and flows in the uniform and homogenous way to the side of the cutting tool forming high ridges.

The flow of the chip on the tool rake face often causes crater wear indeed the tool chip contact occurs under extreme condition (high temperature and pressure, intense friction, significant sliding velocity, etc) Moreover the concentration gradient of chemical species between the tool and work piece material is often very important.

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. These problems are more predominant in grinding where cutting temperature is, as such, very high due to much higher specific energy requirement and cutting velocity. 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.

Surface roughness is the machinability indicators used in experiment. Machined surface is measured minimally three times then average is found for all experiment runs. Adequate regression models have been established and presented. According to these models graphical presentation is also alone. In industries, the machining temperature and its detrimental effects are generally reduced by:

i. proper selection of process parameters and geometry of the cutting tools

ii. proper selection and application of cutting fluid

iii. 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).

The temperature at the cutting tool interface is one of the important factors influencing the machining process. 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 heat 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.

The temperature reached in metal cutting is important since it affects the thermally activated mass transport phenomena in the cutting tool-workpiece contact zone.

Cutting fluid not only cools the tool and job but also provides lubrication and cleans the cutting zone and protects the nascent finished surface from contamination by the harmful gases present in the atmosphere. The lubricants or cutting fluids are used in the first place for several important reasons. These are:

i. To remove heat generation in cutting
ii. To reduce friction
iii. To remove chips from the cutting region
iv. To protect the work piece against rust and other undesirable reactions.
v. To prevent build up in cutting or the metal chips adhering to the tool surface.

Coating separate tools from the workpiece material in cutting and offer a possibility of replacing coolants. Hard coating such as TiAlN may increases tool performance and tool life by arresting or slowing down certain types of wear. However, these coatings retain a high coefficient of friction and require a lubricant.

The geometric and kinematical errors can also come mostly from inaccuracy of the tool system such as insert tool holder and insert clamping device. Investigation has suggested that after re-clamping insert, the repeatability errors at the tip of the insert can reach up to several microns. And the displacement of the tool tip under the cutting load can also reach several microns

The major socio-economic problems that arise due to conventional type and method of application of cutting fluids are:

i. inconveniences due to wetting and dirtiness of the working zone
ii. possible damage of the machine tool by corrosion and mixing of the cutting fluid with the lubricants
iii. environmental pollution due to break down of the cutting fluid into harmful gases
iv. biological hazards to the operators from bacterial growth in the cutting fluids
v. requirement of additional systems for local storage, pumping, filtration, recycling, re-cooling, large space and disposal of the cutting fluid, which causes soil contamination and water pollution.

The modern industries are, therefore, looking for possible means of dry, clean, neat and pollution free machining and grinding.

Ample researches have been carried out and are still going on this direction. Cryogenic cooling by agents like liquid nitrogen appears to be a promising technique for effective cooling without the problems associated with conventional cutting fluid applications. But it is also essential to be assured that productivity and overall economy are not affected while deriving the environmental benefits of cryogenic cooling. Rather it is necessary to explore the possible technological benefits of such cryogenic cooling and optimise it for maximum overall socio-economic benefits.

1.2 Environmental Friendliness in Machining and Grinding

1.2.1 General requirement of Manufacturing- Present and Future

The present and future manufacturing industries are essentially required to address the following challenges and needs,

- High production rate and high quality of the products
- Development and use of advanced materials to suite specific needs
- Cost competitiveness
- Environment friendliness

All manufacturing industries and activities need to plan their strategies and resources in light of the above factors.

The development and use of advanced materials like nickel and titanium based super alloys in wide range applications also pose difficulties in manufacturing. Such alloys are engineered to end usability but are extremely difficult to shape into finished products because of their high strength and thermal properties which necessitate the new approaches, strategies and technology.

The emphasis in present day engineering activities in on precision and ultra precision manufacturing with engineering technologies like near net shape manufacturing, rapid prototyping etc. Even in such cases for example, imparting final shape and dimensional accuracy to a given part by machining or grinding have been easier and more economical. Hence, manufacturing industries employing conventional technologies need to have the know-how to supplement and offer solution to difficulties faced by the emerging technologies as well.

The liberalization of economy has forced manufacturing industries to compete at the global level and for any manufacturing industry to survive in the global free market, cost competitiveness is very essential. Resource planning, existing or those to be acquired will be a major thrust area for economy of manufacture.

Finally the manufacturing industries presently and in future, apart from meeting the technological challenges of the user industries while being cost effective, have to ensure environmental friendliness in manufacturing and the society at large.

1.2.2 Problems in High Production Machining and Conventional Cutting Fluid Application

The performed parts essentially need finishing to the desired dimensional accuracy and surface integrity by process like machining and grinding. Dimensional accuracy and surface finish of several engineering components are essential not only for their ability to fulfill their ability to fulfill their functional requirement but also for their improved performance and prolonged service life. Machining including grinding is basically a process of producing jobs of desired size and shape by gradually removing the excess material from the performed blanks in the form of chips.

High production and finish machining and grinding are inherently associated with generation of intense heat and cutting temperature at the cutting zone. Such high cutting temperature not only reduces tool life but also impairs the surface integrity of the job. The problem becomes more acute when the materials are hard and tough and the finished products are used in dynamic loading conditions. Such problems arising out of high cutting temperatures are tried to be controlled or reduced to some extent.

- Appropriate selection of
  - ❖ Process parameters, i.e., cutting velocity and feed
  - ❖ Cutting tool geometry
- Proper selection of cutting tools
- Proper selection and application of cutting fluids
- Application and special techniques if feasible

1.2.3 Limitation of Conventional Cutting Fluid Application and Probable Solution

Application of conventional cooling in machining and grinding is aimed at,

- Cooling the tool and job particularly at their interface
- Lubrication of the chip-tool interfaces
- Cleaning of the machining zone by flushing away the machined chips/debries
- Protection of the nascent machined surface from atmospheric contamination

Though it would appear that generous use of coolant and lubricants always assist in controlling the cutting zone temperature, it may not be the case always, especially under high speed machining as the tool chip/work piece contact will be under seizure condition and no coolant/lubricant can penetrate the interfaces. Conventional coolants undergo film boiling at around 350°C and loose their cooling property **[Paul and Chattopadhyay, 1995]**.

The cutting zone in machining is often flooded with coolant without taking into account the requirements of the specific process. Scientific investigations and industrial applications have indeed shown that the type of coolant and its supply influence the component quality and tool life in machining for which coolants and lubricants are important technological parameters in machining. But in some cases application of cutting fluids is considered undesirable, especially in machining some advanced and exotic materials.

Also, coolant and lubricants incur a significant part of the manufacturing cost. For instance in the production of camshafts in European automotive industry, the cost of coolants/lubricants constituted 16.9% of the total manufacturing cost, storage, care and disposal of coolants are two times higher than the cost of tools [**Brinksmeir et al. 1999**].

Furthermore, ordinary coolants have been found to cause health hazards to workers as well as environmental pollution [**Suliman et al. 1997, Wilfried and Bartz, 1998**]. The limitations and problems associated with conventional cutting fluid application can be summarized as,

- Ineffectiveness
  - ➢ Inability to penetrate tool-chip/workpiece interface
  - ➢ Chances of film boiling at 350^0 C and beyond
- Impairment of machining system (corrosion, Contamination of hydraulic system)
- Health Hazards
  - ➢ Direct contact with cutting fluid in liquid state (irritation, allergy, skin cancer, other skin diseases due to bacterial growth in the cutting fluid)

- Prolonged inhalation of cutting fluid mist or aerosol or gases (breathing problem, bronchitis, asthma, cancer of throat, lunges and rectum, drop in blood viscosity and heart attack, internal erosion of respiratory channel)

- Environmental (Soil and water contamination by disposed spent cutting fluids)
- High cost of storage, pumping, filtering. Recycling and disposal

Thus from technological, economic and ecological perspective, as well as increasing legislations, efforts are being made to reduce or eliminate the use of coolants in machining. But with the need for high production machining, the control of cutting zone temperature is an important aspect of modern machining and grinding operations. Dry machining technologies and minimum quantity lubrication (MQL), which uses the fine spray of cooling medium, are being perused as alternatives for conventional coolants. However use of dry machining and MQL will only be acceptable on condition that the main tasks of coolants in machine process can be successfully replaced. The tasks that will have to be addressed are heat reduction, machined surface protection, cleaning of the cutting zone [**Brinksmeir et al. 1999**].

1.2.4 Cryogenic Machining with Liquid Nitrogen Jets

The use of conventional coolants and lubricants in high production machining and grinding is being reviewed or minimized because of the following concerns,

- Lack of significant technological benefits
- Increasing cost of storage and disposal of used cutting fluids
- Potential health hazards to worker
- Environmental pollution due to disposal of used coolants

Strict legislations in most of the countries have imposed stringent conditions on use and disposal of used coolants and lubrications. Under these circumstances, the spent coolant and lubricant disposal costs have spiraled up. All these factors have forced the machining industries to look for alternative ways and methods of controlling the high cutting temperatures. The focus is on effective and efficient cooling and lubrication with eco-friendliness as well as cost competitiveness. In this regard cryogenic cooling with its excellent cooling ability and eco-friendliness appears to be a viable option.

Cryogenic cooling in machining, first investigated by Bartly **[1953]** in 1953 with liquid CO_2 as coolant has involved into a promising cooling technique. Several researchers have worked in the area of cryogenic machining and have reported substantial technological benefits in machining of steel and titanium alloys. Hollis **[1961]** in 1961 reported substantial enhancement in tool life when machining various titanium alloy with liquid CO_2 at around -78^0 C. Over the years several researchers have employed liquid nitrogen as the cryogenic cooling (mostly in the form of jets) in machining and grinding of steels and advanced materials like titanium alloys and reported that if employed judiciously and efficiently, cryogenic cooling with liquid nitrogen can effectively combat the high cutting temperature inherent in high production machining and grinding.

There are lot of scope and necessity to carry out intensive research and development work for more effective and efficient machining and grinding of such increasingly used unique but difficult to machine and grind super alloys. Such research and development work through understanding of mechanism and mechanics of machining of this critical alloy will essentially enable enhanced productivity, product quality, tool life and overall economy in machining and grinding of super alloys through optimum selection of process parameters, tool material and geometry and environment.

Application of special techniques like cryogenic cooling is also a very potential area requiring further investigations for best utilization.

Chapter-2

Literature Review

2.1 Literature Review

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

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, V, feed rate, f, Depth of cut, d, 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 and Chandrshekran, 1982**]. The tool material composition and properties are crucial to the behaviour of machining forces, which in turn affect tool life and surface roughness [**Huang and Liang, 2003**].

2.1.1 On causes, effects and control of cutting temperature

Machining is inherently characterized by generation of heat and high cutting temperature. At such elevated temperature the cutting tool if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material.

It was observed [**Jawahir and van Luttervelt 1993**] that, in machining ductile metals producing long chips, the chip-tool contact length has a direct influence on the cutting temperature and thermo-chemical wear of cutting tools. The cutting temperature becomes 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 maximum almost at the centre of the chip-tool contact surface where then crater wear begins and grooves intensively.

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.

The heat generated during machining **[Trent 1984]** also raises the temperature of the cutting tool tips and the work-surface near the cutting zone. Due to such high temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increase in cutting forces and premature tool failure. On the other hand, the cutting temperature, if it is high and is not controlled, worsens the surface topography and impairs the surface integrity by oxidation and introducing residual stresses, micro-cracks and structural changes.

Chip shape evaluation is very common way to evaluate machinability of some material, especially in manufacturing conditions at floor. But chip shape as well as white layer features might be also used for defining transition region from conventional to high speed machining **[Schulz, 1992]**.

Reed et al. **[1983]** reported that the hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate. Moreover, thermal stresses in the tool increase with the temperature resulting in more cracks in the tool and premature failure of the tool. The high cutting temperature also causes mechanical and chemical damage of the finished surface.

Vleugels et al. **[1995]** observed that the contact length between the tool and chip has a direct influence on the cutting temperatures and the amount of heat energy that is dissipated in the tool which enhances thermally activated chemical wear. Maximum temperature is found to develop on the rake face of the tool, at a certain distance from the cutting edge, where cratering occurs. The amount of energy dissipated through the rake face of the tool also raises the temperature at the flanks of the tool.

With respect to theoretical models to predict the surface roughness in the high speed machining, these are really limited, being empirical the majority of them and based in experiments in laboratory conditions .In the present there are only a few mathematical relations between surface parameters and cutting conditions allowing us to predict surface roughness in a correct and general form. **[Dewes and Aspinwall, 1997]**

The high specific energy required in machining under high cutting velocity and unfavourable 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.

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**].

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.

Tool wear development with cutting time shows, after high initial wear rate, flank wear land-width (V_B) increases in a linear behaviour .it is observed that tool nose radii in the range of 0.8 -2.4 mm seem to have no effect on tool wear process , showing comparable wear rate and similar tool life. Surface finish and tool wear results in detail in **[Chou and Song, 2001]**.

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.

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.

A cutting fluid may impart two more actions, namely the mechanical strength reducing action and the electro-chemical action. The mechanical strength reducing action (known as the Rehbinder effect) seemed to be negligible when steel jobs are machined at moderate cutting speeds with carbide tools [**Kurimoto and Barroe 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.

The machining temperature could be reduced to some extent by improving the machinability characteristics of the work material metallurgically, optimizing the tool geometry and by proper selection of the process parameters [**Muraka 1979, Dieter 1981 and Jawahir 1988**]. Some recent techniques have enabled partial control of the machining temperature by using heat resistance tools like coated carbides, CBN etc. The thermal deterioration of the cutting tools can be reduced [**Narutaki and Yamane 1979**] by using CBN tools. If properly manufactured, selected and used, CBN tool provides much less cutting forces, temperature and hence less tensile residual stresses [**Davies et al. 1996**]. But CBN tools are very expensive.

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.

A recent development **[Chandrasekaran et al. 1998]** in this context is the use of CO_2 snow as the coolant in machining. This is feasible if CO_2 in liquid form under pressure (60 bar) is fed to the cutting zone and diffused through a capillary jet. This results in a change of state and the formation of CO_2 snow (endothermic reaction resulting in a temperature of -79^{O}C). Earlier investigations **[Thoors and Chandrasekaran 1994]** observed that CO_2 snow could function as a good cutting fluid/coolant under certain circumstances, which are very much related to the tool-work combination and the actual mode of feeding the coolant to the cutting zone.

2.1.2 On adverse effects of cutting fluid applications

Traditionally, the manufacture of a product had been attempted to be done as quickly and inexpensively as possible. Now that more environmental regulations are being put in place, manufacturers are forced to re-evaluate their manufacturing processes and reduce or eliminate their waste streams. The waste streams present in machining include cutting fluid flow, chip flow, and cutting tool usage.

The application of cutting fluid may not always reduce the cutting tool wear as is commonly believed. Rather some conditions like machining steels by carbide tools, the use of coolant may increase tool wear.

It has been experienced [**Shaw et al. 1951**] that there was more tool wear when cutting with coolant than cutting dry in case of machining AISI 1020 and AISI 4340 steels by M-2 high speed steel tool cutting. Seah et al. [**1995**] also reported that at the first stage of machining (first 40 seconds or so), tool wear was faster in wet cutting than in dry cutting. Later on, the wear rate stabilized and was somewhat the same for both dry and wet cutting.

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.

Another experimental investigation was conducted [**Cozzens et al. 1995**] on single point boring. This was aimed to study the role of cutting fluid, tool and workpiece material, tool geometry and cutting conditions on machinability. The results indicated that the cutting fluid conditions had no significant effect on surface texture, forces and built-up edge. Since boring is a high-speed operation and lubrication is ineffective, no effect was seen on the forces. However, the cutting fluid was found to have a significant effect on surface integrity.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained

[Satoshi et al. 1997] by such cutting fluid. But surface finish did not improve significantly.

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]**.

Manufacturing by machining constitutes major industrial activities in global perspective. Like other manufacturing activities, machining also leads to environmental pollution **[Ding and Hong 1998 and Hong et al. 1999]** mainly because of use of cutting fluids. These fluids often contain sulfur (S), phosphorus (P), chlorine (Cl) or other extreme-pressure additives to improve the lubricating performance. These chemicals present health hazards. Furthermore, the cost of treating the waste liquid is high and the treatment itself is a source of air pollution. The major problems that arise due to use of cutting fluids are **[Aronson 1995]**:

i. environmental pollution due to breakdown of the cutting fluids into harmful gases at high cutting temperature,

ii. biological hazards to the operators from the bacterial growth in the cutting fluidsnoramlrequirements of additional systems for pumping, local storage, filtration, temporary recycling, cooling and large space requirement

iii. disposal of the spent cutting fluids which also offer high risk of water pollution and soil contamination.

Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. Typically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Minimum quantity lubrication (MQL) presents itself as a viable alternative for machining with respect to heat dissertation, chip formation, and dimensional deviation. Dhar et al. **[2005]** suggest that the use of minimum quantity lubrication leads to reduced chip reduction coefficient, lower cutting temperature and lower dimensional deviation.

Dhar et al. **[2004]** also suggest that MQL reduced the cutting temperature; such reduction has been more effective for those tool-work combinations and cutting conditions, which provided higher value of chip reduction coefficient, ζ for adverse chip-tool interaction causing large friction and built-up edge formation at the chip-tool interface. 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 MQL. Dimensional accuracy also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of MQL.

Since beginning of twentieth century people **[Peter et al.1996, Welter 1978, Kennedy 1989 and Thony et al. 1975]** were concerned with possible harmful effects of various cutting fluid application.

It has been estimated **[Bennett 1983]** that about one million workers are exposed to cutting fluids in the United States alone. Since cutting fluids are complex in composition, they may be more toxic than their constituents and may be irritant or allergenic. Also, both bacteria and fungi can effectively colonize the cutting fluids and serve as source of microbial toxins. Hence significant negative effects, in terms of environmental, health, and safety consequences, are associated with the use of cutting fluids. The effects of exposure to the fluids on health have been studied for over 50 years; beginning with the concern that cutting fluid (oil) is a potential etiologic factor for occupational skin cancer (Epidemiological studies indicate that long-term exposure to metalworking fluids can lead to increased incidence of several types of cancer). The international Agency for Research on Cancer has concluded that there is □sufficient evidence□ that mineral oils used in the workplace are carcinogenic **[Peter et al.1996]**. Basically, workers are exposed to metal cutting fluids via three routes **[Bennett et al. 1985]**; skin exposure, aerial exposure and ingestion.

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.

Iowa Waste Reduction Centre (**1996**) reported that besides potential skin and eye contact, inhalation is also a way to occupational exposure. Mists are aerosols comprised of liquid particles (less than 20 μm). During machining process, a considerable amount of heat is generated for which the cutting fluid may attain a temperature sufficiently higher than the saturation temperature. The vapour is produced at the solid-liquid interface as a result of boiling. Vapour may be generated also at the liquid-air interface when the fluid vapour pressure is less than the saturation pressure, namely as evaporation phenomena. Vapour generated then may condense to form mist. The non-aqueous components of the cutting fluid, such as the biocide additives, appear as fine aerosol that can enter the workroom air. Additionally, the cutting fluids impact with both stationary and rotating elements within the machine tool system, which leads to mechanical energy being transmitted to the fluid. Thus, the cutting fluid has higher surface energy and becomes less stable and disintegrates into drops (atomization). The spray from the fluid application also may generate mist. A total fluid loss of 5 to 20 percent may occur due to evaporation, atomization, splashing and dragout processes. Whether formed by atomization or evaporation/

condensation, small droplets may be suspended in the air for several hours even several days in the workers breathing zones. These drifting droplets tend evaporate further. Inhaled particles (with aerodynamic diameters less than 10 μm) deposit in the various regions of the respiratory system by the complex action of the different deposition mechanisms. The particulates below 2.5 μm aerodynamic diameter deposit primarily in the alveolar regions, which is the most sensitive region of lung. The particulates in size ranging from 2.5 μm to 10.0 μm deposit primarily in the air-ways. The potential health effects of exposure to cutting fluid mists have been the subjects of epidemiological studies in the automotive industry. The mist droplets can cause throat, pancreas, rectum, and prostate cancers, as well as breathing problems and respiratory illnesses. One acute effect observed is mild and reversible narrowing of airways during exposure to cutting fluid mist **[Kennedy 1989]**.

Several other epidemiological studies have also suggested that exposure to fluid mist may be associated with increased risk of airway irritation, chronic bronchitis, asthma and even laryngeal cancer **[Bennett et al. 1985 and Eisen et al. 1994]**. The Occupational Safety and Health Administrations (OSHA) standard for airborne particulate (largely due to fluid mist) is 5 mg/m^3, and the United Auto Workers (UAW) has proposed a reduction in the standard to 0.5 mg/m^3. The oil mist level in a plant ranged from 4.2 to 15.6 mg/m^3 but fell to between 0.47 to 1.68 mg/m^3 when a different cutting fluid was substituted in the system **[Welter 1978]**.

Anti misting compounds, such as a polymethaacrylate polymer, polyisobutylene and poly-n-butane in concentrations of 0.2% as well as poly (1, 2-butene oxide) have been suggested for addition into cutting fluids [**Bennett et al. 1985**]. But, consideration must be given to the effects of these chemicals upon humans. The most effective way to control mist exposure is to use mist collector to prevent mist from entering plant air **[Leith et al. 1996]**. Many collectors use several stages of filters in series for the purpose. Other collectors use centrifugal cells or electrostatic precipitators as intermediate stages. Any collector using a 95% Dioctyl Phthalate (DOP) or High-Efficiency Particulate Air (HEPA) filter as a final collection stage has been tested as high efficiency when new. However, its efficiency will decrease with time. Moreover, the oil droplets may undergo partial or complete evaporation as they travel to collector [**Raynor et al. 1996**]. The generated organic vapours may return to the room and affect work health, and may recon dense on the cool surface causing safety and maintenance problems.

Pollution free manufacturing is increasingly gaining interest due to recent development of pollution-prevention legislation, European initiatives on product take-back or recycling, which affect many export industries in the US, and a growing consumer, demand for green products and production processes. Concern for the environment, health and safety of the operators, as well as the requirements to enforce the environmental protection laws and occupational safety and health regulations are compelling the industry to consider a cryogenic machining process as one of the viable alternative instead of using conventional cutting fluids.

Cutting fluids are widely used in machining operations to obtain accuracy of part dimensions, longer tool life and in some cases better surface finish. The research literature identifies two primary functions of cutting fluids in machining operations: lubrication to reduce process friction and cooling to remove process generated heat. A secondary function of the cutting fluid is to transport the chips from the cutting zone. Cutting fluid systems are used in industry to deliver fluid to the cutting process, recirculate fluid, separate chips, and collect fluid mists. The machining costs (labour and overhead) in the US alone is estimated to be $300 billion/year [**Komanduri and Desai 1983**]. The costs associated with the use of cutting fluids is estimated to be about 16% of the manufacturing costs [**Byrne and Scholta 1993**] which is many more times than the labour and overhead figures quoted above. A recent study in Germany found that 16% of machining cost in the high volume manufacturing industries is associated with the use of cutting fluids (procurement, maintenance and disposal) while only 4% of the cost was associated with cutting tools [**Aronson 1995**]. The use of cutting fluids also requires additional equipment for plant housekeeping.

2.1.3 On effects of cryogenic cooling in machining

Growing demand for high MRR in machining necessitated much increase in cutting velocity, which eventually required the efficiency of cooling to be increased in order to cope with the increase in the cutting temperature. On the other hand, legislation in many countries is restricting much use of coolants, because of environmental issues. There are limits on the amount of coolant mist, and some coolants and coolant-coated chips have been treated as toxic materials. Outside the plant, the rising cost of chip disposal and the potential secondary effects of coolant vented to the atmosphere are new concerns [**Aronson 1995**]. In some applications the consumption of cutting fluids has been reduced drastically by using mist lubrication. However, mist in the industrial environment can have a serious respiratory effect on the operator [**Kennedy 1989**]. Consequently, high standards are being set to minimize this effect. Use of cutting fluids will become more expensive as these standards are implemented leaving no alternative but to consider environmentally friendly manufacturing.

Recently the process of cryogenic turning has been investigated [**Bhattacharya et al.1972**]. The forces and cutting energy reportedly decreased when machined cryogenically compared to those with dry machining. Significant improvement in surface finish and other surface properties were noticed and such beneficial affects were attributed to low temperature and controlled tool wear. It has been further reported [**Uhera and Kumagai 1968, Uhera and Kumagai 1969 and Fillippi and Ippolito 1970**] that cryogenic machining with liquid nitrogen resulted in relatively lesser cutting forces, longer tool life and better surface conditions.

Cryogenic machining was first investigated in around 1953 **[Bartley 1953]** by using liquid carbon dioxide as the coolant. In 1961, later it was reported **[Hollis 1961]** that during high speed turning of various titanium alloys, the life of carbide tools could be enhanced substantially by cryogenic cooling with liquid CO_2 at around -78°C. In another work it was reported **[Chattopadhyay et al. 1985]** that the use of cryogen as coolant, if employed effectively and efficiently, might play a very important and successful role to meet the challenge offered by the heat generated in the grinding of high strength alloys and its effects. In addition to the improvement of surface qualities, the cryogenic grinding was found to reduce the cutting forces, improve the dimensional accuracy and enhance the life of the cutting tools. In another approach **[Evans 1991]**, the temperature in the cutting zone could be reduced by cryogenic cooling (with liquid nitrogen) in turning of stainless steel with diamond tool and the temperature-dependent wear decreased significantly.

While machining ceramic (Si_3N_4) by PCBN tool it was found **[Wang et al.1996]** that the cutting temperature, surface roughness and tool wear rate substantially decreased by cryogenic cooling. The wear on the tool was mainly attrition wear and abrasive wear. It was further reported **[Yamaya and Shibuki 1974]** that ceramic tools also provide greater tool life under cryogenic machining.

An investigation **[Chattopadhyay et al. 1985]** on the role of cryogenic cooling on the different machinability parameters under different conditions of surface grinding of some steels revealed significant reduction in surface damage, cutting forces and cutting temperature. It has also been reported **[Banerjee and Chattopadhyay 1985]** that proper application of liquid nitrogen jet reduces grinding temperature drastically and protects the surface from chemical and galvanic deterioration, which results in much better surface integrity, lesser grinding forces, and longer wheel life.

A comparative study **[Paul 1997 and Paul et al. 1996,1995,1994,1993]** on conventional surface grinding, without coolant, with soluble oil as coolant and cryogenic cooling depicted that the cutting forces decrease considerably, surface temperature decreases significantly and surface integrity improves when liquid nitrogen was employed as coolant in grinding.

It has already been reported **[NICE3 1997]** that the cryogenic machining technology has a potential to save about two billion Btu of energy per year for a turret lathe of 20 to 30 horsepower. In addition, reduction in 1,538,000 tons of CO_2 emissions and 520,000 tons of waste will result by using this technology. Extended life of cutting tool as well as lesser power requirements will aid in reducing the operating cost.

2.2 Summary of the review

A review of the literature on machinability of different commercial steel highlights the immense potential of the control of machining temperature and its detrimental effects. 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. 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. The conventional cutting fluids are not that effective in high speed machining. Further the conventional cutting fluids are not environment friendly. The disposal of the cutting fluids often leads to local water pollution and soil contamination.

Cryogenic cooling is a promising new technology in high production machining, which economically addresses the current processes' environmental and health concerns. In this unique process liquid nitrogen is impinged through a nozzle precisely at the narrow cutting zone. Chilling the cutting tool in liquid nitrogen (-196°C) enhances tool hardness and life. Cooling the chip makes it brittle and aides its removal. Since nitrogen is an abundant atmospheric constituent and the quantities used are small, there is no unfavourable environmental or health impact or coolant disposal cost, and the chips may be reused.

Chapter-3

Objectives of the Present Work

3.1 Objectives of the Present Work

It is revealed from the aforesaid literature survey that cryogenic cooling can substantially control the cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy. The growing demands for high MRR, mainly the high cutting temperature restrains precision and effective machining of exotic materials. Thorough investigation is essential to explore the potential benefits of cryogenic machining in such cases. But enough work has not been done systematically yet in this direction.

The objective of the present work is to study the effects of cryogenic cooling by liquid nitrogen jet in turning AISI-8740 steel by coated carbide insert (SNMG-120408 PM) at different cutting velocity and feed rate combinations on

i. average chip tool interface temperature (θ_{avg})

ii. chip reduction coefficient (ζ)

iii. average principal flank wear (V_B)

iv. average auxiliary flank wear (V_S)

v. surface finish (R_a) and

vi. dimensional deviation

These results are being expected to improve machinability due to reduction in cutting zone temperature enabling favourable chip formation and chip tool interaction. It will also provide reduction in tool wear, which will enhance the tool life, dimensional accuracy and surface finish.

The scopes of the present work are

(a) Design and fabrication of a

i. cryogenic machining set up

ii. suitable nozzles for liquid nitrogen jet

iii. tool work thermocouple for measuring average chip tool interface temperature

(b) Analysis of data by

i. measuring chip reduction co-efficient (ζ)

ii. measuring average chip tool interface temperature (θ_{avg})

iii. measuring tool wears (V_B, V_S) under microscope

iv. monitoring pattern and extent of tool wear under Scanning Electronic Microscope (SEM)

v. measuring dimensional deviation and surface roughness (R_a)

Chapter-4

Experimental Investigations

4.1 Introduction

High Speed machining, like the cutting of hard materials, at higher speeds are those technologies, which are recently being increasingly applied in the production industries especially in mould producing. These machining process are characterized by their productivity, good surface finish quality and higher dimensional tolerances. This high speed causes the high cutting temperature.

The high cutting temperature generated during machining not only reduces tool life but also impairs the product quality. The temperature becomes more intensive when cutting velocity and feed are increased for higher MRR (Material Removal Rate) and the work materials are relatively difficult to machine for their high strength, hardenability and lesser thermal conductivity are characterized by their productivity, good surface finish quality and higher dimensional tolerances.

Cutting fluids are widely used to reduce the cutting temperature. But the major problems associated with the use of conventional methods and type of cutting fluids, which are mostly oil based, are:

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

In this regard, it has already been observed through previous research that proper application of cryogenic cooling by agents like liquid nitrogen may play vital role in providing not only environment friendliness but also some techno-economical benefits.

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

i. effective cooling by enabling liquid nitrogen jet reach as close to the actual hot zones as possible

ii. avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes

iii. minimum consumption of cryogen by pin-pointed impingement and only during chip formation

4.2 Liquid Nitrogen Delivery System

The liquid nitrogen needs to be drawn at high pressure from the dewar and impinged at high speed through the nozzle. Considering the conditions required for the present research work and uninterrupted supply of liquid nitrogen at consistent pressure around 10 bar over a reasonably long cut, a vacuum insulated and self pressurized stainless steel dewar of large capacity (480 liter) has been procured and used. The photographic view and the circuit of the Dewar are shown in Fig.4.1.

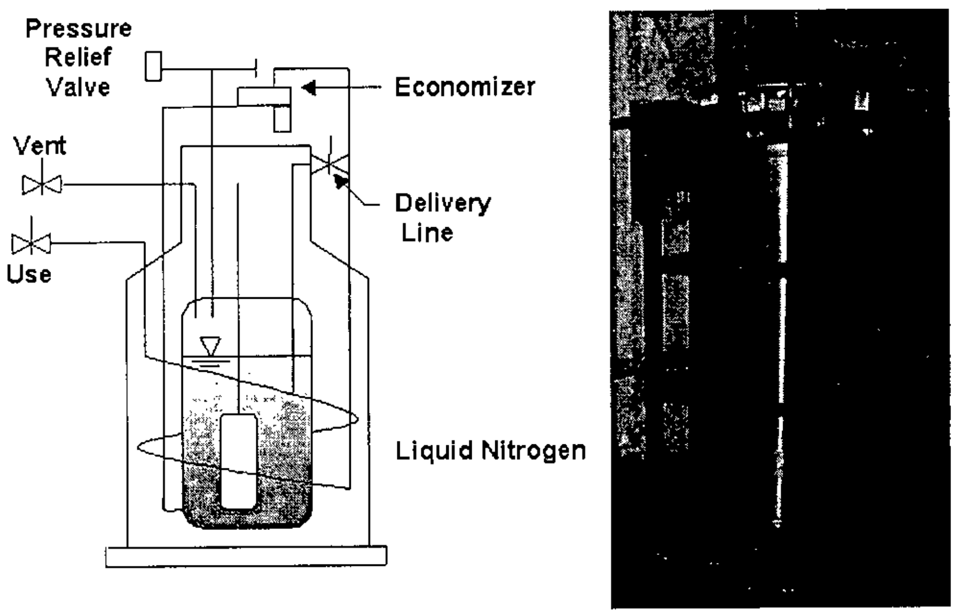


Fig.4.1 Dewar and its operating circuit

The liquid nitrogen is contained in the Dewar and a pressure building circuit is used to ensure desired high driving pressure during the high withdrawal periods. This is accomplished by opening a hand valve that creates a path from the liquid at the bottom of the container, through the pressure-building regulator, to the gas space in the top. When the pressure-building valve is open and the container pressure is below the pressure building regulator setting, liquid taken from the inner container is vaporized in a heat exchanger, which is inside the outer casing. The expanding gas is fed into the upper section of the container to build pressure. The resulting pressure will drive either the liquid or gas delivery system.

An economizer circuit withdraws gas preferentially from the headspace over the liquid in the container otherwise that gas would be lost to venting. Excess pressure in the headspace of the container is relieved by allowing gas to flow from this area directly to the use valve outlet while gas is being withdrawn from the container. The economizer is automatic and requires no operator attention.

The internal heat exchanger inside the vacuum space attached to the container's outer casing provides a means of introducing heat from outside the container's insulated jacket, to vaporize liquid as gaseous product.

Liquid product is added or withdrawn from the container through the connection controlled by the liquid valve. It has the CGA fitting that is required for liquid line connections. The valve is opened for fill or liquid withdrawal after connecting a transfer hose with compatible fittings to the Liquid line connection. Pressure building valve isolates the liquid in the bottom of the container to the Dual Pressure Building/Economizer Regulator. This valve must be opened to build pressure inside the container. The Vent valve controls a line into the head of the container. It is used during the fill process. The Vent valve acts as a fill point during a pump transfer, or to vent the headspace area while liquid is filling the inner container during a pressure fill through the Liquid valve.

The container contents a float type level sensor that indicates liquid content through magnetic coupling to a yellow indicator band. This gauge is an indication of approximate container contents only and should not be used for filling. These cylinders have a gas service relief valve and inner container-bursting disc with setting of 16 bars and 380 psig or 26 bars respectively. A 1.5 bar relief valve is provided for liquid delivery applications.

4.3 Design of Nozzle for Liquid Nitrogen Jet

The Nozzle is one of the important components of this experimental set up. The outlet diameter of the nozzle is so small that it can converts all this pressure into velocity. The nozzle has been designed so that the nozzle spray pattern, covering area and liquid nitrogen rate can be controlled. The inlet diameter of the nozzle is 6 mm and the outlet diameter of the nozzle is 1.5 mm. The nozzle developed and used and it's setting along the tangential direction of the cutting zone, which are shown in Fig.4.2 and Fig.4.3 respectively. The nozzle of 1.5 mm bore diameter was fixed to rake surface of the tool is connected with insulated copper pipe to supply liquid nitrogen in the form of jet to the cutting zone. The expected result of this arrangement is effective cooling with economical liquid nitrogen dispensing. The construction and setting of the nozzle tips have been made primarily aiming:

i. less interference with the flowing chips
ii. high speed liquid nitrogen jet reaching quite close to the cutting zone and
iii. simple and low cost.

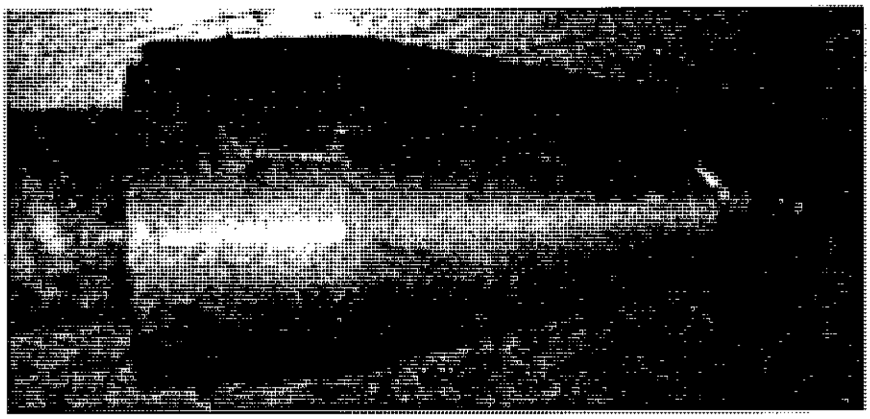


Fig.4.2 Photographic view of the nozzle used for liquid nitrogen delivery at the cutting zone

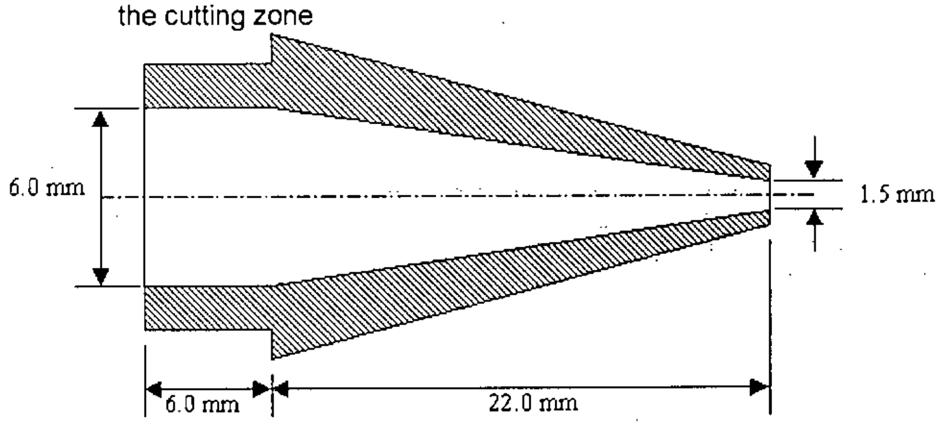


Fig.4.3 Schematic view of the nozzle used for liquid nitrogen delivery at the cutting zone

4.4 Experimental Procedure and Conditions

The beneficial role of cryogenic cooling by agents like liquid nitrogen on environment friendliness has already been established. The aim of the present work is primarily to explore and evaluate the role of such cryogenic cooling on machinability characteristics of some commonly used tool-work combinations mainly in terms of cutting forces, cutting temperature, tool life, surface finish and chip-forms, which govern productivity, product quality and overall economy.

The machining tests have been carried out by straight turning of steel in a rigid and reasonably powerful lathe (Lathe Machine, France, 3Hp) by standard carbide inserts at different cutting velocities (V_c) and feeds (S_o) under both dry and cryogenic cooling.

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. 0The compositions, strength, hardness and industrial use of those steels are given in Table 4.1.

Table-4.1 Characteristics of the used steels [**Rothman 1988 & Bagchi 1979**].

Work material	BHN	UTS (Kgf/mm^2)	Chemical composition (wt %)
AISI-8740	250	960	C-.40%, P-.035%, Mn-.85%, S-0.04%, Si-0.25%, Ni-.65%, Cr-.60%, Mo-.30%

Machining industries generally use sintered carbide tools, both uncoated and coated for machining steels. High performance tools like ceramics toughened and strengthened by stabilized zirconia [**Mondal et al. 1992**] metals [**Tuan and Brook 1990 and Wang et al.1993**] and SiC whiskers [**Li and Low 1994**] and CBN [**Narutaki and Yamane 1979**] are also used now-a-days by the modern industries. But such tools are not only expensive but also require very rugged and powerful machine tools, which common industries cannot always afford. Diamond tools [**Hinterman and Chattopadhyay 1993**] are excellent performing for exotic materials excepting ferrous metals which graphitise diamond.

Considering common interest and time constraint only coated carbide insert (TiCN + Al_2O_3) has been used for the present work. Wide scope will remain for further study on cryogenic cooling effect in machining steels by coated carbides and exotic materials by high performance ceramics, CBN and diamond.

Effectiveness of cooling and the related benefits depend on how closely the cryogenic jets can reach the chip-tool and the work-tool interfaces where, apart from the primary shear zone, heat is generated.

The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view two different tool configurations (Sandvik) namely SNMM and SNMG have been undertaken for the present investigation. The inserts were clamped in a PSBNR 2525 M12 (Sandvik) type tool holder.

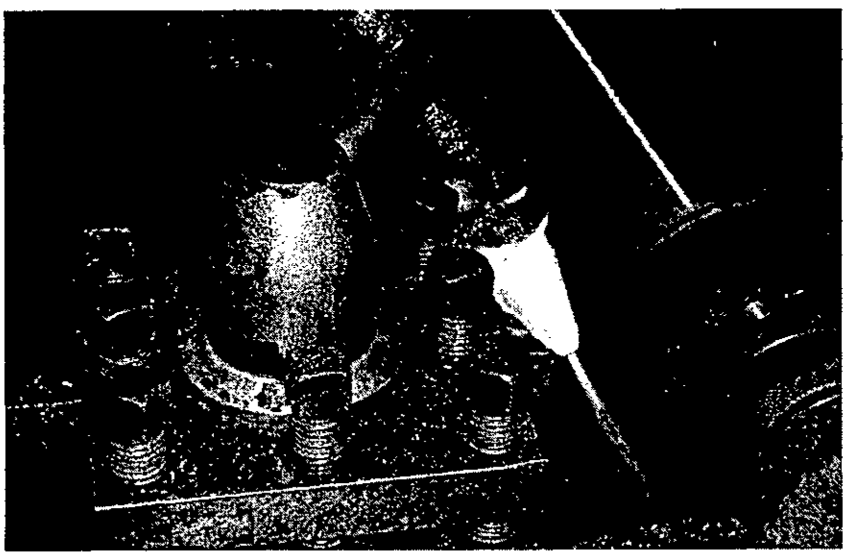


Fig.4.4 Photographic view of liquid nitrogen delivery nozzle injecting liquid nitrogen during machining

The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The final arrangements made and used have been shown in Fig.4.4. The cryogenic jet is directed along the auxiliary cutting edge to reach at the auxiliary flank and partially under the flowing chips through the inbuilt groove parallel to the cutting edges. The experimental set-up is schematically shown in Fig.4.5 and the photographic view of the same is shown in Fig.4.6.

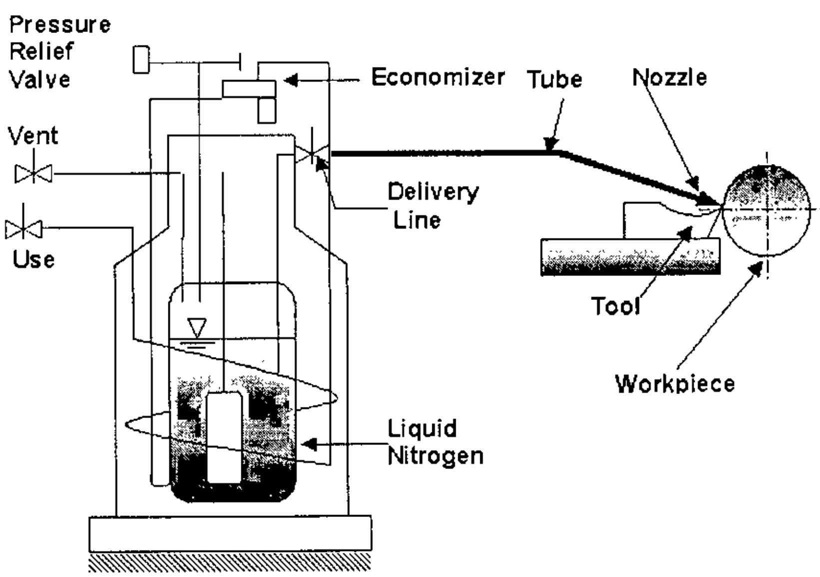


Fig.4.5 Schematic view of the experimental set-up for turning steel with liquid nitrogen

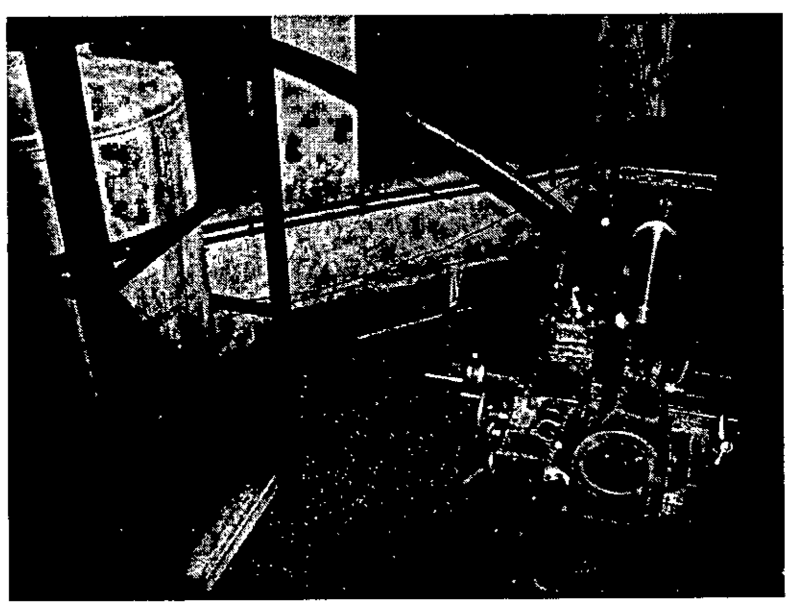


Fig.4.6 Photographic view of the experimental set-up for turning steel with liquid nitrogen

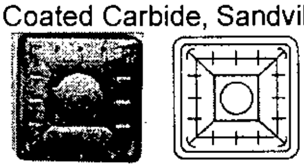
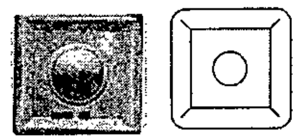
The machining responses that have been studied and evaluated for assessing the machinability characteristics of the steel specimens under dry, wet and cryogenic cooling conditions are indicated by a matrix in Table-4.2. It has already been reported **[Paul et al. 2000 and Seah et al. 1995]** that use of conventional cutting fluids (wet cutting) does not serve the desired purpose in machining steels by carbides, rather reduces tool life and often may cause premature failure of the insert by brittle fracture. However, the steel undertaken has been machined with conventional method and type of cutting fluid (1:20 soluble oil) in addition to dry and cryogenic conditions to see again the relative role of wet cutting under the same speeds and feeds, particularly in respect of condition and life of the cutting tips, surface finish and dimensional deviation. The conditions under which the machining tests have been carried out are briefly given in Table-4.3.

Table-4.2 Machining responses investigated

Work material: AISI-8740 steel (φ125 X 760 mm)			
Tool insert	**SNMM & SNMG Coated carbide**		
Investigated responses	**Working environment**		
	Dry	**Wet**	**MQL**
Temperature calibration	√	√	√
Chips	√	√	√
Cutting temperature	√	√	√
Tool wear	√	√	√
SEM worn tool	√	√	√
Machined Surface roughness	√	√	√
Dimensional deviation	√	√	√

A number of cutting velocity and feed 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 effectiveness of cryogenic cooling. Keeping in view less significant role of depth of cut (t) on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.0 mm, which would adequately serve the present purpose. The machining responses have been monitored and studied using sophisticated and reliable equipments and techniques as far as possible.

Table-4.3 Experimental conditions

Machine tool	: Lathe Machine (France), 4 hp	
Work material	: AISI-8740 steel (φ125 X 760 mm)	
Cutting tool (insert)		
Cutting insert	: Coated Carbide, Sandvik	
	 **SNMM 120408**	 **SNMG 120408**
Coating	: TiCN + Al_2O_3	
Tool holder	: PSBNR 2525M12(ISO specification), Sandvik	
Working tool geometry	: Inclination angle	: -6^{o}
	Orthogonal rake angle	: -6^{o}
	Orthogonal clearance angle	: 6^{o}
	Auxiliary cutting edge angle	: 15^{o}
	Principal cutting edge angle	: 75^{o}
	Nose radius	: 0. 8 mm
Process parameters		
Cutting velocity, V_c	: 223, 246, 348 and 483 m/min	
Feed rate, S_o	: 0.10, 0.13, 0.16 and 0.18 mm/rev	
Depth of cut, t	: 1.0 mm	
Environment	: Dry, wet and cryogenic cooling by liquid nitrogen	

Cutting temperature can be measured using direct and indirect techniques [**Venkatesh 1987**]. Direct methods include the use of temperature sensitive powders [**Narutaki and Yamane 1979**], infrared measurement [**Prins 1971 and Abrao et al. 1996**], the tool-work thermocouple techniques [**Stephenson 1993, Gottwein 1925**] and embedded thermocouple techniques [**Matsumoto and Hsu 1987 and Kitagawa et al. 1997**] whereas indirect methods mainly include microstructural changes [**Wright and Trent 1973**] and microhardness changes [**Wright and Trent 1973**] in the tool materials due to high cutting temperature.

Tool-work thermocouple technique **[Stephenson 1993, Gottwein 1925 and Herbert 1926]** is simple but quite reliable for measurement of average cutting temperature in machining with continuous chip formation like plain turning. But proper functioning of this technique need care about;

i. parasitic emf generation by secondary junction

ii. proper calibration

iii. electrical insulation of the tool and the job

In the present work the average cutting temperature has been measured by tool-work thermocouple technique as indicated in Fig.4.7 taking care of the aforesaid factors. Tool-work thermocouple can be calibrated in several ways, which include;

i. furnace calibration **[Bus et al. 1971 and Byrne 1986]**

ii. resistance heating **[Alvedid 1970]**

iii. embedded silver bit technique **[Barrow 1973]**

iv. induction heating **[Braiden 1967]**

v. lead bath technique **[Shaw 1984]**

vi. flame heating **[Leshock and Shin 1997]**

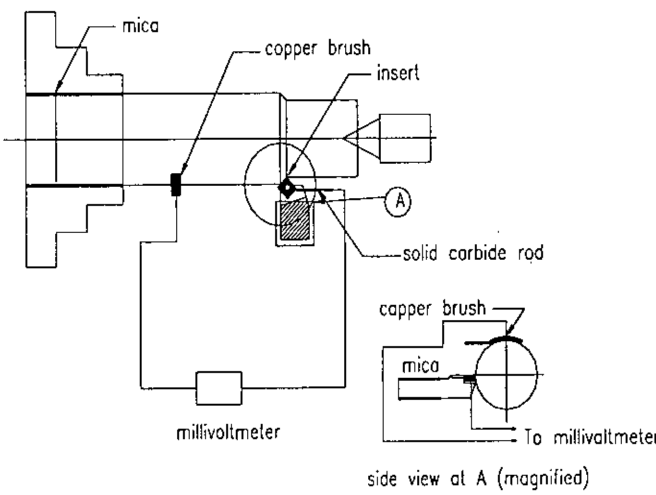


Fig.4.7 Schematic view of the tool-work thermocouple loop

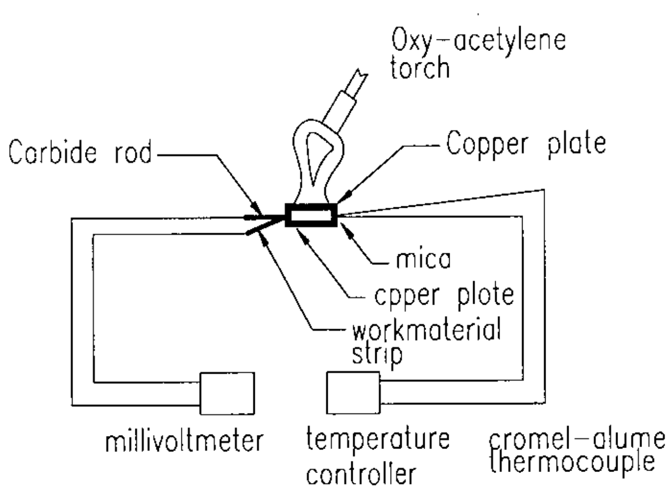


Fig.4.8 Scheme of calibration of present tool-work thermocouple

For the present investigation, the calibration of the work-tool thermocouple has been carried out by external flame heating. Fig.4.8 schematically shows the set-up. The work-tool thermocouple junction was constructed using a long continuous chip of the concerned work-material and a tungsten carbide insert to be used in actual cutting. To avoid generation of parasitic emf, a long carbide rod was used to extend the insert. A standard chromel-alumel thermocouple is mounted at the site of tool-work (junction of chip and insert) junction. The oxy-acetylene torch simulated the heat generation phenomena in machining and raised the temperature at the chip-tool interface. Standard thermocouple directly monitored the junction temperature (measured by a Eurotherm Temperature Controller and Programmer, model: 818P, made in UK) when the emf generated by the hot junction of the chip-tool was monitored by a digital multimeter (model: DH 334, Philips). Fig.4.9 shows the photographic view of the present tool-work thermocouple set up.

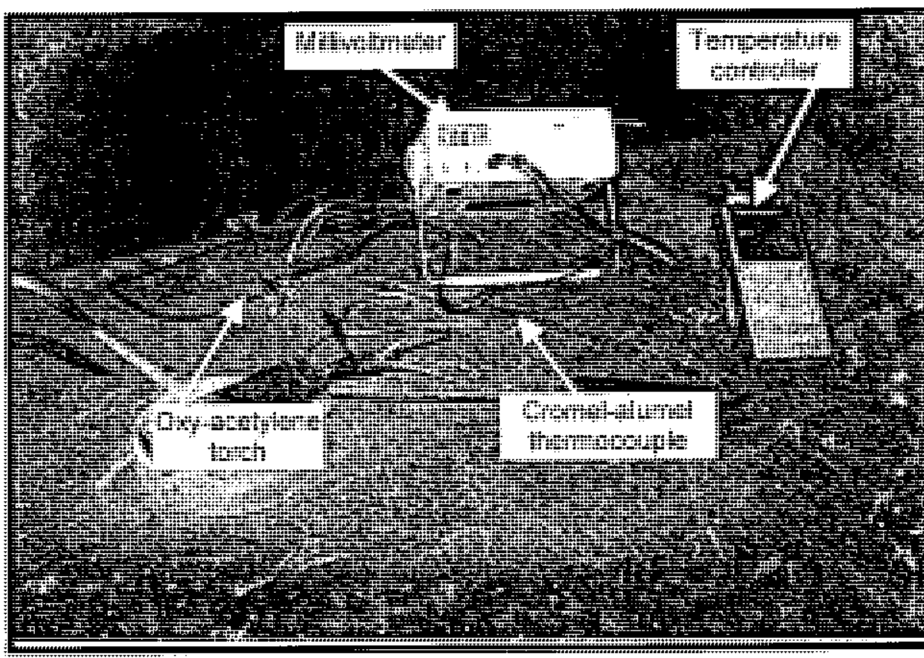


Fig.4.9 Photographic view of the present tool-work thermocouple set up

Fig.4.10 shows the calibration curves obtained for the tool-work pair with coated carbide as the tool material and the different steels undertaken as the work materials. In the present case, almost linear relationships between the temperature and emf have been obtained with multiple correlation coefficients around 0.994.

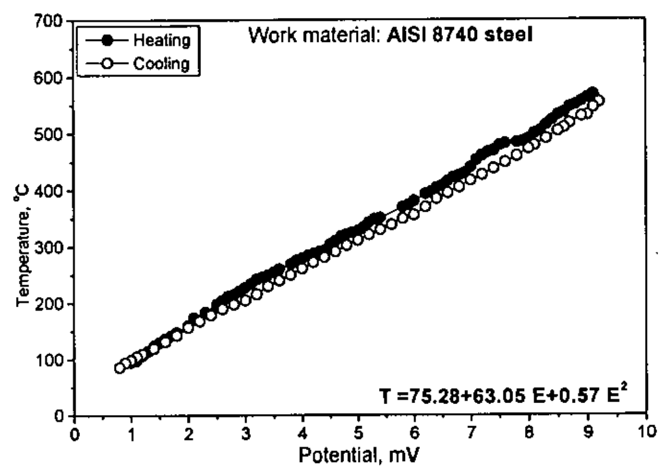


Fig.4.10 Temperature calibration curve

The form, colour and thickness of the chips also directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples were collected during both short run and long run machining for all the work-tool and V_c-S_o combinations under dry and cryogenic cooling conditions. The form and colour of all those chips were noted down. The thickness of the chips was repeatedly measured by a slide caliper to determine the value of chip reduction coefficient, ζ (ratio of chip thickness after and before cut) that is an important index of machinability.

Form-stability and service life of cutting tools play a major role on productivity, product quality and overall economy in manufacturing by machining. Cutting tools generally fail, particularly while machining ductile metals like steels by hard as well as strong tools like sintered carbides, by gradual wear at their flanks and the rake surface. Often failure may occur only by plastic deformation or macro fracturing under stringent conditions due to excessive cutting temperature and pressure and thermal-cum-mechanical shocks.

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

During machining under each condition, the cutting insert was withdrawn at regular intervals and then the salient features like, V_B, V_S etc. were measured under a light microscope (Olympus inverted metallurgical microscope, model: CARL ZEISS 351396,Germany) fitted with a precision micrometer. At the end of machining and attaining sufficient wear the pattern and extent of wear of each tool was examined under Scanning Electron

Microscope (model: Phillips New XL-30, Netherlands) and the photographs are taken for onward comparative study.

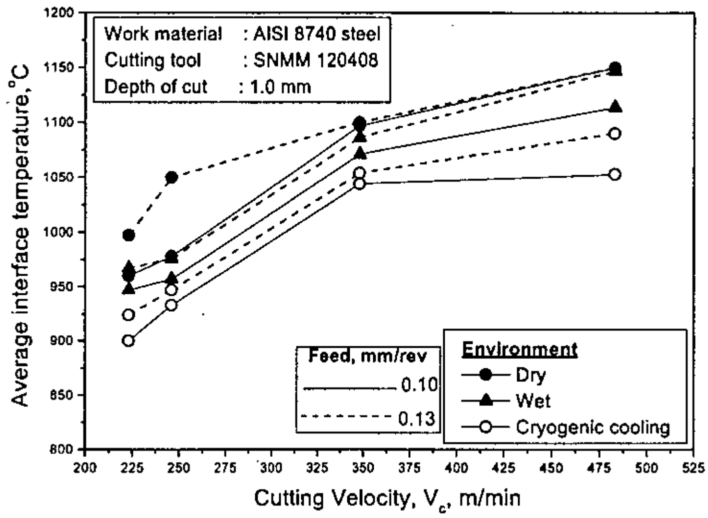
After machining the steel rod by the different inserts, at different V_c-S_o combinations under dry, wet and cryogenic cooling, the surface finish and dimensional deviation on diameter in axial direction of the machined jobs were measured respectively by a surface measuring equipment (Surtronic 3P, Rank Taylor Hobson Limited) and by a sensitive dial gauge which was firmly fitted on the saddle and traveled slowly parallel to the job axis.

4.5 Experimental Results

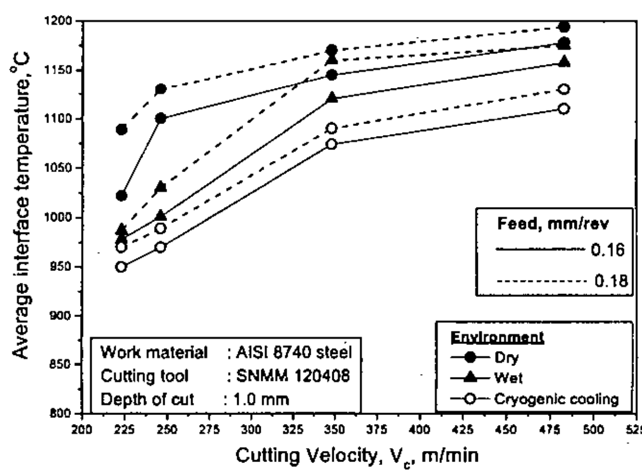
4.5.1 Cutting temperature

During machining of any ductile materials, 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 and (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. Therefore, attempts are made to reduce this detrimental cutting temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface where the temperature is maximum. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V_c when the chip-tool contact becomes almost fully plastic or bulk.

However, it was observed that the liquid nitrogen jet in its present way of application enabled reduction of the average cutting temperature by about 10 to 20% depending upon the levels of the process parameters, V_c and S_o. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices. The cutting temperature generally increases with the increase in V_c and S_o, though in different degree, due to increased energy input and it could be expected that cryogenic cooling would be more effective at higher values of V_c and S_o. But actually it had been otherwise as can be shown in Fig.4.11 and Fig.4.12.

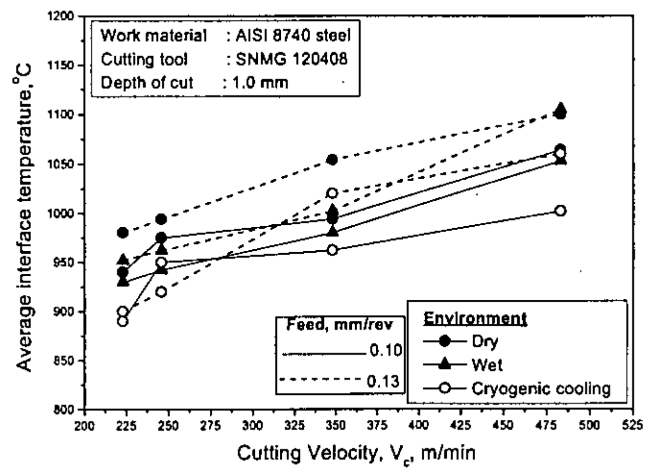


(a)

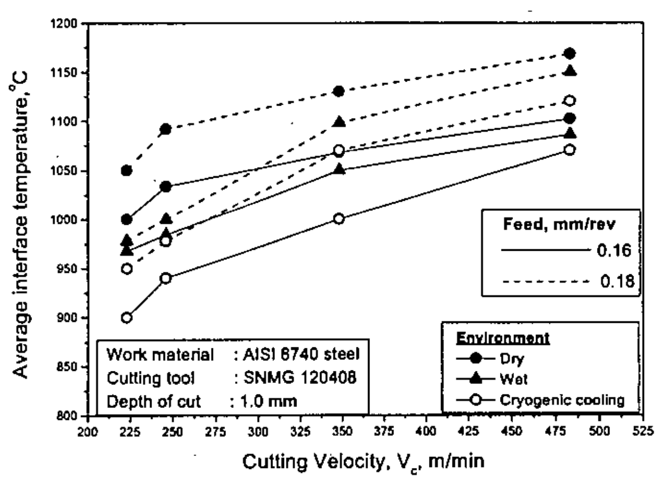


(b)

Fig.4.11 Variation in θ_{avg} with that of V_c and S_o in turning steel by **SNMM** insert under **dry, wet** and **cryogenic** cooling conditions at (a) lower and (b) higher feed rates



(a)



(b)

Fig.4.12 Variation in θ_{avg} with that of V_c and S_o in turning steel by **SNMG** insert under **dry**, **wet** and **cryogenic** cooling conditions at (a) lower and (b) higher feed rates

4.5.2 Machining chips

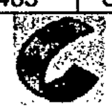
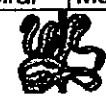
The chip samples collected while turning the steel by the insert of configuration SNMM at different V_c-S_o combinations under dry, wet and cryogenic cooling condition have been visually examined and categorized with respect to their shape and colour. The results of such categorization of the chips produced at different conditions and environments by the steel at different feed rates have been shown in Table-4.4 and Table-4.5.

Table-4.4 Comparison of chip shape and colour at different S_o and V_c produced by **SNMM** insert under **dry**, **wet** and **cryogenic** cooling conditions

Feed rate, S_o (mm/rev)	Cutting velocity V_c (m/min)	Environment					
		Dry		Wet		Cryogenic cooling	
		Shape	Colour	Shape	Colour	Shape	Colour
0.10	223	Spiral	Burnt blue	Spiral	Golden	Half turn	Metallic
	246	Ribbon	Burnt blue	Spiral	Golden	Tubular	Metallic
	348	Ribbon	Burnt blue	Ribbon	Golden	Half turn	Golden
	483	Ribbon	Burnt blue	Spiral	Golden	Half turn	Metallic
0.13	223	Ribbon	Burnt blue	Spiral	Golden	Half turn	Metallic
	246	Ribbon	Burnt blue	Spiral	Golden	Tubular	Golden
	348	Ribbon	Burnt blue	Spiral	Golden	Spiral	Metallic
	483	Ribbon	Burnt blue	Ribbon	Burnt blue	Half turn	Metallic
0.16	223	Spiral	Burnt blue	Spiral	Golden	Tubular	Metallic
	246	Spiral	Burnt blue	Spiral	Golden	Spiral	Metallic
	348	Spiral	Burnt blue	Spiral	Golden	Half turn	Golden
	483	Spiral	Burnt blue	Spiral	Golden	Half turn	Metallic
0.18	223	Ribbon	Burnt blue	Tubular	Golden	Spiral	Metallic
	246	Spiral	Burnt blue	Spiral	Golden	Spiral	Metallic
	348	Ribbon	Burnt blue	Spiral	Golden	Tubular	Metallic
	483	Ribbon	Burnt blue	Spiral	Golden	Half turn	Metallic

Chip shape				
Group	Half turn	Tubular/helical	Spiral	Ribbon

Table-4.5 Comparison of chip shape and colour at different S_o and V_c produced by **SNMG** insert under **dry**, **wet** and **cryogenic** cooling conditions

Feed rate, S_o (mm/rev)	Cutting velocity V_c (m/min)	Environment					
		Dry		Wet		Cryogenic cooling	
		Shape	**Colour**	**Shape**	**Colour**	**Shape**	**Colour**
0.10	223	Ribbon	Golden	Ribbon	Metallic	Ribbon	Metallic
	246	Ribbon	Golden	Ribbon	Metallic	Ribbon	Metallic
	348	Ribbon	Golden	Ribbon	Metallic	Ribbon	Metallic
	483	Ribbon	Golden	Ribbon	Metallic	Ribbon	Metallic
0.13	223	Spiral	Golden	Spiral	Golden	Spiral	Metallic
	246	Spiral	Golden	Spiral	Golden	Spiral	Metallic
	348	Spiral	Golden	Spiral	Golden	Spiral	Metallic
	483	Spiral	Burnt blue	Spiral	Burnt blue	Spiral	Metallic
0.16	223	Spiral	Golden	Spiral	Golden	Spiral	Metallic
	246	Spiral	Golden	Spiral	Golden	Half turn	Metallic
	348	Spiral	Golden	Spiral	Golden	Spiral	Metallic
	483	Spiral	Golden	Spiral	Golden	Spiral	Metallic
0.18	223	Spiral	Burnt blue	Spiral	Golden	Half turn	Metallic
	246	Spiral	Burnt blue	Spiral	Golden	Half turn	Metallic
	348	Spiral	Burnt blue	Spiral	Golden	Spiral	Metallic
	483	Spiral	Burnt blue	Spiral	Golden	Spiral	Metallic
Chip shape							
Group	Half turn		Tubular/helical		Spiral		Ribbon

The actual forms of the chips produced from steel during machining by the SNMM type insert with a different feed rates and cutting velocities under dry and cryogenic cooling conditions are shown in Fig.4.13, Fig.4.14, Fig.4.15, Fig.4.16, Fig.4.17, Fig.4.18, Fig.4.19 and Fig.4.20.

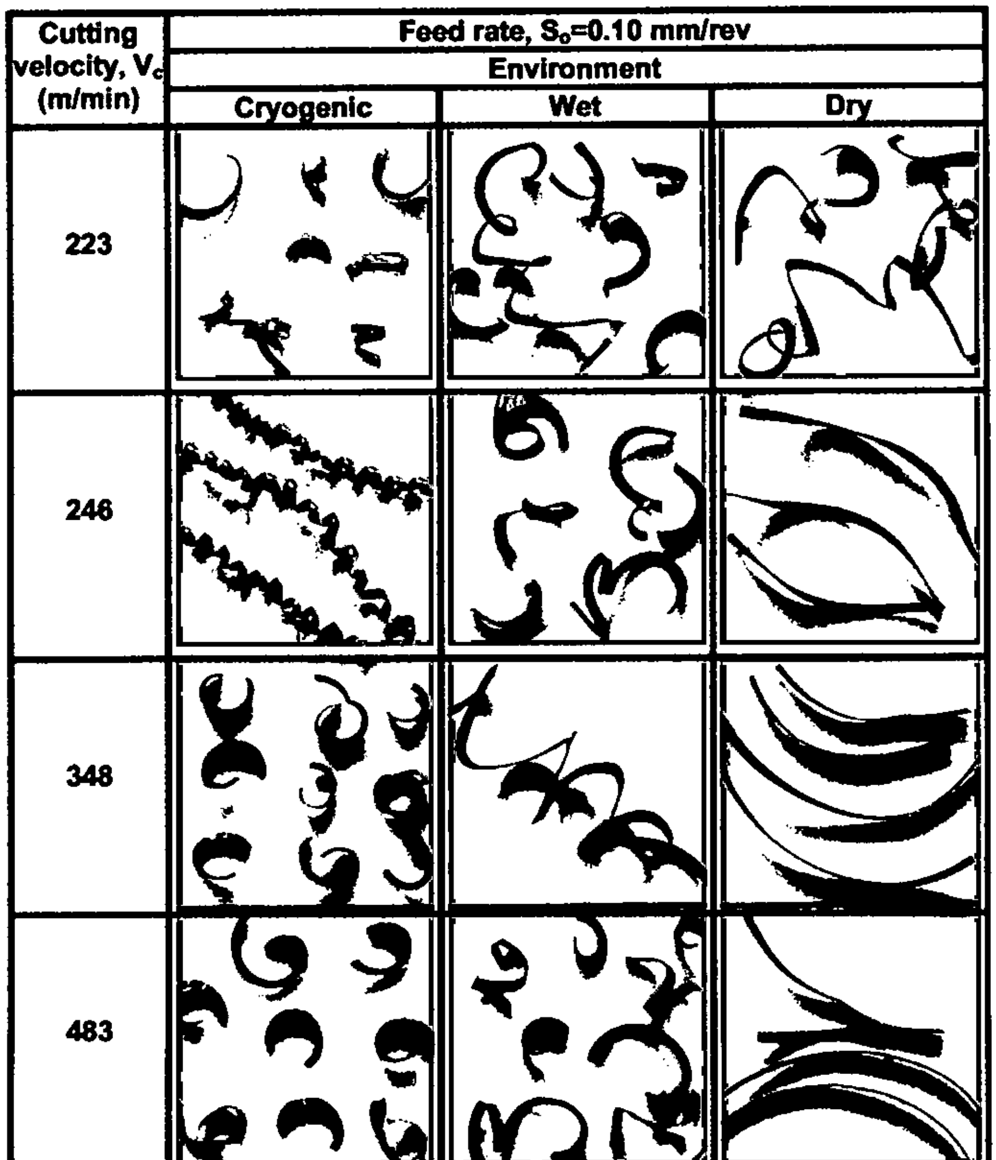


Fig.4.13 Chips produced during turning steel by **SNMM** insert at different V_c and 0.10mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

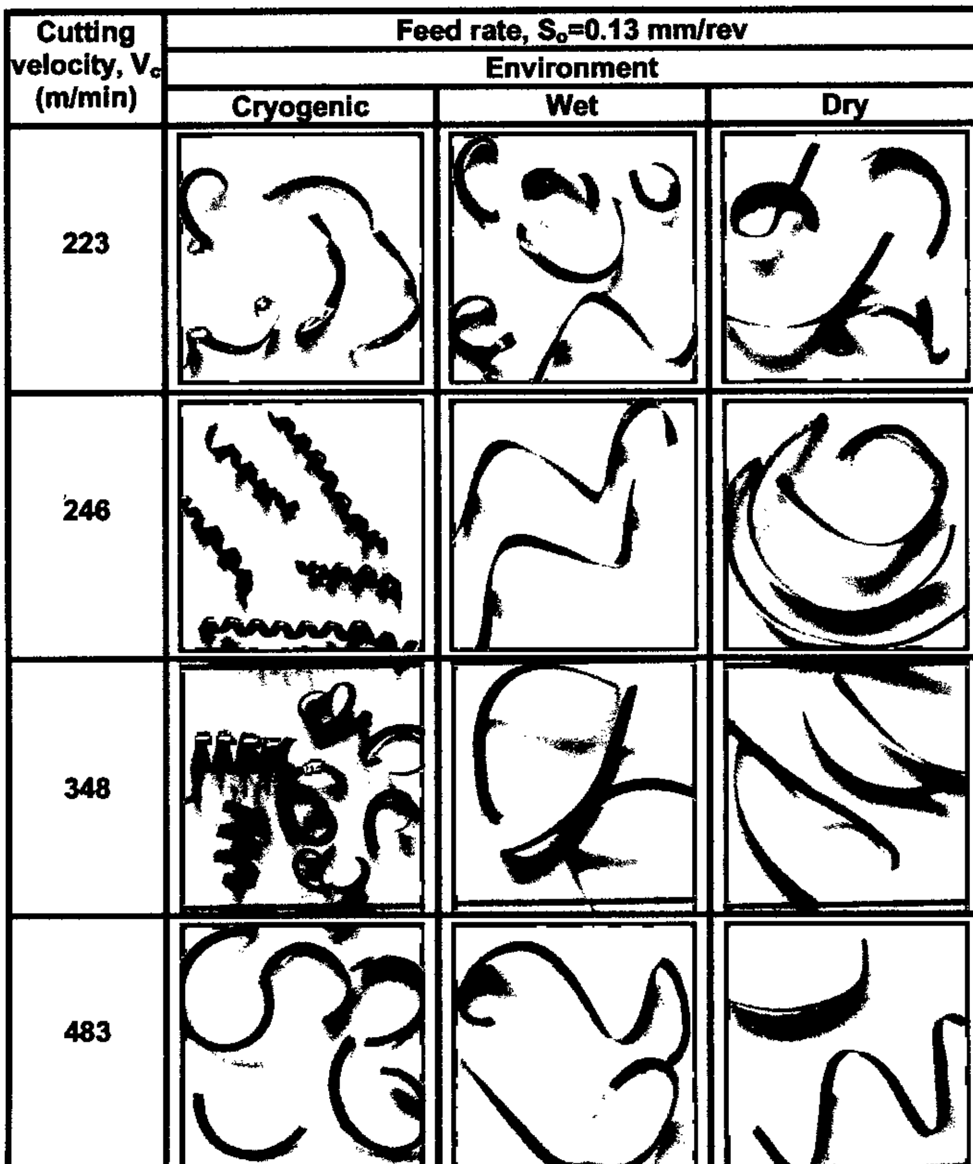


Fig.4.14 Chips produced during turning steel by **SNMM** insert at different V_c and 0.13mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

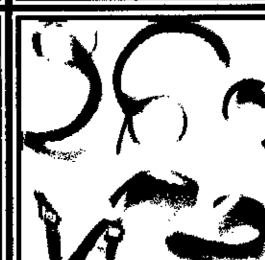
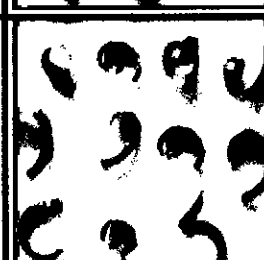
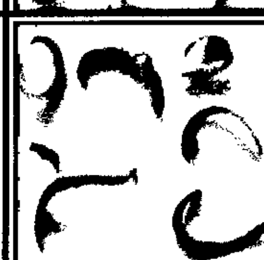
Cutting velocity, V_c (m/min)	Feed rate, S_o=0.16 mm/rev		
	Environment		
	Cryogenic	Wet	Dry
223			
246			
348			
483			

Fig.4.15 Chips produced during turning steel by **SNMM** insert at different V_c and 0.16mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

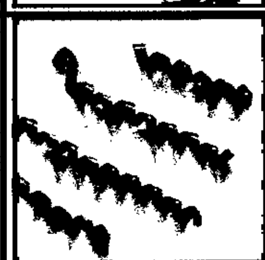
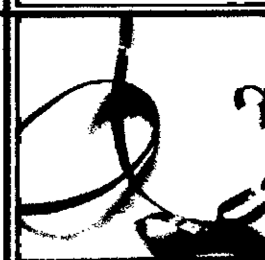
Cutting velocity, V_c (m/min)	Feed rate, S_o=0.18 mm/rev		
	Environment		
	Cryogenic	Wet	Dry
223			
246			
348			
483			

Fig.4.16 Chips produced during turning steel by **SNMM** insert at different V_c and 0.18mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

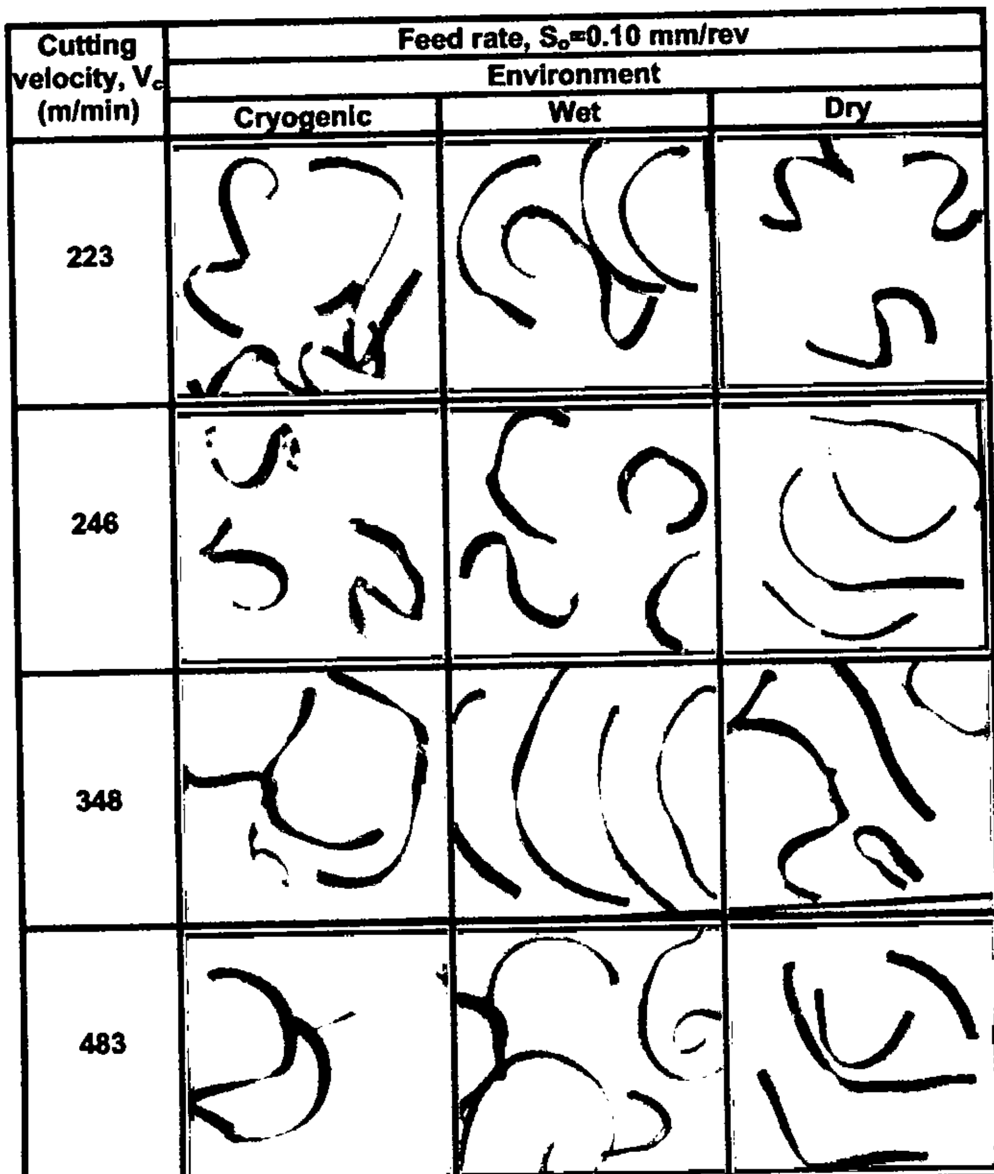


Fig.4.17 Chips produced during turning steel by **SNMG** insert at different V_c and 0.10mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

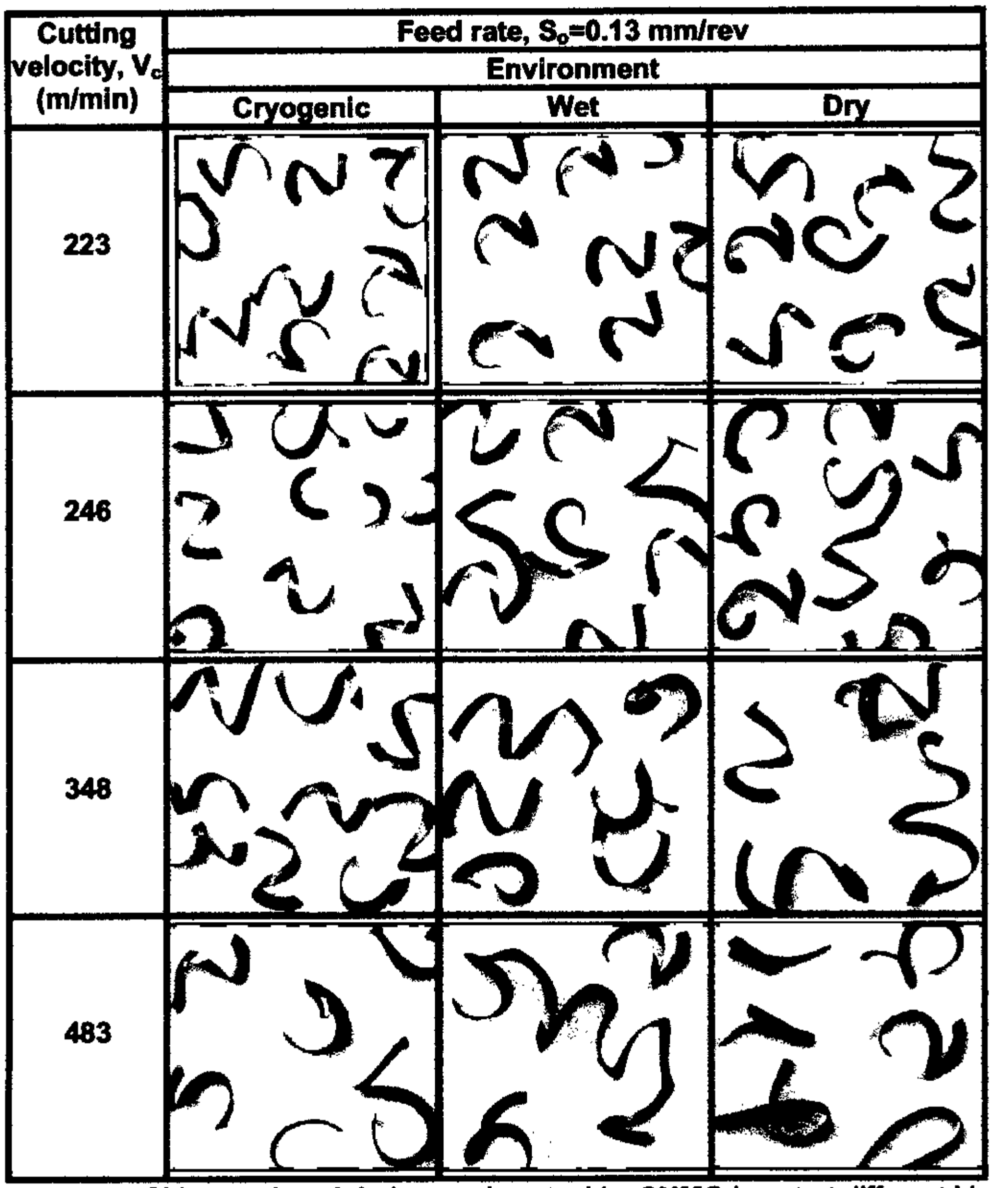


Fig.4.18 Chips produced during turning steel by **SNMG** insert at different V_c and 0.13mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

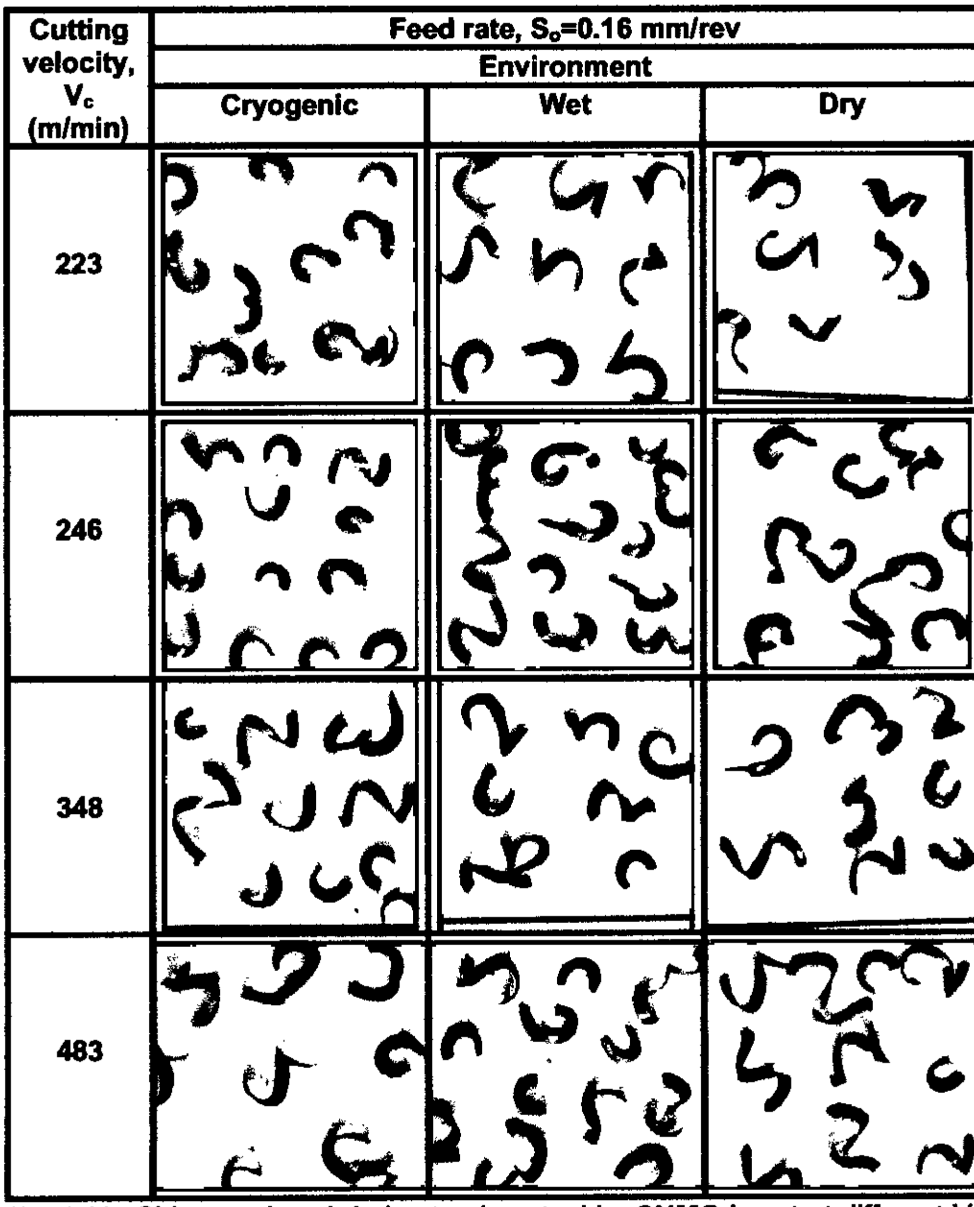


Fig.4.19 Chips produced during turning steel by **SNMG** insert at different V_c and 0.16 mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

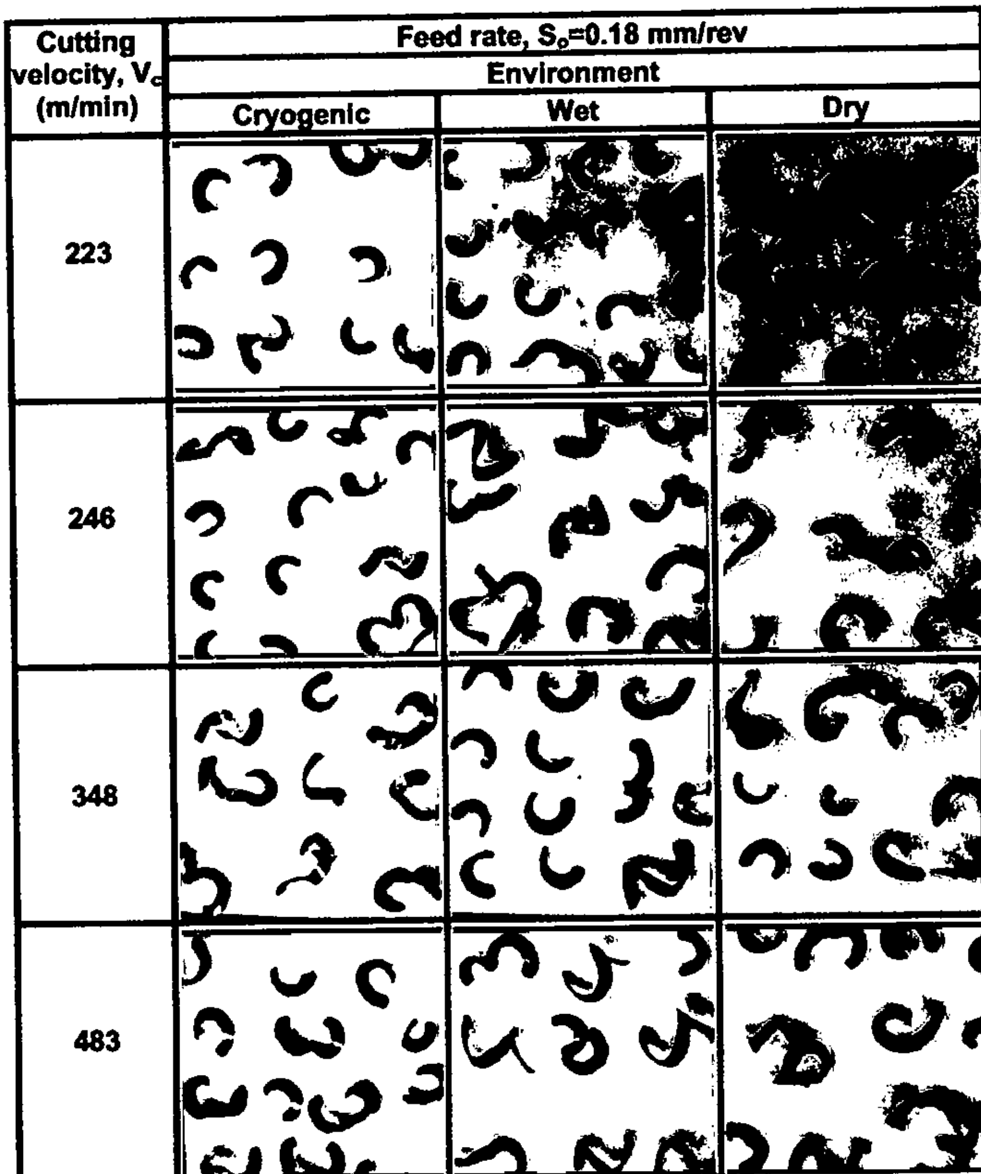
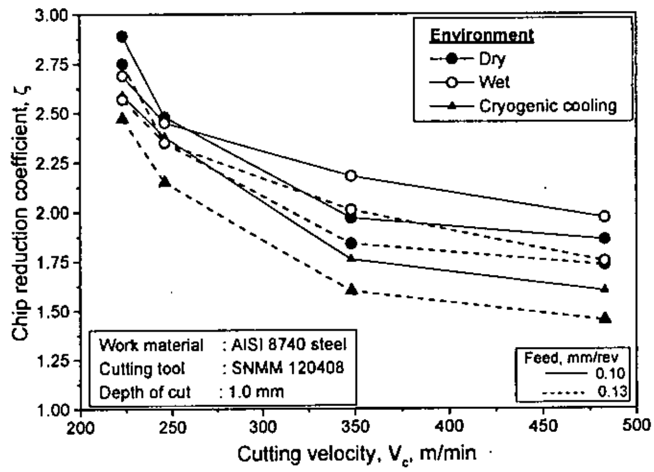
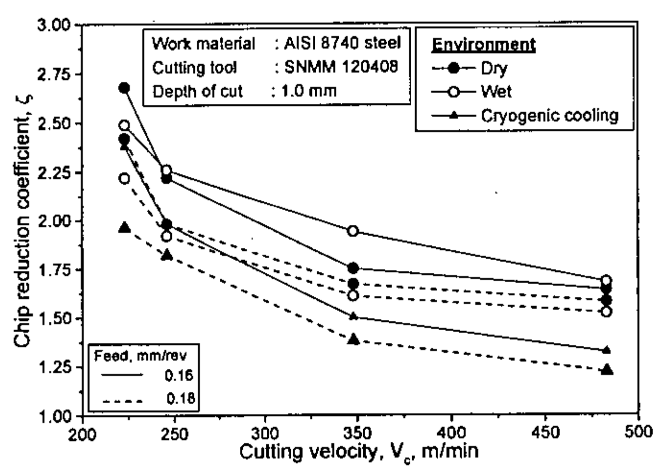


Fig.4.20 Chips produced during turning steel by **SNMG** insert at different V_c and 0.18mm/rev under **dry**, **wet** and **cryogenic** cooling conditions.

Another important machinability index is chip reduction coefficient, ζ (ratio of chip thickness after and before cut). For given tool geometry and cutting conditions, the value of ζ depends upon the nature of chip-tool interaction, chip contact length and chip form all of which are expected to be influenced by liquid nitrogen in addition to the levels of V_c and S_o. The variation in value of ζ with V_c and S_o as well as machining environment evaluated has been plotted and shown in Fig.4.21 and Fig.4.22.

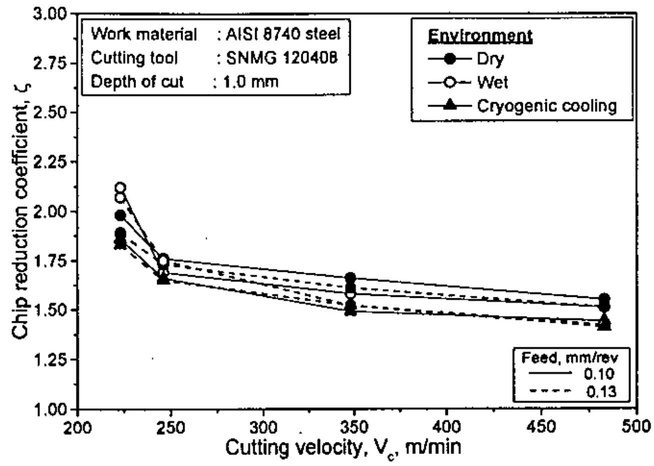


(a)

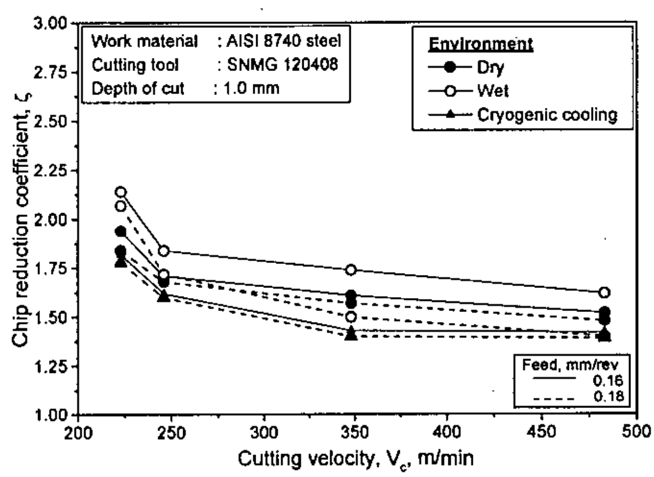


(b)

Fig.4.21 Variation in ζ with that of V_c and S_o by **SNMM** insert under **dry**, **wet** and **cryogenic** cooling conditions at (a) lower and (b) higher feed rates



(a)



(b)

Fig.4.22 Variation in ζ with that of V_c and S_o by **SNMG** insert under **dry, wet** and **cryogenic** cooling conditions at (a) lower and (b) higher feed rates

4.5.3 Cutting tool wear

Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tools. Cutting tools may fail by brittle fracture, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears. With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces, as schematically shown in Fig.4.23 due to continuous interaction and rubbing with the chips and the work surfaces respectively. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems. The life of carbide tools, which mostly fail by wearing, is assessed by the actual machining time after which the average value (V_B) of its principal flank wear reaches a limiting value of 0.3 mm. The values established in accordance with ISO Standard 3685 for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of rejection criteria **[Ezugwu et al. 2005]**:

i. Average Flank Wear ≥ 0.3 mm
ii. Maximum Flank Wear ≥ 0.4 mm
iii. Nose Wear ≥ 0.3 mm
iv. Notching at the depth of cut line ≥ 0.6 mm
v. Average surface roughness value ≥ 1.6 μm
vi. Excessive chipping (flanking) or catastrophic fracture of cutting edge.

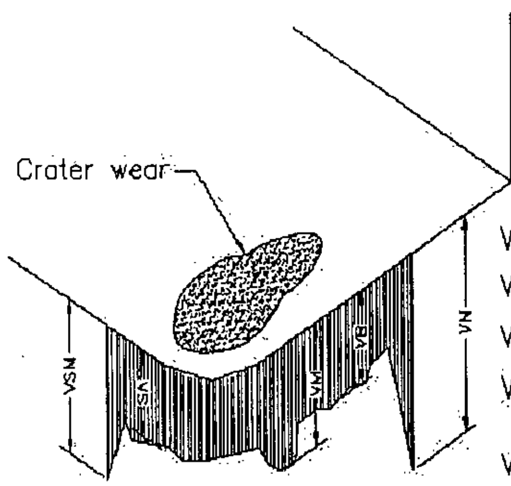


Fig.4.23 Geometry of wear of turning tool

The growth of flank wear, V_B with progress of machining recorded while turning steel, undertaken, by the SNMM and SNMG type inserts at the same feed and depth of cut but moderately high cutting velocity (384 m/min) under dry, wet and cryogenic cooling conditions have been shown in Fig.4.24 and Fig.4.25 respectively.

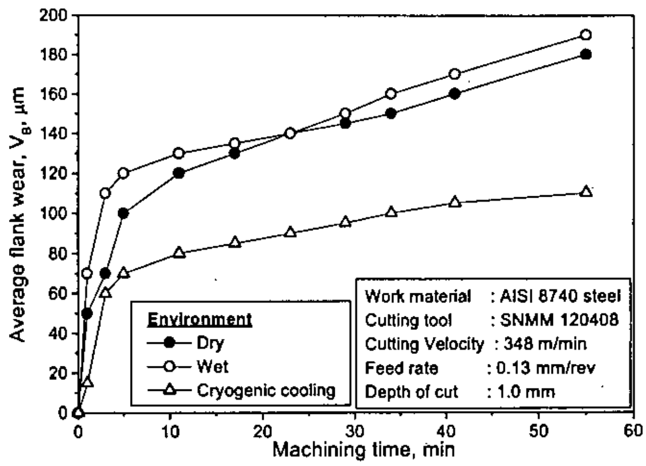


Fig.4.24 Growth of average flank wear, V_B with time in machining steel under **dry**, **wet** and **cryogenic** cooling conditions at cutting velocity 348 m/min by **SNMM** insert

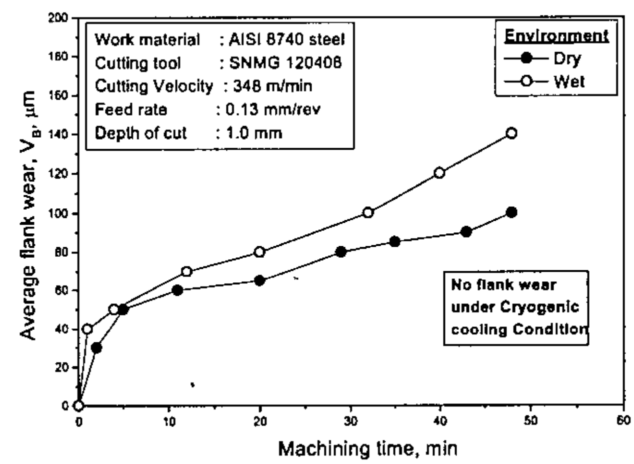


Fig.4.25 Growth of average flank wear, V_B with time in machining steel under **dry**, **wet** and **cryogenic** cooling conditions at cutting velocity 348 m/min by **SNMG** insert

The auxiliary flank wear which affects dimensional accuracy and surface finish have also recorded at regular intervals of machining under all the conditions undertaken. The growth of average auxiliary flank wear, V_S

with machining time under dry, wet and cryogenic cooling conditions have been shown in Fig.4.26 and Fig.4.27 respectively.

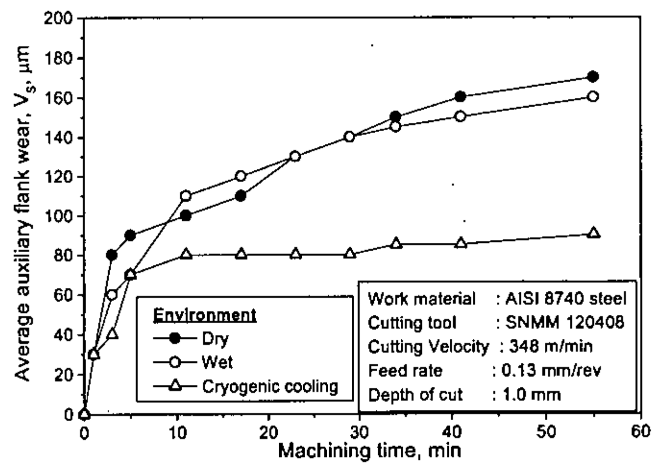


Fig.4.26 Growth of auxiliary flank wear, V_S with time in machining steel under **dry, wet** and **cryogenic** cooling conditions at cutting velocity 348 m/min by **SNMM** insert.

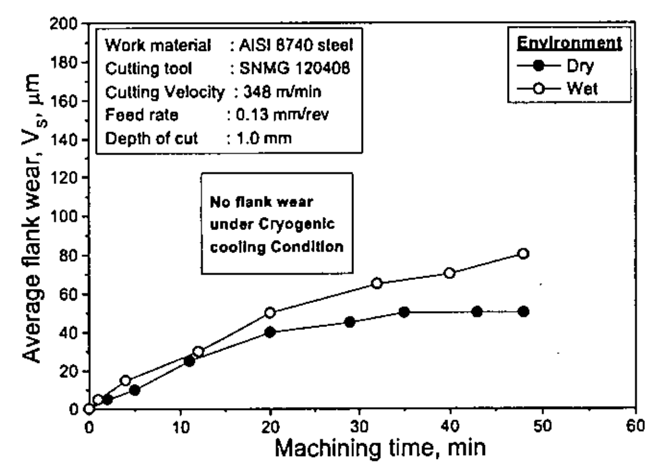
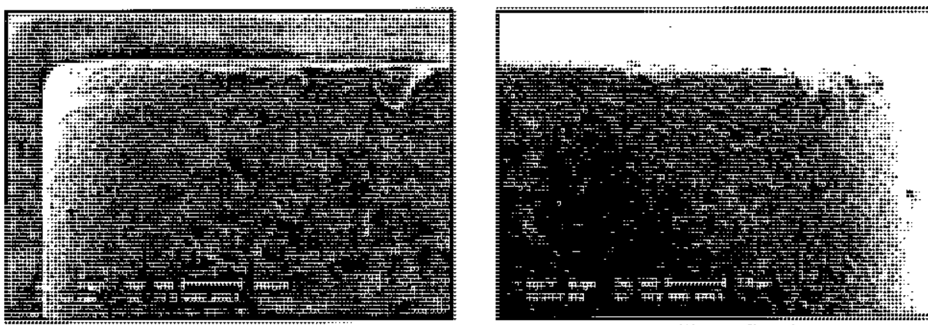


Fig.4.27 Growth of auxiliary flank wear, V_S with time in machining steel under **dry, wet** and **cryogenic** cooling conditions at cutting velocity 348 m/min by **SNMG** insert.

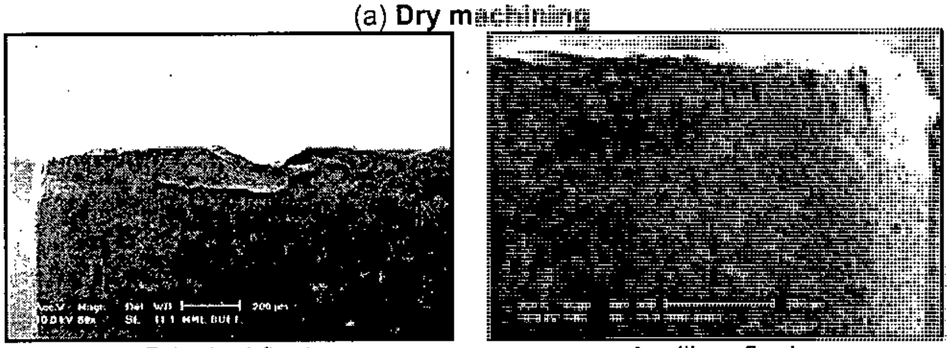
The pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining the steel over reasonably long period have been observed under SEM to see the actual effects of different environments on wear of the coated carbide inserts of present configurations.

The SEM views of the worn out SNMM and SNMG inserts after about 50 minutes of machining of steel under dry, wet and cryogenic cooling conditions have been shown in Fig.4.28 and Fig4.29 respectively.



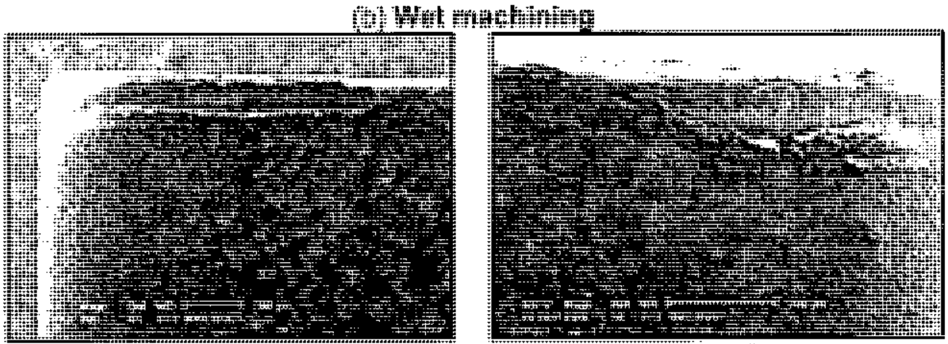
Principal flank Auxiliary flank

(a) **Dry machining**



Principal flank Auxiliary flank

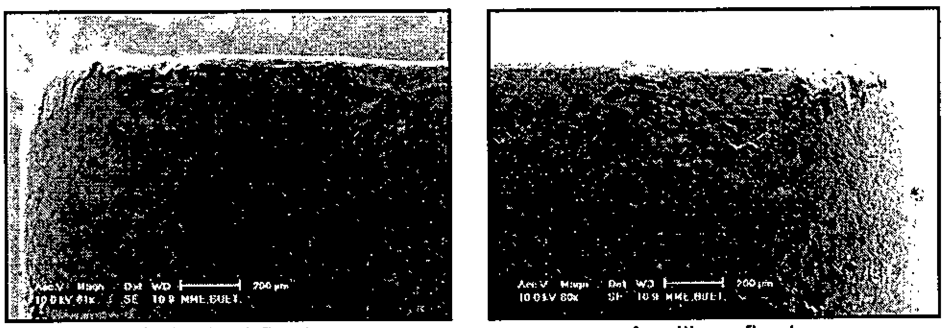
(b) **Wet machining**



Principal flank Auxiliary flank

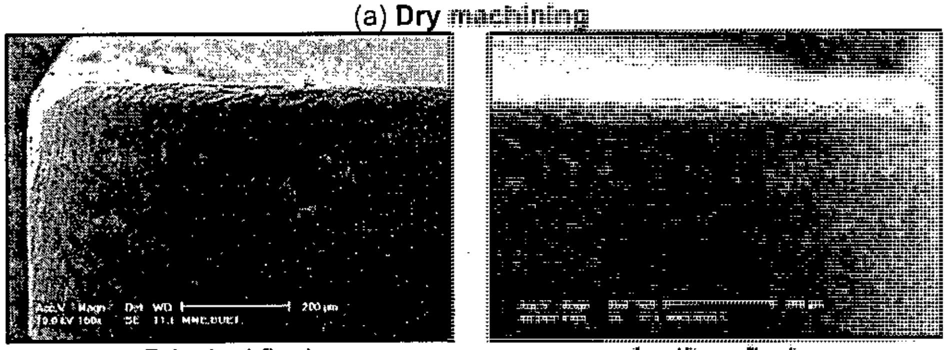
(c) **Cryogenic machining**

Fig.4.28 SEM views of worn out tip of **SNMM** insert after machining steel under (a) **dry**, (b) **wet** and (c) **cryogenic** condition after 50 min of machining.



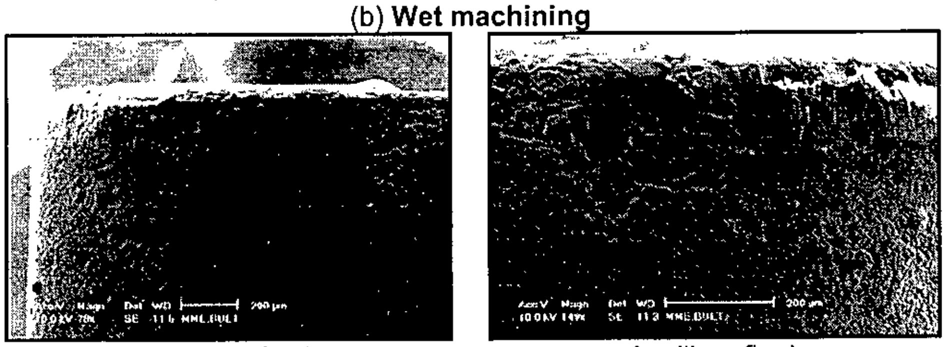
Principal flank Auxiliary flank

(a) **Dry machining**



Principal flank Auxiliary flank

(b) **Wet machining**



Principal flank Auxiliary flank

(c) **Cryogenic machining**

Fig.4.29 SEM views of worn out tip of **SNMG** insert after machining steel under (a) **dry**, (b) **wet** and (c) **cryogenic** condition after 50 min of machining.

4.5.4 Product quality

The performance and service life of any machined part are governed largely by quality of that product, which for a given material is generally assessed by dimensional and form accuracy and surface integrity of the product in respect of surface roughness, oxidation, corrosion, residual stresses and surface and subsurface microcracks.

In the present work, only dimensional deviation on diameter and surface roughness has been investigated to evaluate the relative role of cryogenic cooling on those two major aspects. Hardness along depth from the machined surface has also been observed.

During straight turning in a centre lathe, the diameter of the machined part is generally found to (i) increase along length of cut due to gradual wear of the tool tip (ii) decrease due to thermal expansion and subsequent cooling of the job if the job temperature rises significantly during machining and (iii) increase due to system compliance of the machine-fixture-tool-work (M-F-T-W) system under the action of the cutting forces.

The order of dimensional deviations possible due to thermal expansion of the job even under dry machining and due to compliance of the M-F-T-W system were calculated for the steel specimens being machined under the present conditions and the values appear to be extremely small (less than 1 μm) compared to that possible due to wear of the tool tips.

Therefore, in the present study, the dimensional deviations are considered to be mainly due to wear of the tool tips.

The variation in diameter of the job was precisely measured along its axis after one full pass of the machining over 400 mm length with full depth, at reasonably high feed and cutting velocity suitable for the tool-work combination. This has been done for all the tool-work-environment combinations undertaken keeping the initial diameter and length of the steel rods same and uniform as far as possible. The gradual increase in dimensional deviations on diameter observed along the length of cut on the steel rod after one full pass of machining at cutting velocity of 348 m/min, 1.0 mm depth of cut and 0.13 mm/rev feed under dry, wet and cryogenic cooling conditions have been shown in Fig.4.30 and Fig.4.31.

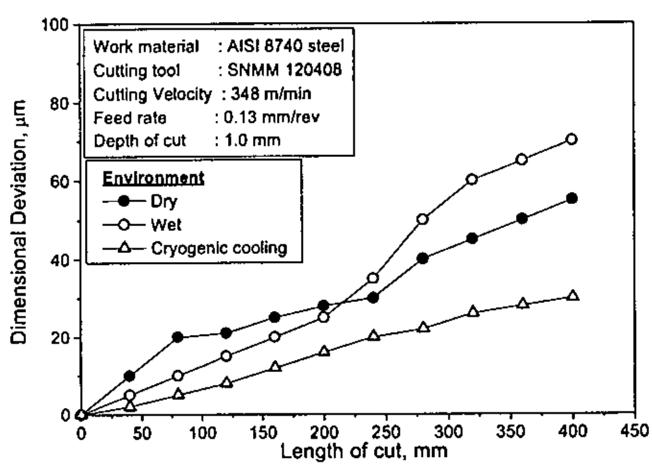


Fig.4.30 Dimensional deviations observed after one full pass turning of the steel rod by **SNMM** insert at cutting velocity, 348 m/min under **dry**, **wet** and **cryogenic** conditions.

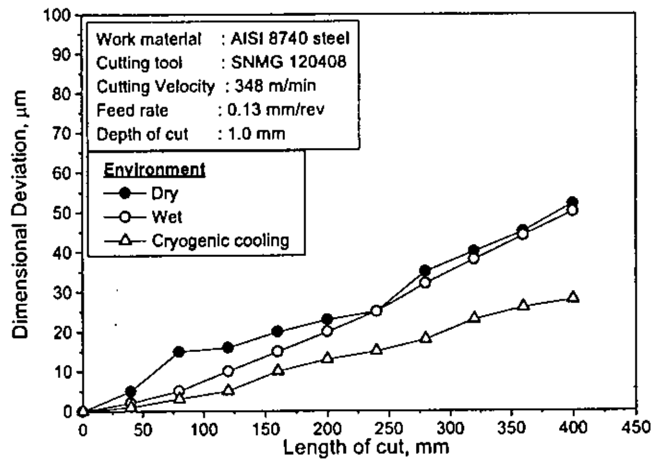


Fig.4.31 Dimensional deviations observed after one full pass turning of the steel rod by **SNMG** insert at cutting velocity, 348 m/min under **dry**, **wet** and **cryogenic** conditions.

Surface roughness is another important index of machinability, which is substantially influenced by the machining environment for given tool-work pair and speed-feed conditions.

Surface roughness has been measured at two stages; one, after a few seconds of machining with the sharp tool while recording the cutting forces and second, with the progress of machining while monitoring growth of tool wear with machining time.

The surface roughness attained after 40 seconds of machining of the steel by the sharp SNMM and SNMG inserts at various V_c-S_o combinations under dry, wet and cryogenic conditions are shown in Fig.4.32 and Fig.4.33.

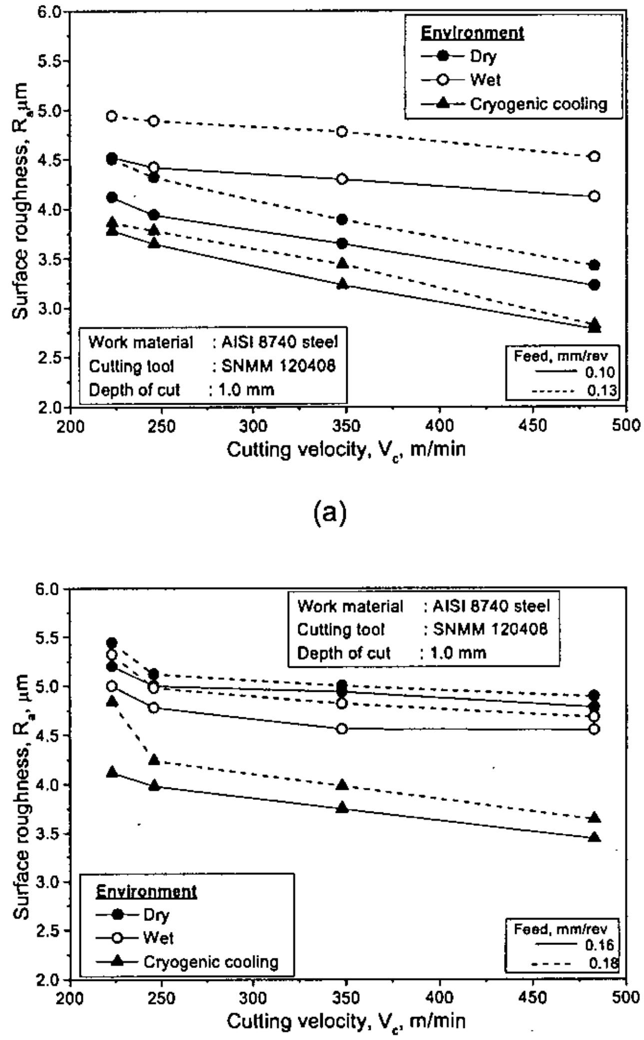
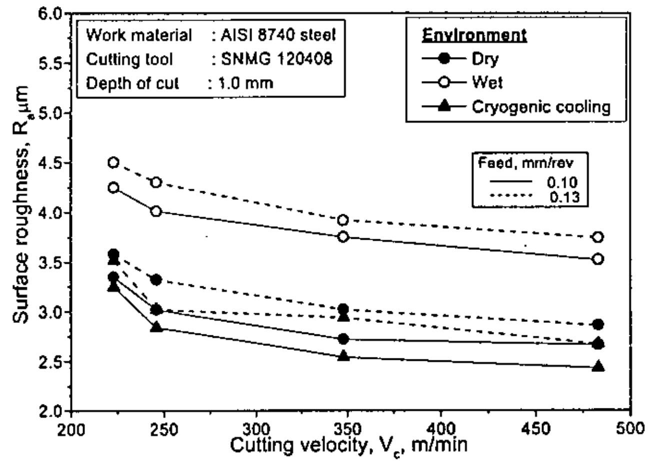
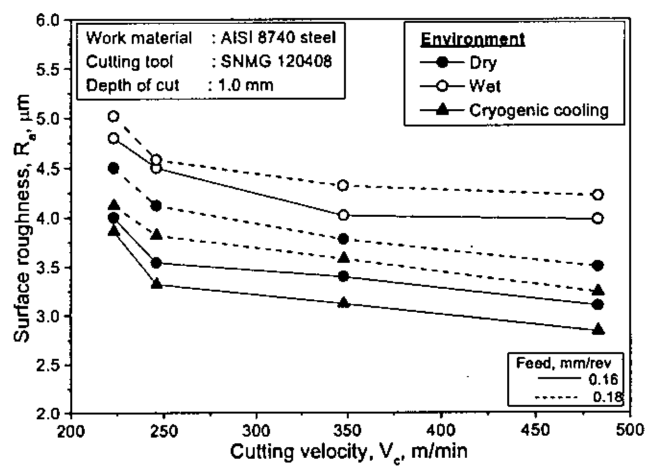


Fig.4.32 Variation in surface roughness observed after turning steel by **SNMM** insert at different V_c and S_o under **dry**, **wet** and **cryogenic** cooling conditions at (a) lower and (b) higher feed rates



(a)



(b)

Fig.4.33 Variation in surface roughness observed after turning steel by **SNMG** insert at different V_c and S_o under **dry, wet** and **cryogenic** cooling conditions at (a) lower and (b) higher feed rates

The variation in surface roughness observed with progress of machining of the steel by the insert at a particular set of V_c, S_o and t under dry, wet and cryogenic conditions has been in shown in Fig.4.34 and Fig4.35 respectively.

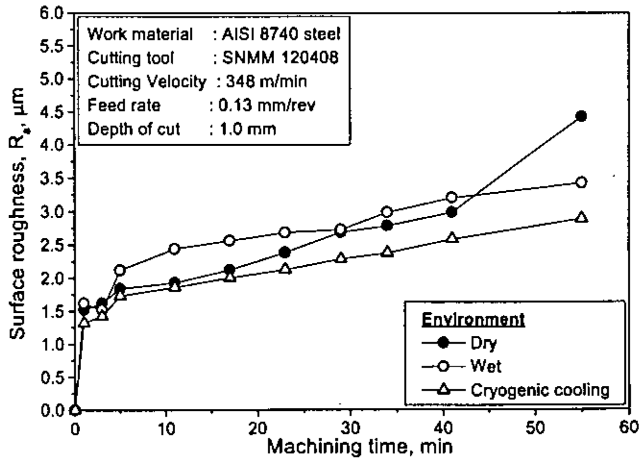


Fig.4.34 Surface roughness developed with progress of machining of the steel by **SNMM** insert under **dry**, **wet** and **cryogenic** conditions

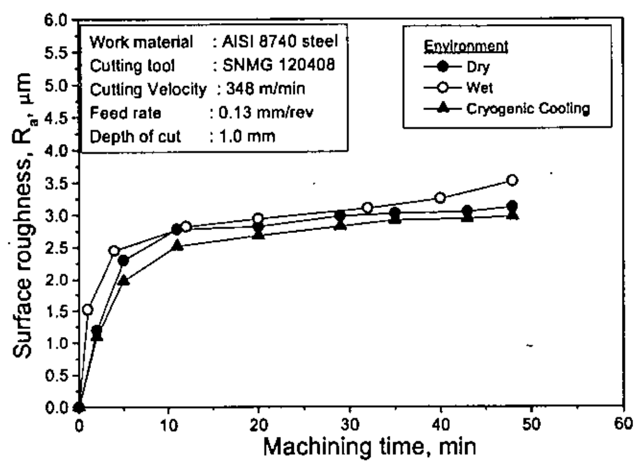


Fig.4.35 Surface roughness developed with progress of machining of the steel by **SNMG** insert under **dry**, **wet** and **cryogenic** conditions

Chapter-5

Discussion on Experimental Results

5.1 Cutting Temperature

The machining temperature at the cutting zone is an important index of machinability and needs to be controlled as far as possible. Cutting temperature increases with the increase in specific energy consumption and material removal rate (MRR). Such high cutting temperature adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products. Therefore, application of cryogenic cooling by liquid nitrogen jet is expected to improve upon the aforesaid machinability characteristics, which play vital role on productivity, product quality and overall economy in addition to environment-friendliness in machining particularly when the cutting temperature is very high.

The average chip-tool interface temperature, have been determined using reliable tool-work thermocouple technique and plotted against cutting velocity for different work-tool combinations, feeds and environments undertaken. Fig.4.11 is showing how and to what extent θ_{avg} has decreased due to cryogenic application under the different experimental conditions by SNMM insert. With the increase in V_c and S_o, average temperature increased as usual, even under cryogenic cooling, due to increase in energy input. And Fig.4.12 also shows that by using SNMG insert the temperature is minimum under cryogenic cooling.

Apparently more drastic reductions in average temperature is expected by employing liquid nitrogen jet at temperature -196°C. But practically it has not been so because the liquid nitrogen has been employed in the form of thin jet along the auxiliary cutting edge and towards only the chip-tool interface and tool flank instead of bulk cooling. Also the jet, like any cutting fluid, could not reach deeply in the chip-tool interface for plastic or bulk contact, particularly when V_c and S_o are large.

5.2 Machining Chips

The pattern of chips in machining ductile metals 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. In absence of chip breaker, length and uniformity of chips increase with the increase in ductility and softness of the work material, tool rake angle and cutting velocity unless the chip-tool interaction is adverse causing intensive friction and built-up edge formation.

Table-4.4 shows that, when machined by SNMM insert under dry condition produced ribbon type chips at low feed rate (0.10 mm/rev) and more or less spiral chips at higher feeds. The geometry of the SNMM 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 machined under wet condition most of the chips are spiral. When machined under cryogenic cooling the form of these ductile chips did not change appreciably but their back surface appeared much brighter and smoother. This indicates that the amount of reduction of temperature and presence of inert nitrogen due to cryogenic application enabled favourable chip-tool interaction and elimination of even trace of built-up edge formation.

Table-4.5 shows, when machined under dry condition by SNMG inserts produced spiral and half turn type chips at low feed rate (0.10 mm/rev) and ribbon type chips at higher feeds. In dry condition the colour of the chips are golden at lower feed. At higher feed rate (.18 mm/rev) most of the chip became burnt blue colour in dry condition because of high temperature generation. The conditions of chip shape and colour are same in wet cooling. When machined under cryogenic cooling condition the chips produced are more or less half turn and the colour of the chips are metallic which indicates lowering cutting temperature and favourable chip tool interaction.

Fig.4.13 to Fig.4.20 typically show that even at high feed of 0.18 mm/rev the same tool-work combination provided relatively longer and smoother chips when machined with liquid nitrogen jet.

By using SNMM insert the colour of the chips have also become much lighter i.e. metallic or golden from burnt blue depending upon V_c and S_o due to reduction in cutting temperature by cryogenic cooling. But the colour of the all chips has become lighter i.e only metallic by using SNMG insert.

It is important to note in Table-4.4 and Table-4.5 that the role of cryogenic cooling has been more effective in respect of form and colour of the chips when machined by the groove type SNMG insert. 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.

5.3 Chip Reduction Coefficient

Almost all the parameters involved in machining have direct and indirect influence on the thickness of the chips during deformation. The degree of chip thickening which is assessed by chip reduction coefficient, ζ, plays sizeable role on cutting forces and hence on cutting energy requirements and cutting temperature.

Fig.4.21 and Fig.4.22 show that by using SNMM and SNMG insert chip reduction coefficient decreases with the increases of cutting velocity under dry, wet and cryogenic cooling condition. For cryogenic cooling, chip reduction coefficient is minimum in comparison to another two conditions for both inserts.

The value of ζ usually decreases with the increases in V_c particularly at its lower range due to plastisization and shrinkage of the shear zone for reduction in friction and built up edge formation at the chip tool interface due to increase in temperature and sliding velocity. In machining steel by tools like carbide, usually the possibility of build 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 V_c and S_o and then decreased with the further increase in V_c due to much softening of the chip material and its removal by high sliding speed.

By cryogenic applications, ζ is reasonably expected to decreases for reduction in friction at the chip tool interface and reduction in detoriation of effective rake angle by build up edge formation and wear at the cutting edges mainly due to reduction in cutting temperature and also possibly for removing of oxygen from the cutting zone by nitrogen.

5.4 Tool Wear and Condition

All the cutting inserts selected and used attained flank wear progressively in varying pattern and magnitude while machining steel under dry, wet and cryogenic cooling condition undertaken for the present investigations. Premature and catastrophic types of tool failure by plastic deformation or macro fracture were not found to occur expectedly within the present experimental domain.

Fig.4.24 and Fig.4.25 show that average flank wear V_B is plotted against machining time when machining steel by both SNMM and SNMG inserts.

In Fig.4.24 shows that average flank wear V_B is higher under dry condition than wet and cryogenic cooling condition. Such wet cutting causes faster oxidation and corrosion of the tool surfaces and rapid micro fracturing of the cutting edges by thermo-mechanical shocks due to fluctuation in temperature and stresses, which compensates or often surpasses the reduction of adhesion and diffusion wear of the carbide inserts expected due to cooling and lubrication by the cutting fluid in continuous machining like turning of steel. But application of cryogenic cooling by liquid nitrogen jet has substantially reduced growth of V_B as can be seen in Fig.4.24. Such improvement by liquid nitrogen jet can be attributed mainly to retention of hardness and sharpness of the cutting edge for their steady and intensive cooling, protection from oxidation and corrosion and absence of built-up edge formation, which accelerates both crater and flank wear.

Fig 4.25 also shows that average flank wear V_B increases with the increase of machining time under both dry and wet condition. But there is no wear under cryogenic cooling condition.

It is evident that Fig.4.24 and Fig.4.25 average flank wear V_B increases much faster in case of SNMM insert than in SNMG insert due to high temperature.

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

Fig.4.26 also shows that the value of average auxiliary flank wear, V_S not only grew quite rapidly but also got accelerated after about 15 minutes of machining by the SNMM insert under dry as well as wet condition. Application of liquid nitrogen jet, towards the auxiliary flank kept the magnitude and rate of growth of V_S all along much low even upto 50 minutes of machining.

But in Fig.4.27, there is no auxiliary flank wear in cryogenic cooling condition. For dry and wet cooling there is low auxiliary flank wear in comparison to the SNMM insert. Unlike principal flank wear, auxiliary flank wear widely varies along the auxiliary flank reasonably for sharp variation in stresses and temperature.

The result of the experimental study presently carried out on tool wear in machining steel under different environments clearly depicts that in machining steel, application of conventional method and type of cutting fluid like soluble oil does not help in reducing wear or improving tool life. But proper application of cryogen like liquid nitrogen in the form of jet provides substantial improvement. Such benefit of the cryogenic cooling may be attributed mainly to reduction of abrasive and chemical wear at the tool flanks and also possible control of chip tool interaction and thereby built-up edge formation which not only adds flaking wear but also accelerates chipping of the cutting edges by inducing vibration.

The SEM views of the worn out SNMM and SNMG insert after machining steel at a particular V_c-S_o-t combination under different environments are shown in Fig.4.28 and Fig.4.29 which clearly indicates that use of conventional cutting fluid did not significantly improve the nature and extent of wear, whereas application of liquid nitrogen has provided remarkable improvement and even after 55 minutes of machining, both flank and crater wear have not been found by machining SNMG insert. No notch appeared on the auxiliary flank. In the process of systematic growth of cutting tool wear, the cutting tools usually first undergo rapid wear called break-in wear at the beginning of machining due to attrition and micro-chipping and then uniformly and relatively slow mechanical wear followed by faster wear at the end.

Fig.4.28 shows that compared to the SNMG insert the SNMM type insert worn out much faster under dry, wet and cryogenic cooling conditions, which indicates that tool geometry plays substantial role on wearing of tool and also on the effectiveness of cryogenic cooling on control of tool wear. This difference might be due to straight and sharp cutting edges and large positive rake of the SNMM inserts.

Principal flank wear excluding notching should generally occur uniformly along the main cutting edge particularly when depth of cut is much larger than the tool nose radius. But in practice it is found that at certain point(s) flank wear becomes relatively larger than V_B. It appears from the SEM view graphs in Fig.4.28 shows that principal flank wear is reasonably occur both dry and wet condition but in cryogenic condition it is small. But using SNMG insert there is no principal flank wear in cryogenic cooling condition.

5.5 Dimensional deviation

It has been mentioned earlier that the diameter in straight turning of long rods may deviate from the theoretically expected value due to progressive wear of the tool-tip, variation of compliance of the 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 cryogenic cooling. The order of dimensional deviation possible due to other two reasons for the present job specimen of so large diameter and L/D ratio less than 4.0 and the cutting conditions undertaken has been roughly estimated and found to be around 1.0 μm.

It can be noted in Fig.4.30 dimensional deviation increases with the increases the length of the job for both dry and wet cooling. By applying liquid nitrogen jet it is comparatively less. Fig.4.31 also shows that for dry and wet cooling dimensional deviation increases with the increase of the length of the job. The dimensional deviation is less in cryogenic cooling condition compared to dry and wet machining by using both inserts due to much lesser break-in wear or initial wear and absence of notching at the auxiliary flank of the insert.

By using SNMM insert dimensional deviation is higher than the using of SNMG inserts. Careful observation of the figures presenting dimensional deviations under various machining conditions and those presenting average auxiliary flank wear visualises that dimensional deviation observed have close relation with corresponding auxiliary flank wear.

5.6 Surface roughness

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 conjugation 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.

(i) regular feed marks left by the tool tip on the finished surface

(ii) irregular deformation of the auxiliary cutting edge at the tool-tip due to chipping, fracturing and wear

(iii) vibration in the machining system

(iv) built-up edge formation, if any.

Even in absence of all other sources, the turned surface inherently attains some amount of roughness of systematic and uniform configurations due to feed marks. The peak value of such roughness depends upon the value of feed, S_o and the geometry of the turning inserts. Nose radius essentially imparts edge strength and better heat dissipation at the tool tip but its main contribution is drastic reduction in the aforesaid surface roughness as indicated by the simple relationship [**Bhattacharyya, 1984**],

$$h_m = \frac{(S_o)^2}{8r} \tag{5.1}$$

where, h_m is the peak value of roughness caused due to feed marks and r is the nose radius of the turning inserts.

Fig.4.32 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 evident in Fig.4.32 that cryogenic cooling could provide marginal improvement in surface finish at the beginning of machining with the fresh cutting edges. This has been more or less true for the entire tool undertaken as can be seen in Fig.4.33 by using SNMG insert. The slight improvement in surface finish by cryogenic cooling might be due to reduction in break-in wear and also possibly reduction or prevention of built-up edge formation depending upon the work material and cutting condition. This may reasonably be attributed to more stability of those steels against attrition and built-up edge formation. It is also to be noted that there was no significant difference in R_a values provided by the present two types of inserts within such a short period of machining any steel.

Fig.4.34 and Fig.4.35 show that surface roughness plotted against machining time. Surface roughness drastically increased first 10 minutes while machining steel by SNMM and SNMG inserts under dry, wet and cryogenic cooling condition. After 10 minutes roughness increased gradually for dry, wet and cryogenic condition. At first roughness drastically increased because of sharp tool tip. Roughness is minimum for cryogenic cooling compared to another two condition (dry and wet) for both inserts.

It is evident that cryogenic cooling by liquid nitrogen jet substantially improves surface finish depending upon the work tool materials and mainly through controlling detoriation of the auxiliary cutting edge by abrasive, chipping and built-up-edge.

Chapter-6

Conclusions

(a) Application of cryogenic cooling by liquid nitrogen jets not only can provide environment friendliness but also substantial technological benefits as has been observed in machining some steels by coated carbide inserts.

(b) Flood cooling by soluble oil did not improve machinability rather accelerated auxiliary tool flank wear, dimensional inaccuracy and surface roughness in machining steel by enhancing chipping and chemical wear at the cutting edges particularly at the auxiliary cutting edge where stresses and temperature are relatively higher.

(c) The present cryogenic cooling systems enabled reduction in average chip-tool interface temperature upto 20% depending upon the tool geometry and cutting conditions and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.

(d) Due to cryogenic cooling application, the form and colour of the steel chips became favourable for more effective cooling and improvement in nature of interaction at the chip-tool interface.

(e) Cryogenic cooling reduced the cutting chip-tool interface temperature. Such reduction has been more effective for those tool-work combinations and cutting conditions, which provided higher value of, chip reduction coefficient, ζ for adverse chip-tool interaction causing large friction and built-up edge formation at the chip-tool interface.

(f) The most significant contribution of application of liquid nitrogen jet in machining the steel by the coated carbide inserts undertaken has been the reduction in flank wear, which would enable either remarkable improvement in tool life or enhancement of productivity (material removal rate, MRR) allowing higher cutting velocity and feed. Such reduction in tool wear might have been possible for retardation of abrasion and notching, decrease or prevention of adhesion and diffusion type thermal sensitivity wear at the flanks and reduction of built-up edge formation which accelerates wear at the cutting edges by chipping and flaking.

(g) Dimensional accuracy and surface finish also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of liquid nitrogen.

(h) The geometry of cutting tools played significant role on the degree of improvement in machinability of the steels by cryogenic application which becomes more effective when the tool geometry allows more intensive cooling of the chip-tool interface and the tool flanks.

(i) Cryogenic cooling, if properly employed, can enable significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of cryogenic cooling system and cryogen.

Chapter-7

References

Alaxender, A., Varadarajan, A. S. and Philip, P. K., "Hard "Turning with Minimum Cutting Fluid: A Viable Green Alternative on the Shop Floor", *Proc. 18th All India Conf. MTDR*, pp.152-155 (1998).

Aronson, R. B., "Why Dry Machining", *Manufacturing Engineering*,Vol.114, pp.33-36 (1995).

Banerjee, A. and Chattopadhyay, A. B., "Control of Residual Stress in Grinding by Cryogenic Cooling", *Proceedings of INCONCRYO□85*, pp.78-48 (1985).

Bartley, E. W., " *Machinery (E)"*, Vol. 83, pp.24 (1953).

Beaubien, S. J. and Cattaneo, A. G., "A Study of the Role of Cutting Fluid in Machining Operations," *Lubrication Engineering*, Vol.10, pp.74-79 (1964).

Bennett, E.O., "Water Based Cutting Fluids and Human Health", *Tribology Int.*, (1983).

Bennett, E.O and Bennett, D.L.," Occupational Airway Diseases in the Metal-working Industry," *Tribology Int.*, Vol.18(3), pp.169-176 (1985).

Bhattacharyya, A., Roy, T. K. and Chattopadhyay, A. B., "Application of Cryogenic in Metal Machining", *J. of Institution of Engineers*, India, (1972).

Bhattacharyya, A., "Metal Cutting-Theory and Practice", *Central Book Publishers, India,* (1984).

Brinksmeier, E., Walter, A., Janssen, R. and Diersen, P., "Aspects of cooling lubrication reduction in machining advanced materials", Proceedings of the Institution of Mechanical Engineers, 213 (Part B), UK, pp. 769–778, (1999).

Byrne, G. and Scholta, E., "Environmentally Clean Machining Process- A Strategic Approach", *Annals of CIRP*, Vol.42/1, pp. 471-474, (1993).

Cassin, C. and Boothroyed, G., "Lubrication Action of Cutting Fluids", *J. of Mechanical Engineering Science,* Vol 7(1), pp.67-81 (1965).

Chandrasekaran, H., Thuvander, A. and Johansson, J. O., "The Influence of Cutting Fluid on Tool Temperature Distribution in Single Point Turning of Steel", *18th AIMTDR Conference, IIT Kharagpur,* India, pp.219-224 (1998).

Chao, B. T. and Trigger, K. J., "Temperature Distribution at the Chip-tool Interface in Metal Cutting", *Trans. of the ASME*, Vol.77, pp.1107 (1955).

Chattopadhyay, A. B., Bose, A. and Chattopadhyay, A. K., "Improvements in Grinding Steels by Cryogenic Cooling", *J. of Precision Engineering*, Vol.7 (2), pp.93 (1985).

Chattopadhyay, A. B. and Bhattacharya, A., "Cutting Characteristics of Constant Pressure", *J. IE (I), ME-2*, pp.255-275 (1968).

Chattopadhyay, A. K. and Chattopadhyay, A. B., "Wear and Performance of Coated Carbides and Ceramic Tools", *Wear*, Vol.80, pp.239-253 (1982).

Chou, Y.K. and Song, H. "Hard turning with different nose radius ceramic tools", SME Technical Paper No.MR01-228, 2001

Cozzens, D. A., Olson, W. W. and Sutherland, J. W., "An Experimental Investigation into the Effect of Cutting Fluid Conditions of the Boring of Aluminium Alloys", *ASME Bound Volume*, (1995).

"Cutting Fluid Management in Small Machine Shop Operations", Iowa Waste Reduction Center, *University of Northern, Iowa75 Biology Research Complex, Cedar Falls, Iowa 50614-0185319/273-2079* (1996)

Davies, M. A., Chou, Y. and Evans, C. J., "On Chip Morphology, Tool wear and Cutting Mechanics in Finish Hard Turning", *Annals of CIRP*, Vol.45/1, pp.77-82, (1996).

Dewes, R.C., Aspinwall, D.K., "A Review of Ultra High Speed Milling of Hardness Steels", J. Mater. Process. Technology, Vol. 69, pp.1-17, (1997).

Dieter, G.E., "Mechanical Metallurgy", *McGraw-Hill Int. Book Co.* (1981)

Ding, Y. and Hong, S. Y.," Improvement of Chip Breaking in Machining Low Carbon Steel by Cryogenically Precooling the Workpiece", *Trans. of the ASME, J. of Manuf. Science and Engg.*, Vol.120, pp.76-83 (1998).

Dhar, N.R, Islam, S. and Kamruzzaman, M. "Experimental Investigation on effect on Minimum Quantity Lubrication (MQL) In Machining Steel" Journal of Engineering and Technology, IUT, Bangladesh.(Vol.4.No.1 Jan-June2005)

Dhar, N.R., Islam, S. and Ahmed, T., "A study of Effects of MQL on Cutting Temperature, Tool Wear and Dimensional Deviation in Turning Steel", Proceedings of International Conference on Industrial Problems on Machines and Mechanisms (IPROMM-2005), Indian Institute of Technology, Kharagpur, India"(2005").

Eisen, E. A., Tolbert, P. E., Hallock, M. F. and Monson, R. R., "Mortality Studies of Machining Fluid Exposure in the Automobile Industry: ii. A Case-control Study of Larynx Cancer", *Am. J. Ind. Med.* , Vol.26: pp.185-202 (1994).

Ellis, J. and Barrow, G. *Annals of CIRP*, 17, pp. 39 (1969).

Evans, C "Cryogenic Diamond Turning of Stainless Steel", *Annals of CIRP*, Vol. 40(1), pp.571-575 (1991).

Farook, A., Varadarajan, A. S. and Philip, P. K., "Machinability Studies on Steel using Hardmetal Inserts with Soft Material Deposit", *Proc. 18th All India Conf. MTDR*, pp.152-155 (1998).

Fillippi, A. D. and Ippolito, R.," Face Milling at 180°C", *Annals of CIRP*, Vol. 19(1) (1970).

Gottwein, K., "Die Messung der Schneidentemperatur beim Abdrehen von Flusseisen", *Maschinenbau,* Vol.4, pp.1129-1135 (1925).

Heginbotham, W. B., and Gogia, S. L.,"Metal Cutting and the Built-Up Nose", *Proc. Inst. Mech. Engrs.*, Vol.175/18, pp.892-909 (1961).

Hollis, W. S., "The Application and Effect of Controlled Atmospheres in the Machining of Metals", *Int. J. of MTDR*, (1961).

Hong, S. Y., Ding, Y. and Ekkins, R. G., " Improving Low Carbon Chip Breakability by Cryogenic Cooling", *Int. J. of Machine Tool and Manufacture*, Vol.39, pp.1065-1085 (1999).

Huang, Y., Liang ,S.Y, "Cutting Forces modelling considering the effect of tool thermal property application to CBN Hard turning," Int .J. mach. Tools Manuf.43 (2003) 307-305

Jawahir, I. S., "The Tool Restricted Contact Effect as a Major Influencing Factor in Chip Breaking: An Experimental Analysis", *Annals of CIRP*, Vol.37/1, pp.121126 (1988).

Jawahir, I. S. and van Luttervelt, C. A., "Recent Development in Chip Control Research and Application", *Annals of CIRP*, Vol.42/2, pp.659-693 (1993).

Kennedy, S.M., "Acute Pulmonary Responses Among Automobile Workings Exposed to Aerosols of Machining Fluids", *American J. of Industrial Medicine*, Vol.15, pp.627-641 (1989).

Kitagawa, T., Kubo, A. and Maekawa, K.," Temperature and Wear of Cutting Tools in High Speed Machining of Inconel 718 and Ti-6V-2Sn" , *Wear*, Vol. 202, pp.142-148 (1997).

Komanduri, R. and Desai, J., "Tool Materials", *Encyclopaedia of Chemical Technology, 3rd Ed., John Wiley & Sons, NY, 23*: pp.273-309 (1983).

Kosa, T. and Ney, R. P.,"Metals Handbook", Vol.16, ASM, pp.681-707 (1989).

Kurimoto, T and Barroe, G., "The Influence of Aqueous Fluids on the Wear Characteristics and Life of Carbide Cutting Tools", *Annals of CIRP*, Vol.31/1, pp.19-23 (1982).

Leith, D., Raynor, P.C., Boundy, M. G. and Cooper, S. J., "Performance of Industrial Equipment to Collect Coolant Mist", *AIHA J. No.*57, (1996). of AISI 4320 Steel, *Wear*, Vol. 116, pp.309-317 (1987).

Mazurkiewicz, M., Kubula, Z. and Chow, J., "Metal Machining with High-Pressure Water-Jet Cooling Assistance- A New Possibility", *J. Eng. Ind.*, Vol.111, pp.7-12 (1989).

Merchant, M. E., " The Physical Chemistry of Cutting Fluid Action", *Am. Chem. Soc. Div. Petrol Chem., Preprint 3, No. 4A*, pp.179-189 (1958),

Muraka, P. D., Barrow, G. and Hinduja, S., " Influence of the Process Variables on the Temperature Distribution in Orthogonal Machining using the Finite Element Method", *Int. J. Mach. Tool Des. Res.* Vol.21, pp.445 (1979).

Narutaki, N. and Yamane, Y., "Tool Wear and Cutting Temperatures of CBN Tools in Machining Hardened Steels", *Annals of CIRP*, Vol.28/1, pp.23-27 (1979).

Nedess, C. and Hintze, W., " Characteristics Parameters of Chip Control in Turning Operations with Indexable Three Dimensionally Shaped Chip Formers", *Annals of CIRP*, Vol.38/1, pp.75-79 (1989).

Paul, S., "Cryogenic Cooling in Grinding - A New Concept", *European J. of Mechanical and Environmental Engineering*, Vol.42, pp.131 (1997).

Paul, S. and Chattopadhyay, A. B., "The Effect of Cryogenic Cooling on Grinding Forces", *Int. J. of Machine Tool and Manufacture*, Vol.36(1), pp.63-72 (1996).

Paul, S. and Chattopadhyay, A. B., " Effects of Cryogenic Cooling by Liquid Nitrogen Jet on Forces, Temperature and Surface Residual Stresses in Grinding", *Cryogenics*, Vol.35, pp.515-523 (1995).

Paul, S., Banerjee, P. P., Das, S. and Chattopadhyay, A. B., " Effects of Cryogenic Cooling on Wheel Loading in Grinding Steels", *16th AIMTDR Conference, CMTI, Bangalore*, pp.478-484 (1994).

Paul, S., Banerjee, P. P. and Chattopadhyay, A. B., "Effects of Cryo-cooling in Grinding Steels", *J. of Mat. Processing Tech.*, Vol.37, pp.791-800 (1993).

Paul, S., Dhar, N. R. and Chattopadhyay, A. B., "Beneficial Effects of Cryogenic Cooling over Dry and Wet Machining on Tool Wear and Surface Finish in Turning AISI 1060 steel", *Proc. of ICAMT-2000, Malaysia*, pp.209-214 (2000).

Peter, C. R., Steven, C. and David, L.," Evaporation of Polydisperse Multi Component Oil Droplets", *American Industrial Hygiene Association*, (1996).

Raynor, P. C., Cooper, S. and Leith, D., "Evaporation of Polydisperse Multicomponent Oil Droplets", *AIHA J.* (57), (1996).

Reed, R. P. and Clark, A. F., "Materials at Low Temperatures", *American Society for Metals, Carnes Publication, Metal Park, OH.* (1983)

Satoshi, I., Teiji, Y., Shinichi, M. and Kazuo, M., "Machinability of Ni_3All Based Intermetallic Compounds", *J. of Material Processing Technology,* Vol.63, pp.181-186 (1997).

Schulz, H." High speed machining", Annals of CIRP 41 (2) (1992) 637-643.

Seah, K. H. W., Li, X. and Lee, K. S., " The Effect of Applying Coolant on Tool Wear in Metal Machining", *J. of Material Processing Technology*, Vol.48, pp.495-501 (1995).

Shaw, M. C., Pigott, J. D. and Richardson, L. P., "The Effect of Cutting Fluid upon Chip-Tool Interface Temperature", Trans. *of the ASME*, Vol.71, pp.45-56 (1951).

Singh, S. B., Chakraborty, A. K. and Chattopadhyay, A. B., "A Study of the Effects of Inclusion Contact on the Machinability and Wear Characteristics of 0.24% Carbon Steel", *Int. J. of Mat. Processing Tech.*, Vol.66, pp.90-96 (1997).

Solaja, V., "Wear of Carbide Tools and Surface Finish Generated in Finish-Turning of Steel", *Wear*, Vol. 2(1), pp.45 (1958).

Thony,C., Thony,J. Lafontaine,M. and Limasset, J.C., " Occurrence of Polycyclic Aromatic Hydrocarbons in Some Cutting Oils. Study of the Corresponding Risk ", Arch. Mal. Prof. Med. Trav. Sec. Soc., Paris 36, pp.37-52 (1975).

Thoors, H and Chandrasekaran, H., "Influence of the Cutting Medium on Tool Wear during Turning", *Swedish Institute for Metal Research*, Report No IM-3118, (1994).

Trent, E. M., "Metal Cutting", Butterworths, *London & Boston*, (1984).

Trent, E. M., "The Tribology of Metal Cutting, in Jones, M.H. and Scott, D. (Eds), Industrial Tribology, The Practical Aspect of Friction", *Lubrication and Wear, Elsevier, Amsterdam*, pp.446-470 (1983).

Uhera, K. and Kumagai, S.," Chip Formation, Surface Roughness, Cutting Forces and Tool Wear in Cryogenic Machining", *Annals of CIRP*, Vol.17 (1), (1968).

Uhera, K. and Kumagai, S., " Mechanisms of Tool Wear", *J. of Japanese Society of Precission Engg.*, Vol. 35 (9), pp.43-49 (1969).

Vleugels, J., "Machining of Steel with Sialon Ceramics: Influence of Ceramic and Workpiece Composition on Tool Wear", *Wear*, Vol.189, pp. 32-44 (1995).

Venkatesh, V.C., and Chandrshekran, C., "Experimental Methods in Metal Cutting," prentice Hall India.1982

Welter, E.S., "Manufacturing Exposure to Coolant-Lubricants", *J. of Occupied. Med.*, Vol.20, pp.535-538 (1978).

Wertheim, R., rotberg, J., "Influence of high pressure flushing through the rake face of the cutting tool", annu .CIRP41(1)(19992)101-106.

Wrethin, R., Rotberg, J. and Ber, A., " Influence of High Pressure Flushing, Through the Rake Face of Cutting Tool", *Annals of CIRP*, Vol.41/1, pp.101-106 (1992).

Yamaya, S. and Shibuki, K., "Study of Alumina Ceramic Tools", *Tungolay*, Vol.19(20)