INVESTIGATIONS ON SURFACE MILLING OF HARDENED STEEL WITH ROTARY LIQUID NITROGEN APPLICATOR

By

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A Thesis
Submitted to the
Department of Industrial & Production Engineering
in Partial Fulfilment of the
Requirements for the Degree
of
M.Sc. in Industrial and Production Engineering

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

December 2013

The thesis entitled as **Investigation on Surface Milling of Hardened Steel with Rotary Liquid Nitrogen Applicator** submitted by A. K. M. Khabirul Islam, Student No. 0411082003, Session- April 2011, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of M. Sc. in Industrial and Production Engineering on December 2013.

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A. K. M. Khabirul Islam

This work is dedicated to my
Loving Parents

Late Abdul Bari
and
Mrs JosnaraBegum

ACKNOWLEDGEMENT

I am very grateful to my respected supervisor, Dr. Nikhil Ranjan Dhar, Professor, Department of Industrial and Production Engineering, BUET for his profound knowledge, timely advice, constant support, able guidance, continuous inspiration, encouragement and valuable suggestions to complete this work successfully.

I would like to express my gratitude and thanks to the board of examiners Dr. Sultana Parveen, Professor, Department of Industrial & Production Engineering, BUET, Dr. A.K.M. Masud, Professor, Department of Industrial & Production Engineering, BUET and Md. Abdus Salam, Head, Department of Aeronautical Engineering, Military Institute of Science and Technology (MIST) for their valuable suggestions and guidance.

I acknowledge the help rendered by the Director, DAERS, BUET who provided machine shop facilities whenever required. The help extended by the Head, Department of Glass and Ceramic, BUET for obtaining the scanning electron micrographs (SEM) is also sincerely acknowledged. I would also like to thank Bangladesh Oxygen Limited for supporting the research work by supplying liquid nitrogen (LN2) along with LN2 Dewar.

My special thanks and appreciation to all my colleagues of the Department of Industrial and Production Engineering, for their help, encouragement and support at various occasions. A special word of thanks are due to all the staff members of Central Machine Shop and Machine Tools Lab who have helped a lot whenever required, especially Manik Chandra Roy, M. A. Razzak, S. C. Das and T. G. Gomes for their helps in conducting the experimental work. I am especially thankful to M. A. Karim of Central Machine Shop for his assistance throughout the experimentation.

My family has always been an important source of support. I devote my deepest gratitude to my parents for their love and support throughout my life. My sincere thanks to my wife Dr. Shagufa Umma Honey and my son Adrib Ahmed, for their love, affection, sacrifice, encouragement and support. Lastly, I offer my thanks to all of those who supported me in any respect during the research work.

ABSTRACT

Conventional cutting fluid, typically comprising one or more natural or synthetic oils, is used to improve the performance of the cutting tool by cooling the tool and the workpiece, lubricating the cutting surface of the tool and flushing waste particles away from the work area. However, the use and disposal of such cutting fluids raises serious environmental and health related concerns. In the present decade, with increased environmental awareness, the researchers are striving to develop environment friendly machining technology. Cryogenic cooling is a promising new technology in high production machining which economically addressed the current process environmental and health concern. The benefits of reduction in machining temperature are reduction in cutting force, tool wear and surface roughness. This benefit of cryogenic cooling depends on the process parameters and cutting tool.

In this research work surface milling of EN24 hardened steel (45 HRC) with cryogenic cooling condition has been investigated and its performance is evaluated on the basis of surface finish, flank wear and cutting force. An effort is made to investigate the effect of cutting parameters (cutting velocity, feed and depth of cut) and the cutting environment on cutting performance. The liquid nitrogen was delivered through a specially designed and developed rotary liquid nitrogen applicator designed based on full factorial analysis (design of experiment) in such a way so that it can deliver liquid nitrogen at critical zones during surface milling. An investigative comparison with dry and conventional wet milling under same conditions has been done to evaluate the relative performance of hard milling with liquid nitrogen application. It was observed that the rotary liquid nitrogen delivery system developed for surface milling on hardened steel can bring forth better performance when compared to dry and conventional wet milling.

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Chapter-1

Introduction

1.1 Introduction

Metal cutting is a process of material removal in which the loss of materials is caused by effecting a relative motion between tool and work piece .It involves complex thermo mechanical phenomena, such as high strain rate at the primary shear zone frictional contact interaction between the chip and tool at the secondary shear zone and elevated temperature in the chip induced by mechanical energy dissipation. Cutting performance can be improved enormously by controlling the chip tool interfacial temperature rise and frictional effects using a coolant/lubricant **[Kramar and Kopac 2009]**. Machining plays important role in producing product from different types of material ranging from soft to hard. Hard materials (45 HRC and harder) include tool steels, mold steels, chilled and chrome irons, weld overlays and some nickel and cobalt-base super alloys. Manufacturers use hard materials to extend wear life and maintain precision in molds, gears, tools and dies, aerospace components and processing equipment. Unfortunately, the characteristics that make hard-material parts perform so effectively also make the materials more difficult to machine. Bringing a hardened part to size traditionally has been slow and tool consuming. The traditional approach is to rough and semi finish parts before hardening via heat treatment if possible, then tediously finish them with round tools, inserts, grinding or EDM Machining. Parts that begin as hard materials or those where hardening would affect final precision, require slow processing right from the start.

Long cycle times, multiple operations and part setups and excessive work-in-process boost manufacturing costs. One way to reduce those costs is milling parts in the hardened state. The mold making industry has been a pioneer in hard milling, applying hard yet tough micro grain carbide cutting tools usually with coatings that increase heat resistance and boost lubricity, CBN, PCBN, Ceramic and diamond tools. Hard milling with carbide tools typically involves small DOCs, generating relatively low cutting forces and usually with coatings that increase heat resistance and boost lubricity a small chip. Typical cutting speeds are moderate to slow. Manufactured products qualities are determined by their surface quality. The high friction between tool and work piece leads to high temperatures, tool wear, and poor surface quality. In order to decrease the friction, cutting fluids are necessary to be applied during machining. However, the application of conventional cutting fluids becomes a source of environmental pollution and creates biological problems to the operators emerging trend of the modern metal cutting operations is to increase the material removal rate [**Reddy and Rao 2006**].Cutting fluids are referred to as coolants are also provide lubricity in order to remove friction and cooling during machining process for cutting, turning, grinding, milling, boring, drilling and other tasks [**Gauthier 2003)**]. Today‟s cutting fluids are special blends of chemical additives lubricants and water formulated to meet the performance demands of the metalworking industry. The main functions of cutting fluids are lubrication at low cutting speeds and cooling at high cutting speeds [**Shaw 2005**]. Cutting fluids help to flush away the swarf and fine metal particles, increase the tool life by reducing heat from the cutting zone, reduce the thermal distortion, reduce frictional heat, and reduce the tool wear [**Jayal and Balaji 2009**]. Though cutting fluids are useful in low cutting speed but at the high cutting speed conventional cutting fluids cannot penetrate into the tool-chip contact where the high temperature is generated. This can be explained that the flowing chip make bulk contact with the tool rake surface which restricts the penetration of conventional cutting fluid into the tool-chip interface. Moreover because of having high temperature conventional cutting fluids evaporates before reaching the cutting zone [**Kamruzzaman and Dhar 2009**]. The selection of cutting fluid for use should be based on- type of machining operation, material being machined, tool material, machining conditions, health, safety, cost. Several types of additives and chemical compounds are used with conventional cutting fluids to increase its cooling and lubrication properties. Chemical agents such as amines and nitrites are used for corrosion inhibitors, phosphates and borates for water softening, soaps and wetting agents for lubrication, phosphorus, chlorine and sulphur compounds for chemical lubrication. Bactericides are added to control the growth of micro-organisms such as bacteria, algae and fungi [**Baradie1996)**]. These chemical compounds and the additives which are used cause the techno-environmental problems [**Paul et al. 2001**] such as:

- Required extra floor space and additional systems for pumping, storage, filtration, recycling, chilling etc.
- Neat oils which are used cause skin disorder and cause irritation of the hair roots.
- Dermatitis are caused by bacteria and the biocides which are used to control the growth of bacteria
- Asthma, bronchitis, irritation of the respiratory tract, breathing difficulties, hypersensitivity pneumonitis and lung cancer are caused metalworking fluid mist and vapor
- Irritations of the respiratory tract or flu-like symptoms are caused by inhalation of bacteria and fungi.
- The use of unrefined mineral oils is responsible to skin cancer.
- Water pollution and soil contamination during disposal of cutting fluids

- ➢ Environmental problems are occurred during dissociation of chemical compounds at high cutting temperature

The effects of cutting fluid on mankind, working environment, the workpiece and machine tool as well as generally on living environment as a whole are usually expressed by their ecological parameters. Fig.1.1 depicts the characteristics of ecological factors of cutting fluids [**Sokovic and Mijanovic 2001**].

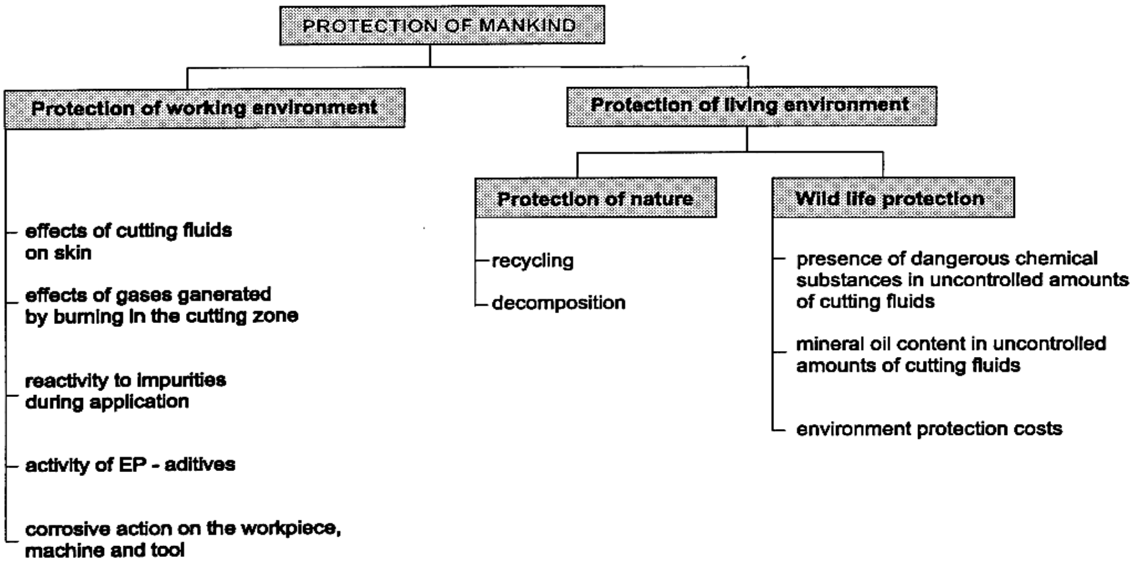


Fig.1.1 Characteristics of ecological factors of cutting fluids [**Sokovic and Mijanovic 2001**]

It is evident that cryogenic cooling is found to be more effective in wear resistance, able to enhance tool life, able to penetrate into tool-chip interface where the high temperature is generated thus reduces the cutting temperature effectively, able to reduce friction co-efficient, able to improve surface quality compare to other cooling approaches in high speed machining. Moreover liquid nitrogen based cryogenic cooling does not left any residues which may cause any hazardous environmental condition **[Dhār et al. 2002)].**

Success in metal cutting also depends on selection of the proper tool (material and geometry) for a given work material. A wide range of cutting tool material is available with a variety of properties, performance capabilities and cost. The tool materials are ranked by the maximum cutting speed needed to machine a volume of steel materials, assuming equal tool lives. Generally, flat end-mill cutting tools are able to perform cutting applications in various kinds of cutting conditions especially in the mold and die making. Each cutting tools are applied on different ways of cutting mechanism and provides its own ability based on the shape of the part required. Flat end-mill cutting tools normally have the capabilities to cut a huge volume of materials with longer cutting time and easy to reuse or regrind. However, these cutting tools have low wear resistance especially when machined in curve area and this causing the cutting edge risk with rapid wear damage .The used of various flat end-mill cutting tools generally divided into two processes, roughing and finishing. When a tool change is needed or anticipated, a performance comparison should be made before selecting the right tool for the job. The best tool is the one that has been carefully chosen to get the job done quickly, efficiently and economically **[Davies et al. 1996]**.

A brief review of some of the attractive and significant contributions in the closely related areas is presented in this section. This chapter also provides the background information relevant to this research. The ecological and economical dry machining and the problems of high temperature rises in dry machining, machining with conventional cutting fluids and the effects of cutting fluids on finish products and environment, other alternative lubrication system, minimum quantity lubricant (MQL) and the high-pressure coolant jet system and its positive effects on the finished products with researchers remarks are described thoroughly in this chapter. Cryogenic cooling machining particularly in milling has been discussed in the following chapter.

1.2 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 review of the literature connected with the work is presented in this section. The topics covered also highlight the latest developments in the areas related to the present work. The features of hard machining including cutting fluids in metal machining and machining with liquid nitrogen application are presented. The review also covers a brief account of design of experiments, parameters optimization techniques etc. A brief review of some of the interesting and important contributions in the closely related areas is presented in this section.

1.2.1. Hard Machining

Traditionally components that require high hardness as functional requirement are machined in the soft state, heat treated to the required hardness and then finish ground to the final dimensions. This long process cycle can be avoided if the components with the required hardness can be directly machined to the final dimensions. In the recent years, the concept of hard machining has gained considerable importance in metal cutting. Direct machining of hardened steel leads to reduction in machining time and very large quantities of cutting fluid. With the advent of new standards regarding the environment, health and safety, some of the ingredients in many cutting fluids used earlier were identified as problematic. During hard machining, operations such as rough machining and final grinding can be eliminated and raw material is supplied in the final hardened condition. The functional behavior of machined parts is influenced by fine finishing process, which represents the last step in the process chain [**Tonshoff et al.1993**]. The hard-materials group comprises hardened steels, high-speed steels, heat treatable steels, tool steels, bearing steels and chilled/white cast irons. These materials are in constant use by the automotive, die, mold and allied industries. The following are the benefits of hard machining [**Christer 2009**]:

- easy to adapt to complex part contours;
- quick change-overs between component types;
- several operations performed in one set-up;
- high metal removal rate;
- Elimination of cutting fluids in most cases.

The limitations and drawbacks of hard machining are as follows:

- The tooling cost per unit is significantly higher in hard machining compared to grinding.
- The hard dry machining requires rigid cutting systems and superior cutting tools like CBN or ceramic tools [**Klocke and Eisenblatter 1997**].The degree of machine rigidity dictates the degree of hard machining accuracy. As required part tolerances become tighter and surface finishes get finer, machine rigidity becomes more of an issue. Machining systems should integrate a number of features to increase rigidity and damping characteristics for hard-machining applications. These include machine bases with polymer composite reinforcement, direct-seating collected

spindles that locate the spindle bearing close to the workpiece, and hydrostatic ways. Maximizing system rigidity means minimizing all overhangs, tool extensions and part extensions as well as eliminating shims and spacers. The goal is to keep everything as close to the turret as possible.

- Surface finish of machined parts deteriorates with tool wear even within the limit of tool life.
- Hard machining also requires machine tools made up of materials with high internal damping capacity so that they can strongly reduce the negative effects of vibrations on the surface finish [**Rahman et al., 1997, Ohama1997, Fowler 1999**].

For hard machining in dry condition, ceramic and CBN tools are widely used. In this purpose, the cutting tool material and tool coatings play a key role. In the last few decades, research has led to the development of cutting tool materials with improved performances such as ultra-fine grain cemented carbides, cermets, ceramics, cubic boron nitrides and diamond in order to withstand the higher temperatures occurring during dry machining and to provide a longer tool life [**Weinert et al. 2004, Uhlmann and Brucher 2002, Noordin et al. 2001, Ueda et al. 1998, Klocke and Einesblatter 1997, Narutaki et al. 1997**]. HSS produced by powder metallurgy (HSS-PM) offers a higher content of alloy elements and a combination of unique properties: higher toughness, higher wear resistance, higher hardness and higher hot hardness. Sintered carbide tools, also known as hard metal tools or cemented carbide tools which are made by a mixture of tungsten carbide micro grains with cobalt at high temperature and pressure are used in hard machining. Hard metal tools are used as integral tools and inserts. Tungsten carbide is very stable regarding chemical and thermal aspects of machining and is very hard as well. Ceramics are very hard and can withstand more than 1500°C without chemical decomposition. These features recommend them to be used for the machining of metals at high cutting speeds and in dry machining conditions. Unfortunately they are fragile, and ceramics without any reinforcement can be used only for turning of continuous shapes. During milling operation, the continuous impact at each tooth leads to the risk of chipping and consequent tool failure.

Hard milling is an offshoot of high speed machining techniques. The essence of high speed machining is taking many light cuts at closely spaced stopovers, thus leaving minimal cusps between passes. The goal is to create an as-machined surface that drastically reduces the need for subsequent processing. For the cutting tool to achieve an effective chip load, feed rates and spindle speeds must be much higher than those normally applied in traditional machining. Hard milling takes the concept of high speed machining one step further. The combination of light cuts at high feed rates and spindle speeds makes it possible to remove steel in the hardened state efficiently when all of the proper conditions are met. Likewise, closely spaced stopovers with small-diameter, radiused tools leave a surface that approaches the fineness of one that has been stoned or polished by hand. The ability to hold extremely tight tolerances (±0.0004 inch or less) is an added benefit of hard milling that is valuable in mold machining. It allows mold contours to be machined without the excess stock normally left for hand spotting. Moreover, by machining to zero stock, mold geometry will perfectly match that of the CAD model. Likewise, this ability allows mating mold surfaces to be machined to a negative stock condition. The concept is to machine shutoff areas along the parting lines, usually on the cavity side, slightly but precisely below the nominal dimension. This leaves a small gap between the surfaces that would normally contact each other when the mold closes. Gap size is too small (0.0008 inch is typical) to allow plastic to flow out during the injection process, so the mold still shuts off effectively. Like any CNC machining process, hard milling depends on a capable machine tool, the appropriate cutting tool/tool holder system and an effective tool path program.

Hard Milling Solutions typically uses ball nose end mills for roughing, semi-finishing and finishing. Two-flute ball nose end mills are used exclusively for finishing, and these finishing cutters are the most critical elements in the hard-milling process. For finishing, the end mill must meet two essential requirements: it must have a near-perfect radius and have virtually unblemished cutting edges. Accuracy of the radius has to be extremely tight so that a high or low flute does not cause uneven metal removal, thus degrading geometry, surface quality and tool life. The end mills used in the shop for finishing are certified to a radius accuracy of at least ±5 μm.

The cutting edges of the flutes must have a minimum of microscopic chips, cracks or other irregularities. The presence of these defects means that the edges will be subject to accelerated wear mechanisms as soon as they contact the workpiece. This leads to a rougher surface finish and a shortened tool life. Tool life is an issue because the shop depends on its end mills to last as expected when running its machines unattended.

Strafford and Audy [**1997**] investigated the relationship between hardness and machining forces during turning of AISI 4340 steel with mixed alumina tools. The results suggest that an increase in hardness leads to an increase in the machining forces. [**Liu et al. 2002**] observed that the cutting temperature is optimum when the work piece material hardness is 50 HRC. With further increase in the work piece hardness, the cutting temperature shows a descending tendency. Liu et al. [**2002**] also suggests that, under different cutting parameters, the role of cutting force changes with work piece hardness. The main cutting force features an increasing tendency with the increase of the work piece hardness. Reed and Clark [**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.

1.2.2. Cutting Fluids in Metal Machining

In metal cutting processes, the basic purpose of employing cutting fluid is to improve machinability characteristics of any work-tool pair through improving tool life by cooling and lubrication, reducing cutting forces and specific energy consumption and improving surface integrity, size accuracy by cooling, lubricating and cleaning at the cutting zone. Cutting fluids also make chip-breaking and chip-transport easier. For reducing the cutting zone temperature through cooling and lubricating action a copious amount of fluid is flushed into the cutting zone to facilitate heat transfer from the cutting zone. Lubricants reduce friction and coolants effectively reduce high cutting temperature of tools/work pieces. It can flush chips away from the cutting zone, protect the machined surface from environmental corrosion and these factors improve tool life and help make a better more efficient cut [**Beaubien and Cattaneo 1964**]. On the other hand, using a cutting fluid may cause the material to become „curly‟, which concentrates the heat closer to the tip. This is detrimental because it decreases the tool‟s life. Some conditions like machining steels by carbide tools, the use of coolant may increase tool wear [**Paul et al. 2001**] though it can reduce temperature. In case of high speed-feed machining, which inherently generated high cutting zone temperature, cutting fluid can‟t reduce the temperature because fluid can‟t reach to the chip-tool interface [**Dhar et al. 2002**].The favorable roles of cutting fluid application depend not only on its proper selection based on the work and tool materials and the type of the machining process but also on its rate of flow, direction and location of application. Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained by such cutting fluid [**Satoshi et al. 1997**]. But surface finish did not improve significantly.

Cutting fluid applied during machining has a function as coolant and lubricant. Coolant is important to cool the heat generation zone in machining process; meanwhile lubricant is used to minimize the friction between the tool, chip, and workpiece interface. Methods of cutting fluid application include flood machining, near-dry machining and also cryogenic machining. Cryogenic acts more as coolant to reduce the temperature generated in machining process. Cryogenic coolant uses liquid gaseous such as liquid nitrogen (LN2) or liquid carbon dioxide (CO_2), which have very low melting temperature, to reduce the temperature at the cutting zone. Cryogenic machining is more advantageous compared to the usage of conventional cutting fluid in term of environmental friendly in such a way that the liquid gas used will evaporate into the air and become part of the atmosphere [**Nalbant and Yildiz, 2011**]. The evaporation of the gaseous also eliminates the cost of cutting fluid disposal [**Umbrello et al. 2012**].

Application of conventional cutting fluids creates several other techno-environmental problems. Additional cutting fluid systems are needed in industry to deliver fluid to the cutting process, re-circulate fluid, separate chips and collect fluid mist. Moreover, for using cutting fluid environment becomes polluted. Because, for improving the lubricating performance Sulfur(S), Phosphorus(P), Chlorine(Cl) or other pressure additives are mixed with cutting fluid [**Peter et al.1996**]. If the cutting fluids are not handled appropriately, it may damage soil and water resource, which can cause serious environment pollution. Additionally in the factory cutting fluid may cause skin and breathing problem of the operator [**Sokovic and Mijanovic 2001**].

Philip et al. [**2000**] investigated the influence of cutting fluid composition and delivery variables such as pressure at the fluid application, rate of application, frequency of pulsing, mode of application, and direction of application on performance in hard turning. They applied the cutting fluid at tool-chip inter face and tool-work interface. When the cutting fluid was applied at the tool-work interface at high velocity in the form of tiny droplets, they reached the root of the chip and had a chance to influence both the primary shear phenomenon as well as the secondary shear at the tool-chip interface. All these effects led to the reduction in cutting force. Apart from this, during application of cutting fluid at the tool work interface, there was also the possibility of some tiny fluid particles reaching the uncut work surface near the cutting edge. These particles, owing to their high velocity and smaller physical size penetrated and firmly adhered to the work surface resulting in the promotion of plastic flow on the back side of the chip due to rebinder effect. This relieved a part of the compressive stress and promoted chip curl that reduces tool-chip contact length. A comparative evaluation revealed a definite advantage for hard turning with pulsed jet application over dry turning and conventional wet turning.

Cutting fluid systems are used in industry to deliver fluid to the cutting process, re-circulate fluid, separate chips and collect fluid mist. In flood cooling method, fluid is used in very large amount (6-10 l/hr). The cost associated with the use of cutting fluid is estimated to be about 16% to 20% of the total manufacturing costs [**Byrne and Scholta 1993, Brockhoff and Walter 1998**], where only 4% of the total manufacturing cost is associated with cutting tools [**Aronson 1995**]. For instance in the production of camshafts in European automotive industry, the cost of coolants/lubricants constituted 16.9% of the total manufacturing cost, while the cost of tools was 7.5%. That is, the cost of purchase, storage, care and disposal of coolants are two times higher than the cost of tool. So, in respect of costs, it is very important to reduce the amount of cutting fluid. Some conditions like machining steels by carbide tools, the use of coolant may increase tool wear [**Paul et al. 2001**].

Furthermore, the permissible exposure level (PEL) for metal working fluid aerosol concentration is 5 mg/m^3 as per the U.S. Occupational safety and health administration [**Aronson 1995**] and is 0.5 mg/m^3 according to U.S. National Institute for Occupational Safety and Health [**Thornberg and Leith 2000**]. The oil mist level in U.S. automotive parts manufacturing facilities has been estimated to be generally on the order of 20-90 mg/m^3 with the use of traditional flood cooling and lubrication [**Bennett and Bennett 1985**]. This suggests an opportunity for improvement of several orders of magnitude.

So, from the viewpoint of cost, ecological and human health issues, manufacturing industries are now being forced to implement strategies to reduce the amount of cutting fluids used in their production lines [**Klocke 1997**]. New approaches for elimination of cutting fluids application in machining processes have been examined and “dry machining” was presented as an important solution [**Sreejith and Ngoi 2000, Popke et al. 1999**]. But sometimes dry machining cannot show better performance if higher machining efficiency, better surface finish and other special cutting conditions are required. For these reasons many special techniques can be used as alternative of the traditional flood cooling method. Such as, Mist lubrication system by water based fluids, Cryogenic Machining where nitrogen and carbon dioxide are used as a coolant, Near-dry cooling/ minimum quantity lubrication (MQL) system with the application of a mist of a mixture of water and cutting fluid, High-pressure coolant (HPC) system, Coolant through the cutting tool system which allows a direct route for the coolant to the hot area. All these methods are proved as good for tool life, good for the environment.

Rahman et al. [**2002**] investigated MQL technique on milling of ASSAB 718HH steel of 35 HRC with uncoated carbide inserts. The rate of flow of cutting fluid was 8.5 ml/h during MQL and 42,000 ml/min during flood application. The comparison of cutting performance indicated that MQL can definitely be regarded as a replacement for dry cutting and conventional flood cooling. They found that there was a considerable reduction in cutting force components for the MQL technique as compared to dry milling and milling with flood cooling. Fracture or chipping was not common for the MQL aided inserts and surface finish obtained during MQL application was comparable to that during milling with conventional flood cooling. Liao et al. [**2007**] investigated the mechanism of MQL in high speed milling of NAK80 die steel of 41 HRC and compared the results with dry milling. They found that the performance was enhanced under all cutting speeds. It was also found that the role of MQL during high speed milling of hardened steel could provide extra oxygen to chip–tool interface so as to promote the formation of a protective oxide layer in between the chip–tool interface. This layer was basically quaternary compound oxides of Fe, Mn, Si, and Al and was proved to act as a diffusion barrier. This lead to the retention of the strength and wear resistance of the cutting tool. Bruni et al. [**2008**] investigated the effect of MQL on surface roughness in finish face milling of AISI 420 B stainless steel. Different cutting speeds and lubrication cooling conditions (dry, wet and MQL) were considered and it was found that the cutting performance was the best during MQL. Thepsonthi et al. [**2009**] explored the performance of minimal-cutting-fluid application in pulsed-jet form in the high-speed end milling of hardened steel using coated carbide ball end mill. The workpiece material was ASSAB DF3 hardened tool steel of hardness 51HRC. The results clearly indicated the advantages of using pulsed-jet application over flood application and dry cutting. Cutting forces, surface finish, tool wear, and cutting temperature were affected beneficially when using the pulsed-jet method. It is proposed to investigate the viability of the fluid application system along with the proprietary cutting fluid developed by Varadarajan et al. [**2002**] for surface milling of hardened AISI4340 steel in the present investigation. Lopez et al. [**2006**] investigated the influence of the position of the injection nozzle in relation to the feed direction during high speed milling of wrought aluminum alloy with minimal quantity lubrication technique. Results indicated that the nozzle position in relation to feed direction is very important in order to obtain the optimum effect of the MQL technique.

Dhar and Kamruzzaman [**2009**] conducted an experiment by turning 17CrNiMo$_6$ and 42CrMo$_4$ under dry and high pressure cooling conditions. It was reported that high pressure cooling enable to reduce cutting temperature up to 25% depending upon process parameters. High pressure coolant reduced friction, built-up-edge formation, thermal distortion of the tool and work. It was observed that high pressure coolant reduced the flank wear, thus the tool life was improved. Better surface finish was obtained under high pressure cooling condition due to reduction of wear and damage at the tool tip. Kovacevic et al. [**1995**] investigated the effect of high pressure coolant/lubricant in improving the thermal/ frictional conditions in milling operations. A high pressure water jet was used during the investigation. Application of cutting fluid at high pressure enhanced the effectiveness of cutting performance and led to the reduction in the quantity of cutting fluid and reduction in the amount of disposal which is a primary concern of Environmental Protection Authorities. From this investigation, it was also evident that applying cutting fluid in the form of a jet at higher pressures into the cutting zone is more beneficial than conventional fluid application techniques such as flood cooling. If the coolant is applied at the cutting zone through a high speed nozzle, it could reduce the contact length and co-efficient of friction at chip-tool interface then cutting force and temperature may be reduced and tool life can be increased [**Mazurkiewicz et al. 1998**, **Kumar et al. 2002**].

High-pressure is often the solution to get the coolant to the target so it can cool, lubricate, and sometimes perform its third function-breaking chips that do not break neatly with ordinary machining processes [**Lacalle et al. 2000**]. 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 high-pressure coolant (HPC) machining process as one of the viable alternative instead of using conventional cutting fluids.

Lathkar and Basu [**2001**] investigated the effect of application of graphite based grease on cutting performance during turning of medium alloy steels with minimum quantity lubrication using tungsten carbide tools and compared the results with dry turning. Results indicated that there was improvement in cutting performance in the form of reduction in tool wear and improvement in surface finish. Deshmukh and Basu [**2006**] investigated the influence of solid lubricants like MoS_2, MoS_2-based grease, graphite based grease and silicon compound mixed with SAE 20 oil and found that the application of such semisolid lubricant improved the cutting performance. On a similar line in the present investigation, it is planned to explore whether silicon grease can act as a cutting performance enhancer during surface milling of hardened AISI4340 steel with minimal fluid application using a high velocity narrow pulsed jet of cutting fluid.

1.2.3. Machining with Liquid Nitrogen Application

Cryogenic machining, by liquid nitrogen (LN2) is used as a coolant, is considered a viable option. Having a temperature as low as -196 °C at 101.325 KPa, super cold LN2 is a good coolant. After absorbing the heat dissipated from the cutting process, it evaporates into nitrogen gas and becomes part of the air (79% of the air is nitrogen). It leaves no harmful residue to the environment. Therefore, it is considered to be environment friendly due to this natural recycling [**Khan and Ahmed 2008**]. Cryogenic fluids with very low temperatures have been considered an interesting alternative of conventional cutting fluid since they present great heat removal capacity. Cryogenic expresses the study and utilization of materials at very low temperatures (below -150°C). Gases like, nitrogen, helium and hydrogen, when in liquid state, have temperatures below - 180°C. Yildz [**2008**] indicate that liquid nitrogen has been explored as a cryogenic coolant since the 1950s. In 1965, the Grumman Aircraft Engineering Corporation reported safe and successful tool life increases using LN2 as a coolant in HSS turning and milling tools. However, great expenses and operational costs involved with subzero gas production delayed the development and growth of this technology until the economical cryogenic approach developed by Hong et al. [**1999**]. This approach suggests the utilization of small amounts of liquid nitrogen only at the region closest to the cutting edge. The most studied method for liquid nitrogen use is through jet of nitrogen applied externally to the tool, at the cutting zone, as can be seen in the experiments carried out by Paul et al. [**2001, 2006**] and Hong et al. [**2001**]. There is also the use of liquid nitrogen spray utilized in the works by Kumar and Choudhury [**2006**]. Finally, the workpiece surface and chip cooling method also was proposed by Bhattacharya et al. [**1993**] Hong et al. [**1999**] and Hong and Ding [**2001**]. Irrespective of the method used in all these works, the results found by the authors indicated increase of tool life and improvement in machined surface roughness divides cryogenic cooling methods in groups, according to the researcher‟s application[**Yildiz 2008**], as follows: (i) cryogenic pre-cooling workpiece by enclosed bath or general flooding, (ii) indirect cryogenic cooling or cryogenic tool back cooling or conductive remote cooling, (iii) cryogenic spraying or jet cooling, with flood or directed approach. Wang and Rajurkar [**2000**] proposed a successful method for cryogenic cooling when machining difficult-to-machine materials like PCBN, Ti alloys, Inconel and Titanium alloys. In this method, a cap coupled over the cemented carbide insert creates a chamber were liquid nitrogen circulates, through an inlet and an outlet tube, so that there is a large contact area with the insert, consequently removing more heat from the tool. Results showed a considerable increase in tool life compared with dry machining. It was also reported that this system offers a stronger and more stable cooling than using liquid nitrogen sprays, without negative effects on workpiece dimensions. Khan and Ahmed [**2008**] presented a study about AISI 304 stainless steel machining with a TiCN coated carbide tool, using liquid nitrogen applied externally and in a small volume on the region of contact between the workpiece and the tool tip. The liquid nitrogen goes through inside the tool holder to a chamber just beneath of the insert and then by a narrow channel pointed at the work piece tool and the tool life increased by five times [**Seker et al. 2003**].

In cryogenic machining, different cooling strategies are needed in order to solve the problems specific to the individual materials being machined. Cooling strategies means the ways in which the cryogenic coolant is used in the cryogenic machining. Cryogenic machining with liquid nitrogen has improved machinability of steel to a certain extent in case of turning, grinding, milling, drilling operations. In high production machining, where conventional cutting fluids are ineffective in controlling the high cutting temperature, force, tool wear, dimensional accuracy and surface finish; cryogenic machining where the cutting tool is chilled by liquid nitrogen jets enhances tool hardness shows better effectiveness [**Paul and Chattopadhyay 1995**]. Favorable chip-tool and work-tool interactions can be achieved by this technique. Cooling the chip makes it brittle and aids metal removal. Moreover, by cryogenic cooling environmental pollution is reduced and it also helps in getting rid of recycling and disposal of conventional fluids [**Paul et al. 2000, Paul et al. 2001, Dhar et al. 2002, Dhar and Kamruzzaman 2007**].

Cryogenic slot milling has been conducted by Ravi and Kumar [**2011]** on hardened steel, Hardened AISI H13 tool steel with TiAlN PVD coated carbide where cutting temperature, flank wear, surface roughness, cutting force were investigated. Nalbant and Yildiz [**2011**] carry out an experiment on cryogenic milling on AISI 304 stainless steel with uncoated cementite carbide cutting tool and cutting force, tool wear, and microstructure were investigated. Kakinuma et al. [**2012**] carried out cryogenic micro-milling on PDMS polymer using tungsten carbide as a cutting tool and surface finish, chip formation, surface roughness, cutting energy were investigated

Muammer and Yakup [**2011**] investigated the effects of cryogenic cooling on cutting forces in the milling process of AISI 304 stainless steel. LN2 sprayed to tool, chips and material interfaces using a pipe with an internal diameter of 1 mm; the flow rate of liquid nitrogen was 5.2 l/min; two cutting directions (climbing and conventional milling), two machining conditions (dry and cryogenic cooling) and four cutting speeds (80, 120, 160 and 200 m/min) were used in the milling process. Cryogenic cooling and cutting speed are found to be effective on cutting forces. Cutting forces and torque in cryogenic milling are higher than those in dry milling. Cutting force is increased as the cutting speed is increased. Tool fritter around insert nose radius is the main problem of climb milling method in cryogenic cooling at low cutting speeds.

Su Y. et al. [**2006**] performed a milling operation with Ti-6Al-4V as workpiece and coated carbide tool as cutting tool under five different machining environments such as dry, flood cooling, nitrogen-oil-mist, compressed cold nitrogen gas, compressed cold nitrogen gas and oil mist. It was observed that under all machining environments, diffusion wear and thermal fatigue wears were the predominant wear mechanism for coated carbide tool. Better tool life was found under compressed cold nitrogen gas and oil mist cooling. It was observed that the tool life obtained under mist cooling conditions was 2.69 times that obtained under dry cutting and 1.93 times that obtained under nitrogen-oil-mist.

Vleugels [**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.

The amount of energy dissipated through the rake face of the tool raises the temperature at the flanks of the tool [**Wu and Matsumoto 1990**]. The cutting temperature and force are tried to be controlled or reduced to some extent by

- appropriate selection of process parameters
- appropriate selection of cutting tool geometry
- proper selection of cutting tools and
- proper selection and application of cutting fluids

Khan et al. [**2010**] carried out turning operation of AISI 304 stainless steel with coated carbide tool under cryogenic machining and reported that liquid nitrogen cooling system enhanced tool life more than four times for the application of coolant from the bottom through the gap between the tool flank and the workpiece. They also mentioned that job surface roughness was much higher during dry machining compared to cryogenic cooling. Seong-chan [**2005**] conducted an experiment to show the effect of liquid nitrogen on the tool-chip interface. It was found that friction coefficient in cryogenic machining can generally be reduced. They showed that friction coefficient can be reduced to about 0.35 for AISI 1018 steel and 0.27 for Ti-6Al-4V with two nozzles on i.e. the application of the liquid nitrogen to the tool flank together with shooting a liquid nitrogen jet to the tool rake.

Better quality workpiece finish was found in cryogenic machining than conventional machining.

Hong et al. [**2001**] carried out an experiment of Titanium alloy Ti-6Al-4V with conventional cooling and various cryogenic cooling approaches. They mentioned that a significant improved tool life was found with optimized chip breaker position and two nozzles on i.e. the application of one nozzle to flood the liquid nitrogen to the general cutting area and one additional nozzle to cool the flank surface. Rajadurai et al. [**2009**] conducted an experimental investigation of cryogenic cooling approach in orthogonal machining of material AISI 1045 steel and Aluminum 6061-T6 alloy. It was shown that cryogenic cooling reduced cutting temperature about 19-40% depending upon the level of process parameters and work material than dry machining. Cutting force increased to a maximum of 15% for AISI 1045 steel and 10% for Aluminum 6061-T6 alloy, chip thickness reduced up to 25% and shear angle increased up to 30% over dry machining.

Sreejith and Ngoi [**2000**] suggest some methods of indirect contact of coolant with the cutting zone as an alternative to dry machining. For such, some techniques should be used such as (i) use of an internal cooling system, where the coolant flows through channels under the insert, without direct contact with the cutting zone, (ii) internal cooling with an evaporation system, where a volatile liquid is introduced into the tool holder and evaporates in contact with the inferior surface of the insert, (iii) cryogenic system, where a cryogenic fluid is conducted through a channel inside the tool and (iv) thermoelectric cooling system, using a device with pairs of thermoelectric materials. When an electric current passes through these materials, one cold and one hot joint are produced in the opposite terminals of each element.

LN2 lubrication capacity by low temperature effect depends on material pairs. It can enhance the lubrication effect or aggravate it. LN2 lubrication by generating a hydrodynamic film yields very low friction coefficients. This hydrodynamic film generates the same lubrication effect regardless of material pair. Coating layer on the tool insert is effective in reducing friction under dry conditions, but it may cause adverse lubrication effects at low temperatures. LN2 cooling provides effective lubrication with uncoated inserts. Maximized LN2 cooling may not have advantages in enhancing the lubrication effect [**Kremer and Mansori 2011**].

Lopez et al. [**2006**] investigated the influence of the position of the injection nozzle in relation to the feed direction during high speed milling of wrought aluminium alloy with minimal quantity lubrication technique. Results indicated that the nozzle position in relation to feed direction is very important in order to obtain the optimum effect of the MQL technique.

1.3 Summary of the Review

A review of the literature on machinability of different 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 cutting forces, tool wear and surface roughness. 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 surface integrity of the workpiece also deteriorates due to high temperature. The conventional cutting fluids are not that effective in high speed machining particularly in continuous cutting of materials likes steels. Further the conventional cutting fluids are not environment friendly. The disposal of the cutting fluids often leads to local water pollution and soil contamination. Recycling and reuse of conventional cutting fluids are further problems.

Cryogenic cooling is a promising new technology in high production machining and grinding, 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^{o} 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.

1.4 Objectives of the Present Work

The objectives of the present investigation are:

(a) Experimental investigation on the roles of cryogenic cooling by liquid nitrogen in respects of
  i) Cutting force
  ii) Flank wear and
  iii) Surface roughness

in surface milling of hardened steel with hardness of 45 HRC using HSS tools at different speeds, feeds and depth of cut combinations.

(b) The scope of the present work are design, development and fabrication of
  i) a suitable rotary liquid nitrogen applicator that can deliver liquid nitrogen at critical zones during surface milling
  ii) a cryogenic machining setup

1.5 Scope of the Thesis

The cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy, can be controlled by the application of Conventional cooling precision cutting tools during dry machining or by application of LN2 as coolant. The growing demands for high MRR, precision and effective machining of exotic materials is restrained mainly by the high cutting temperature. Keeping that in view, the present research work has been taken up to explore the role of Cryogenic coolant on the major machinability characteristics in machining (surface milling) hardened steels by HSS end mill cutter under different machining conditions as well as to predict tool wear, surface roughness and cutting force in machining when machining under different cooling and lubrication environmental condition.

Chapter 1 presents the survey of previous work regarding general requirements in machining industries, technological-economical-environmental problems associated with the conventional cooling practices as well as dry machining practice and expected role of LN2 on machining hardened steel. It presents specific objectives of this thesis work and also outlines the methods which have been followed to draw effective results that commensurate with the goals of the thesis.

Chapter 2 presents the design the rotary liquid nitrogen applicator for delivering LN2 from the Dewar to the effective cutting zone. Commonly used DOE methods, steps to follow DOE method and Full factorial analysis, one of the powerful and popular DOE methods has been adopted to optimize the important parameters of the Applicator are described in this chapter. Before finalizing the design solid works drawings are created for making every components of the applicator.

Chapter 3 presents the material preparation steps and detail processes involved for bulk hardening of the sample workpiece for the experimental investigations. Liquid nitrogen delivery from the dewar to the cutting zone through the applicator are described in length. Complete experimental set up with experimental conditions are briefly describe in this chapter. Finally the experimental results in terms of surface roughness, cutting forces and tool wear are represented by different graphs. Machine responses under different environmental conditions are graphically presented to observe the behavior of the workpiece, cutting tool on different environment. Effects of LN2, relative to dry and conventional cooling on surface roughness, tool wear and cutting forces in milling hardened steel of hardness about 45 HRC by HSS end mill cutter under different cutting conditions are also discussed.

Chapter 4 contains the detailed discussions on the experimental results, possible interpretations on the results obtained.

Finally, a summary of major contributions and recommendation for the future work is given in **Chapter 5** and references are provided at the end.

Chapter-2

Design of Rotary Applicator

2.1 Introduction

Experimental design is a critically important tool in engineering for continuous improvement of the performance of manufacturing process. It is essentially a strategy of planning, designing, conducting and analyzing experiments so that valid and reliable conclusions can be drawn in the most effective manner. Statistical experiments are generally carried out to explore, estimate or confirm [**Antony 2003**]. Experimental design has proved to be very effective for improving the process performance and process capability. Experimental procedures require a structured approach to achieve the most reliable results with minimal wastage of time and money. Experimental design, based on sound statistical principles, can be used to give an overall view of a manufacturing process using a limited number of experiments. The information gained can be used to optimize a process and define which parameters need to be placed under the most influencing in order to maintain the repeatability of a process. The traditional approach of experimental design is empirical in nature. In this approach one factor is varied at a time keeping all other variables in the experiment fixed. This approach depends upon guesswork, luck, experience and intuition for its success. Moreover, this type of experimentation requires large resources to obtain a limited amount of information about the process. One variable-at-a-time experiments often are unreliable, inefficient, time consuming and may yield false optimum condition for the process. Statistical thinking and statistical methods play an important role in planning, conducting, analyzing and interpreting data from engineering experiments. When several variables influence a certain characteristic of a product, the best strategy is then the statistical design of experiment (DOE) which can give valid, reliable and sound conclusions that can be drawn effectively, efficiently and economically [**Antony 2003**].

The first principle of an experimental design is randomization, which is a random process of assigning treatments to the experimental units. The random process implies that every possible allotment of treatments has the same probability. An experimental unit is the smallest division of the experimental material and a treatment means an experimental condition whose effect is to be measured and compared. The purpose of randomization is to remove bias and other sources of extraneous variation which are not controllable. Another advantage of randomization is that it forms the basis of any valid statistical test. Hence the treatments must be assigned at random to the experimental units. Randomization is usually done by drawing numbered cards from a well-shuffled pack of cards or by drawing numbered balls from a well-shaken container or by using tables of random numbers.

The next principle of an experimental design is replication; which is a repetition of the basic experiment. In other words, it is a complete run for all the treatments to be tested in the experiment. In all experiments, some variations are introduced. This type of variations can be removed by replication. The experiments are to be performed more than once. An individual repetition is called a replicate. The number of replicates depends upon the nature of the experimental material.

It has been observed that all extraneous sources of variation are not removed by randomization and replication. This necessitates a refinement in the experimental technique. In other words, a design is to be selected in such a manner that all extraneous sources of variation are brought under control. For this purpose, one has to make use of local control, a term referring to the amount of balancing, blocking and grouping of the experimental units. Balancing means that the treatments should be assigned to the experimental units in such a way that the result is a balanced arrangement of the treatments. Blocking means that similar experimental units should be collected together to form a relatively homogeneous group. Blocking reduces known but irrelevant sources of variation between units and thus allows greater precision in the estimation of the source of variation under study. The main purpose of the principle of local control is to increase the efficiency of an experimental design by decreasing the experimental error. Control in experimental design is used to find out the effectiveness of other treatments through comparison.

Orthogonality concerns the forms of comparison (contrasts) that can be legitimately and efficiently carried out. Contrasts that can be represented by vectors and sets of orthogonal contrasts are uncorrelated and independently distributed if the data are normal. Because of this independence, each orthogonal treatment provides different information to the others.

In many fields of study it is hard to reproduce measured results exactly. Comparisons between treatments are much more reproducible and are usually preferable. Often one compares against a standard or traditional treatment that acts as baseline. The following steps are involved in the design of experiment:

- Defining the objective of the experiment
- Selection of the response or output
- Selection of the process variables or design parameters (control factors)

- Determination of factor levels and range of factor settings
- Choice of appropriate experimental design
- Experimental planning
- Experimental execution
- Experimental data analysis and interpretation

2.2 Design of Experiment (DOE)

There are many methods of design of experiment (DOE) like Multi-vari chart, Variable search, Full factorials, Taguchi methods etc. Out of several methods of DOE, Full factorial analysis is a power full and popular homing in technique and hence frequently used DOE method. Fig.2.1 shows the commonly used DOE method. Almost all the methods follow some basic methodologies which are appended below:

- Identify the important variables or parameters that effect quality through extensive brainstorming with different expert opinion/participation
- Separates those variables into different categories, generally not more than 4 important and most severe variables which are known as Red X (most serious variable that effects quality) and pink X (Moderately serious which has moderate impact on quality)
- Reduce variations of Red X and pink X through redesign and process improvement
- Other than Red X and Pink X there may be lot many variable that do not effects quality should not take into consideration for controlling for minimizing the cost.

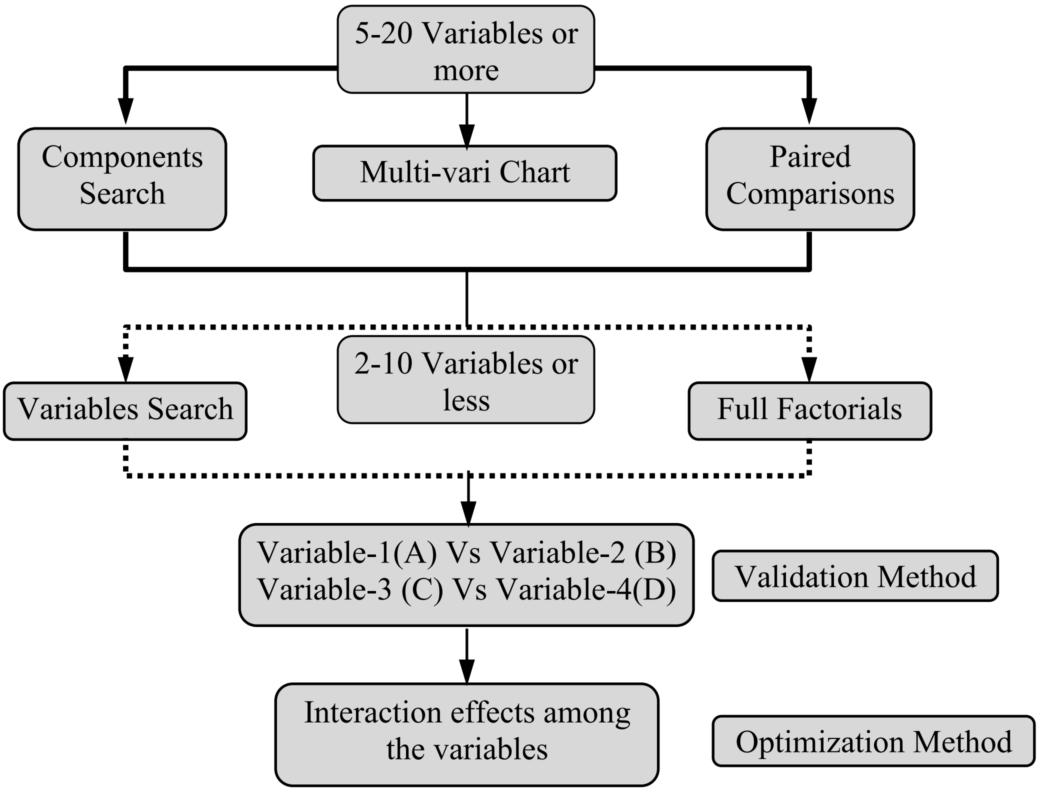


Fig.2.1 Commonly used DOE method

2.3 Full Factorial Analysis for Rotary Applicator

In full factorial analysis in investigation involving 4 variables and two levels of each factor is called 2^4 factorial analysis which involve 16 groups of test or combinations. Normally not more than 4 factors/variables at a time are taken to segregate Red X and Pink X from the all rest of the variables. Full factorial DOE method is one of the power full and popular tools for identifications of the most severe variables which may cause or affect the performance of the product. Basic principle of the analysis is that every variable can be tested with all levels (generally two) of every other variable. Experimental testing of all possible combinations of pre-selected variables and levels allows for the systematic separation and quantification of all main and interaction effects, thereby giving the chance of narrowing down the number of variables to one or two which are comparatively more severe. The complete full factorial analysis involves two main steps such as preparation of combinatorial matrix which identifies the impact of all individual variables having two levels for each variables and preparation of ANOVA table to identify main effect and interaction effect and possibly Red X and Pink X variables. The rotary liquid nitrogen applicator is design based on full factorial analysis

First of all visualize the components of the applicator and identify the variables that affect the performance of the applicator functionality. Identify also the response variable i.e. independent variable and dependent variable and some other factors which are not that important but have some impact on the overall performance after interacting with each other‟s. These variables are:

(i) Volume and weight of the applicator
(ii) Adapter material and size (length and diameter)
(iii) Container size (length and diameter), material and sealing
(iv) Material and size of the connector
(v) Bearing for the applicator
(vi) Milling cutter type and material
(vii) Internal hole of the milling cutter (diameter)
(viii) Pressure and flow of the liquid nitrogen
(ix) Process parameters (cutting velocity, table feed and depth of cut)
(x) Machining responses (surface roughness, cutting force and flank wear)

After several brain storming session with concern technical staff and all levels of experts, it has been provisionally identified that out of the above mentioned variables, depending on the severity following 4 variables as shown in Table 2.1. Table 2.1 are seems to be vulnerable for the optimized performance of the applicator.

Table 2.1 Most severe variables that effects performance of the applicator

Symbol	Factors or variables	Level (- or +)	
		Present Value (-)	Experimental(+)
A	Internal hole of the cutter	2 mm	4 mm
B	Volume of the container	50 cc	80 cc
C	Weight of the applicator	1000 gm	800 gm
D	Pressure of the liquid nitrogen	10 bar	15 bar

Several experiments with the above 4variables each with 2 levels are performed and roughness is recorded. Though, a 2^4 factorial analysis involve 16 groups of test or combinations supposed to conduct but due the time and resources constrained only few tests have been carried out as shown in Table 2.2.

Table 2.2 Combinatorial matrix for 4 variables

Factor C and D			Factor A and B				Total
			A-		A+		
			B-	B+	B-	B+	
	C-	D-	01 4 3.0 2	07 8 7.5 7	09 8 6.0 4	12 2 2.5 3	18.5
		D+	10 5 4.0 3	16 5 6.0 7	11 7 6.5 6	06 5 5.5 6	22.0
	C+	D-	05 2 3.0 4	03 4 5.0 6	13 7 6.5 6	02 4 4.5 5	19.0
		D+	04 4 4.0 4	08 3 3.5 4	15 5 6.0 7	14 8 7.5 7	21.0
	Total		14.0	22.0	25.0	20.0	

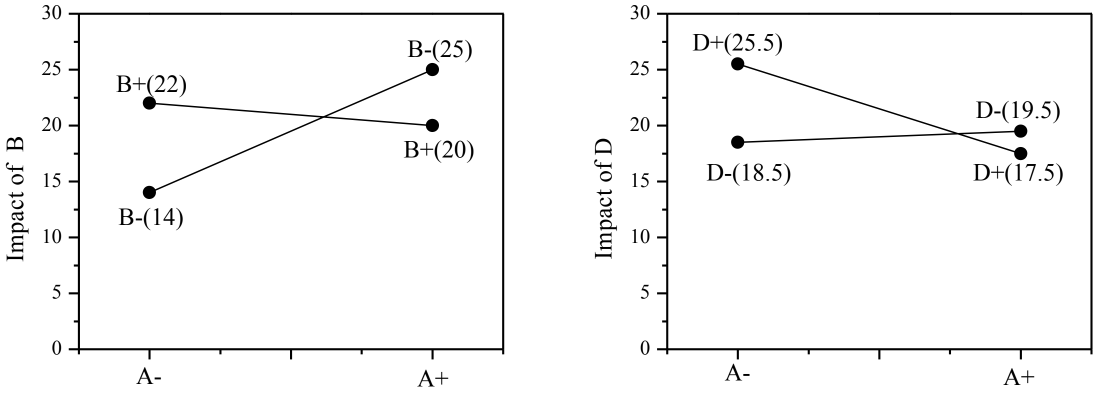
Table 2.3 Contribution of individual fact

Factors	**Total score/roughness**	**Difference**
A-	14+22=36	A+ is worse than A- by 9
A+	25+20=45	
B-	25+14=39	B+ is worse than B- by 3
B+	20+22=42	
C-	18.5+22=40.5	C- is worse than C+ by 0.5
C+	21+19=40	
D-	18.5+19=37.5	D+ is worse than D - by 5.5
D+	21+22=43	

Table 2.3 shows that contributions of individual factor are not significant though factor A has considerable importance. 2 factor interactions are responsible for the roughness. More specifically if 2 factors are selected for elimination in the 1st attempt, the right choice are AB interaction, AD, AC and ABC interaction. Thus AB interaction can be considered the Red X, while AC, AD and ABC considered as Pink X as shown in Table 2.4. Fig.2.2 shows the interaction effects among the various factors (A, B and D).

Table 2.4 Full factorial ANOVA table for rotary liquid nitrogen applicator

Cell No.	Factors				2 Factor interaction						3 Factors interaction				4 Factors interaction	Output
	A	B	C	D	AB	AC	BC	AD	BD	CD	ABC	ABD	ACD	BCD	ABCD	
1	-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	
2	+	-	-	-	-	-	+	-	+	+	+	+	+	-	-	
3	-	+	-	-	-	+	-	+	-	+	+	+	-	+	-	
4	+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	
5	-	-	+	-	+	-	-	+	+	-	+	-	+	+	-	
6	+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	
7	-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	
8	+	+	+	-	+	+	+	-	-	-	+	-	-	-	-	
9	-	-	-	+	+	+	+	-	-	-	-	+	+	+	-	
10	+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	
11	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	
12	+	+	-	+	+	-	-	+	+	-	-	+	-	-	-	
13	-	-	+	+	+	-	-	-	-	+	+	+	-	-	+	
14	+	-	+	+	-	+	-	+	-	+	-	-	+	-	-	
15	-	+	+	+	-	-	+	-	+	+	-	-	-	+	-	
16	+	+	+	+		+	+	+	+	+	+	+	+	+	+	
Interaction effect	+9	+3	-.5	+5.5	+13 Red X	+9 Pink X	-3	+9 Pink X	+1	-2.5	+9 Pink X	+6	-7.5	-5.5	-5	



(a) (b)

Fig.2.2 Graphs(a) and (b) shows the interaction effects among A & B and A & D

From Fig.2.2, it is clear that convergence of 2 lines in both graphs show that they have very high level of interaction effects thus needs to be eliminated on priority basis. Additionally the AB interaction effect is less, when both A and B are minus. Thus in order to eliminate the interaction effects between A and B, it would be suggested that setting both at minus condition i.e. internal hole 2 mm and volume of the container 50 cc, similar condition are applied for A and D interaction and value should be set at D+, that is pressure of the liquid nitrogen should be 15 bar. Same conclusion can be drawn for AC and ABC interaction effects also and the weight of the applicator can be taken as the experimental value which is 800 gm.

2.4 Fabrication of Rotary Liquid Nitrogen Applicator

Based on outcome of full factorial analysis, parameters of the rotary liquid nitrogen applicator are finalized as shown in Table 2.5 and the components of the applicator are describe below.

Table 2.5 Selected parameters for final design of liquid nitrogen applicator

Symbol	**Factors or variables**	**Present Value (-)**	**Experimental (+)**	**Selected parameters for final design**
A	Internal hole of the Cutter	2 mm	4 mm	2 mm
B	Volume of the container	50 cc	80 cc	50 cc
C	Weight of the applicator	1000 gm	800 gm	800 gm
D	Liquid nitrogen pressure	10 bar	15 bar	15 bar

Adapter is the main part of the applicator, which is made in such a way that it holds the liquid nitrogen container, bearing, seals, upper portion of the adapter is rigidly tighten with the vertical milling machine‟s spindle through a collet and jam nut. A small hole is provided as a passage of liquid nitrogen such a way that liquid nitrogen will flow from the dewar to the nitrogen container and flows through the hole of adapter and finally through the internal hole of the end mill cutter transfer to the cutting zone of tool work piece interface. It transfer spindle power to the cutter, housing for collet and external thread on it to hold tightly the cutter with jam nut to carry out machining. Fig.2.3 shows the photographic view of the adapter.

Liquid nitrogen container with connector is a small stationary cylindrical shaped, small through hollow container with connector fitted to contain small amount of liquid nitrogen for continuously supplying to the tool work piece interface through the adapter and cutter internal hole. Container is held stationary on the adapter using a bearing in such a way that though adapter rotate as per spindle rotation but container remain standstill always. A small hole on the radial direction of the container allow to fix a connector that is connected with the liquid nitrogen delivery set up with a high pressure special hose pipe

(Fig.2.4). A double jet bearing is used to fixed liquid nitrogen container with the adapter and teflon seals are used to protect the leakage of liquid nitrogen in the system starting from the connector to the tool (Fig.2.5).

Fig.2.3 Photographic view of adapter for rotary liquid nitrogen applicator

Fig.2.4 Photographic view of liquid nitrogen container for rotary liquid nitrogen applicator

A special nut has been designed and fabricated as per the collet tapper and holding the cutter through collet with the adapter. It should sustain proper tightening torque to fix tightly with the adapter. A high speed steel (HSS) milling cutter will be modified by making internal small hole (Ø2 mm) with the help of electrical discharge machining (EDM) for applying liquid nitrogen directly at the cutting zone (Fig.2.6). The sectional view and complete view of the rotary applicator is shown in Fig.2.7 and Fig.2.8 respectively.

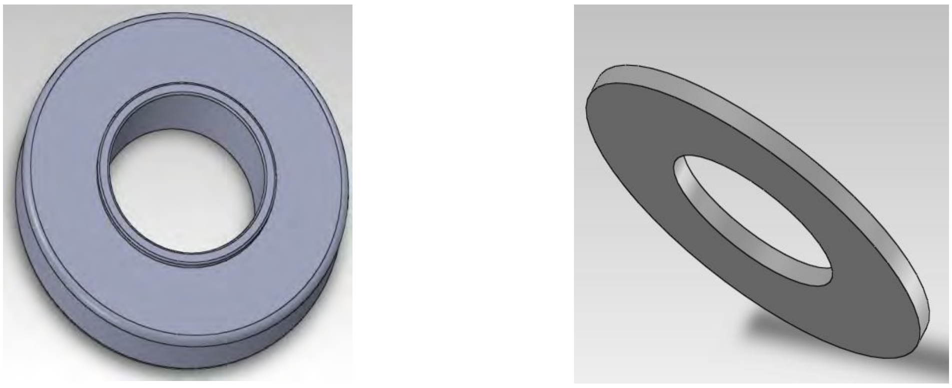


Fig.2.5 Photographic view of double jet bearing and teflon seal

Fig.2.6 Photographic view of milling cutter with internal hole

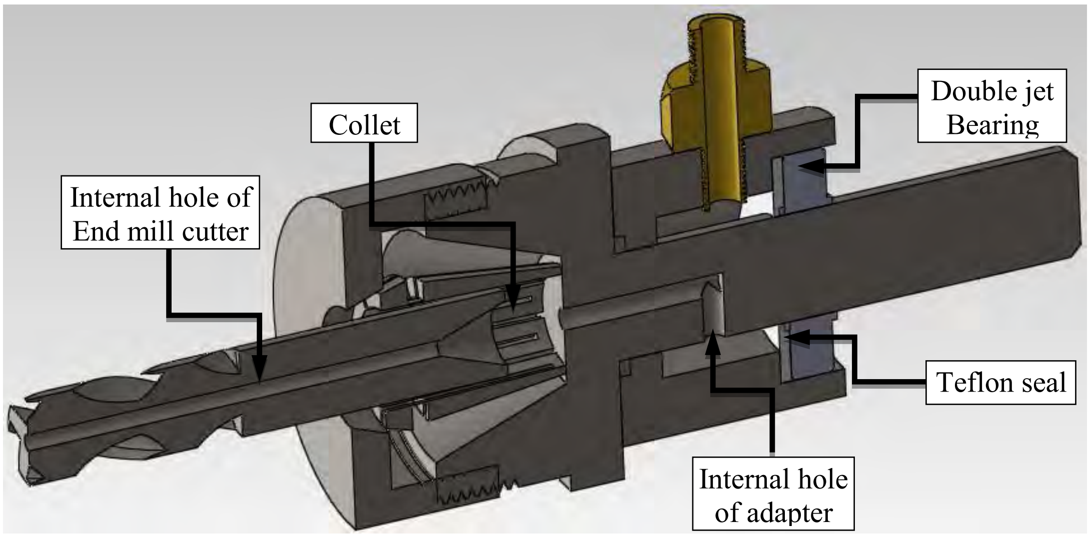


Fig.2.7 Sectional view of rotary liquid nitrogen applicator for injecting liquid nitrogen during milling operation

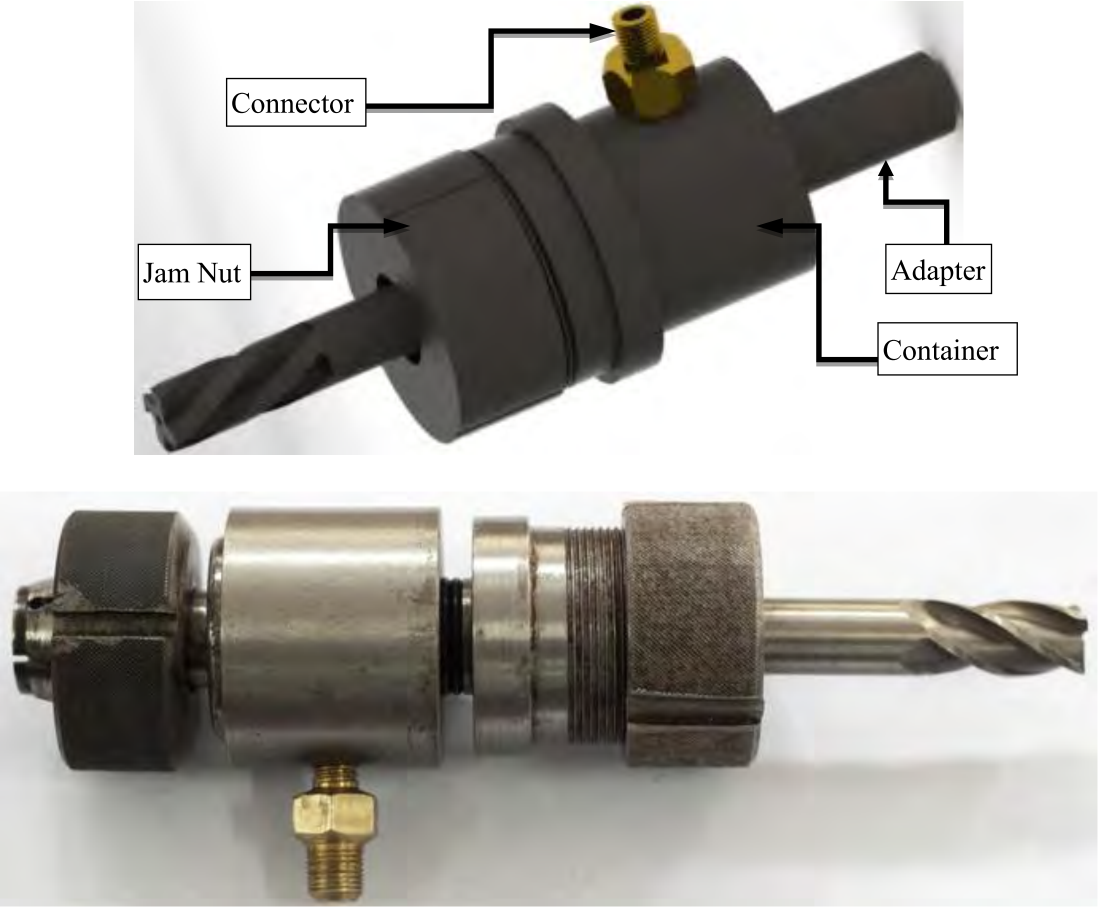


Fig.2.8 Photographic view of rotary liquid nitrogen applicator for injecting liquid nitrogen during milling operation

Chapter-3

Experimental Investigations

3.1 Introduction

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

- ineffectiveness in desired cooling and lubrication
- health hazards due to generation of obnoxious gases and bacterial growth
- inconvenience due to uncleanliness of the working zone
- corrosion and contamination of the lubricating system of the machine tools
- need of storage, additional space, pumping system, recycling and disposal
- 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:

- effective cooling by enabling liquid nitrogen jets reach as close to the actual hot zones as possible
- avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes
- minimum consumption of cryogen by pin-pointed impingement and only during chip formation
- control of pressure and flow rate of cryogen according to need

3.2 Material Preparation

The EN24 grade of steel is considered as the work material in the present investigation considering its wide range of application in the industry. It has a composition as shown in the Table 3.1.

Table 3.1 Chemical composition of work material

Chemical composition	Weight %	Tensile Strength (MPa)	Applications
Carbon	0.36-0.44%	930	Heavy-duty axles, shafts, heavy-duty gears, spindles, pins, studs, collets, bolts, couplings, pinions, torsion bars, connecting rods, conveyor parts etc.
Silicon	0.10-0.35%		
Manganese	0.45-0.70%		
Sulphur	0.040 (max)		
Phosphorus	0.035 (max)		
Chromium	1.00-1.40%		
Molybdenum	0.20-0.35%		
Nickel	1.30-1.70%		
Fe	Balance		

The material used in the thesis was EN24 steel. It was a plate of 200mm length, 100mm breadth and 40mm thickness. A test sample made from the same material was also prepared. It was a rectangular block with dimension 100 mm×40 mm×10 mm. This was made for the hardness test. Fig.3.1 presents the photographic view of the work piece used in this investigation.

Fig.3.1 Photographic view of the workpiece

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

A quench tank having capacity 600 liters was used for quenching the work material. The quench tank was large enough to hold the part being treated and have adequate circulation and temperature control. The temperature of the oil (Bluta oil grade 27) should not exceed 40°C. This oil reduces the absorption of atmospheric gases that, in turn reduces the amount of bubbles. As a result, oil wets the metal surface and cools it more rapidly than water. In addition to rapid and uniform cooling, the oil removes a large percentage of any scale that may be present.

The work piece as well as test sample was pulled quickly but carefully out from the furnace using a tong and was immersed vertically into the oil quenching tank. The oil is stirred vigorously for about 20 minutes for uniform cooling and was continued until the specimen is cool enough. The test sample was also quenched in the same oil following same manner.

Quenched EN24 steel always required to temper because of steels are often more harder than needed and too brittle for most practical uses. Also, several internal stresses like residual stresses are set up during the rapid cooling from the hardening temperature. As a result, to relieve the internal stresses and reduce brittleness, tempering was done. It was done by heating the workpiece as well as test sample to a specific temperature (300^0C), holding it at that temperature for two hour, and then cooling it, usually instill air. The resultant strength, hardness, and ductility depend on the temperature to which the specimen is heated during the tempering process. The purpose of tempering was also to produce definite physical properties within the specimen. The sample was cleaned and ground a flat surface of 0.5 mm deep along the face of the sample. Hardness of the sample was measured on the C scale of Rock-well hardness tester. The hardness of the sample before heat treatment was 163 HRB and after heat treatment it became around 45 HRC. The hardness distribution within the sample is shown Fig.3.2.

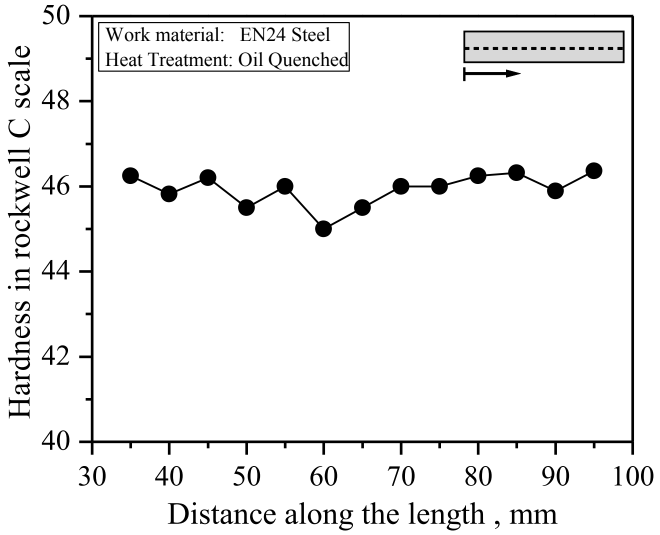


Fig. 3.2 Hardness distribution curve of sample

3.3 Liquid Nitrogen Delivery System

The liquid nitrogen needs to be drawn at high pressure from the dewar and impinged at high speed through the applicator. Considering the conditions required for the present research work and uninterrupted supply of liquid nitrogen at consistent pressure around 15 bar over a reasonably long cut, a vacuum insulated and self pressurized stainless steel dewar of large capacity (200 liter) has been used. The photographic view of the liquid nitrogen dewar and the circuit of the dewar (DOT-4L200) are shown in Fig.3.3.

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.

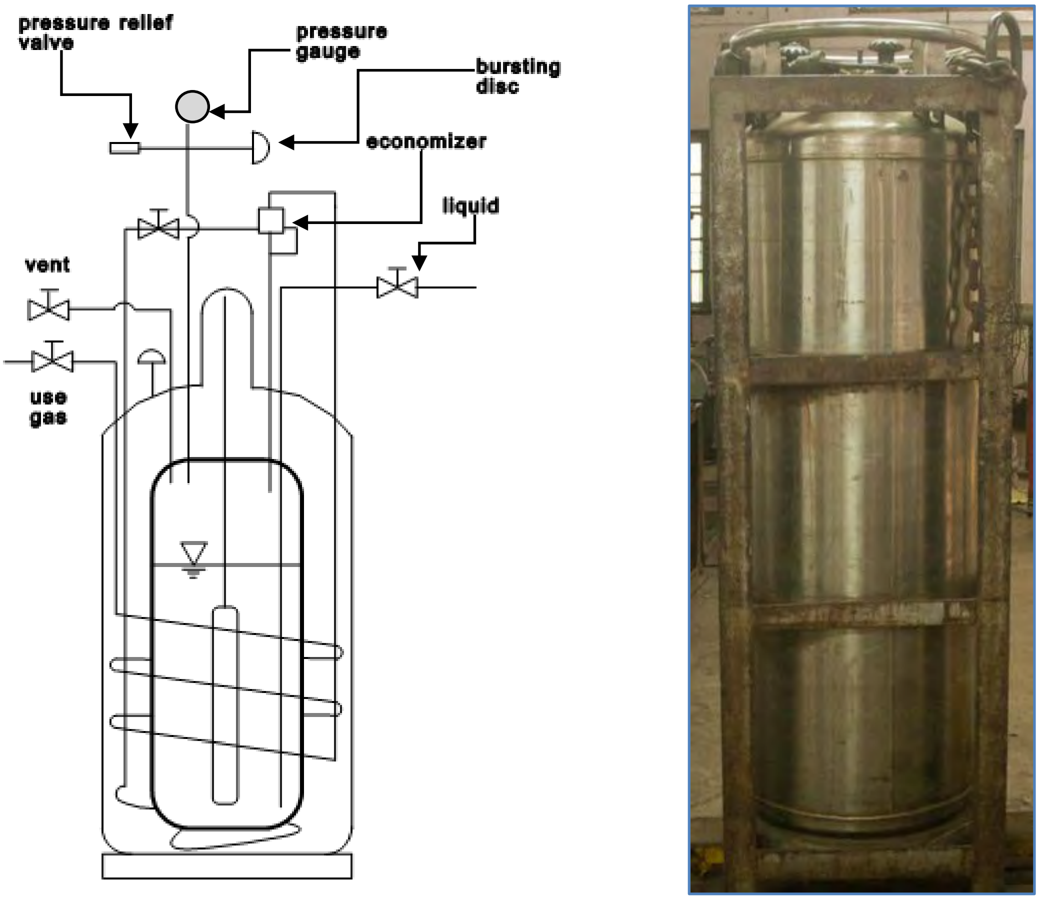


Fig.3.3 Liquid nitrogen dewar and its operating circuits

An economizer circuit withdraws gas preferentially from the head space over the liquid in the container otherwise that gas would be lost to venting. Excess pressure in the head space 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. 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 head space area while liquid is filling the inner container during a pressure fill through the liquid valve.

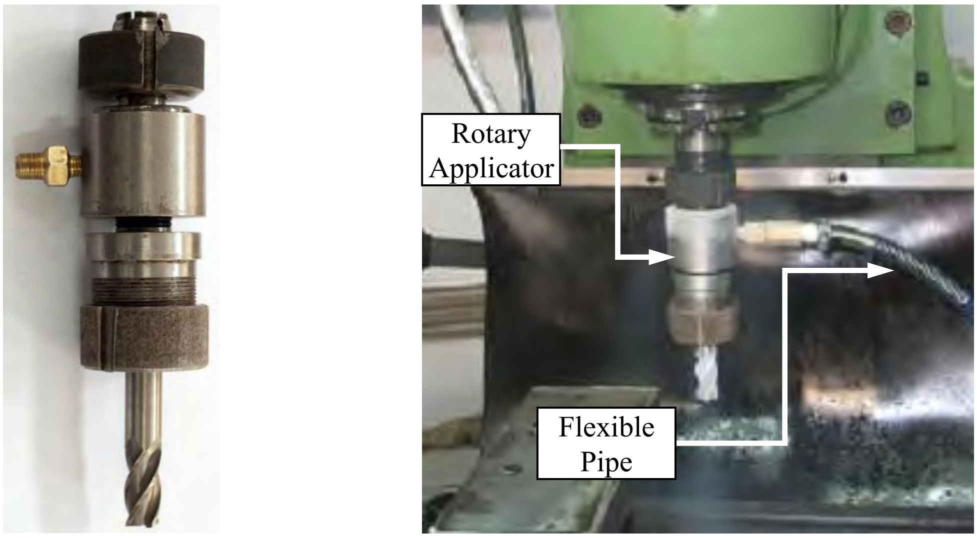


Fig. 3.4 Photographic view of rotary liquid nitrogen applicator

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 bar and

26 bar respectively. A 1.5 bar relief valve is provided for liquid delivery applications. The liquid nitrogen is delivered from the dewar to the applicator using flexible teflon coated stainless steel delivery tube as shown in Fig.3.4.

3.4 Experimental Procedure and Conditions

The beneficial role of cryogenic cooling by 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 milling characteristics of hardened steel (45HRC) mainly in terms of cutting force, flank wear and surface roughness.

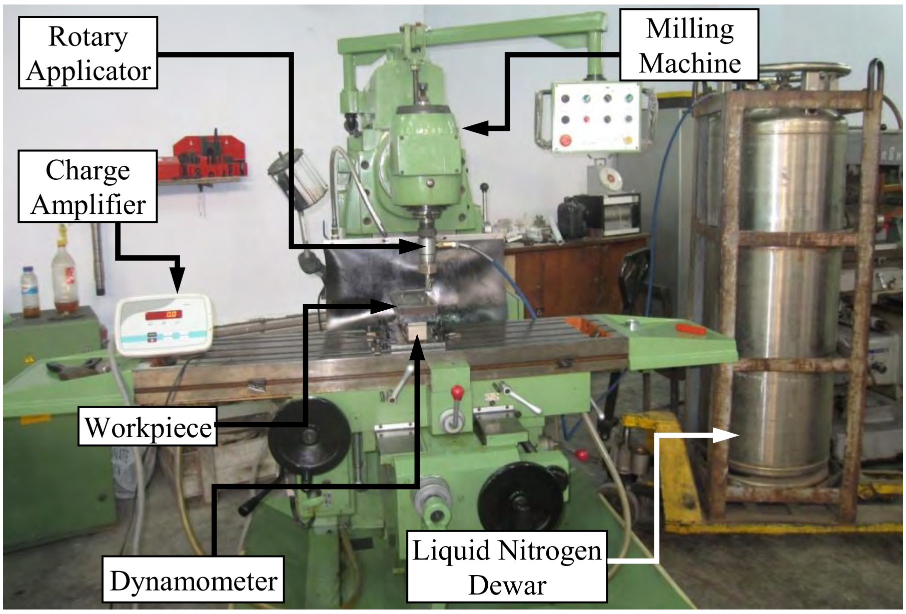


Fig.3.5 Photographic view of the experimental set up

The machining test has been carried out by milling of hardened steel in a column and knew type vertical milling machine (7.5 hp, Sunlike, China) by standard high speed steel (HSS) milling cutter at different cutting velocities (V_c) and feeds (S_o) under dry, wet and cryogenic cooling conditions. The photographic view of the experimental set-up is shown in Fig.3.5. The conditions under which the machining tests have been carried out are briefly given in Table 3.2.

Table 3.2 Experimental conditions

Machine Tool : Vertical Knee and Column type Milling Machine , China

Work Materials : EN24 Hardened steel (size: 200X 100x40 mm)

Hardness : 45 HRC

Cutting Tool : HSS End Milling Cutter (Ø16 mm)

Process Parameters

Cutting speed : 14, 19, 22 and 26 m/min

Table feed : 22, 34, 44, 68 and 75 mm/min

Depth of cut : 0.60 mm

Environment : Dry, wet and cryogenic cooling

High speed steel (HSS) end mill cutter (Ø16 mm) which has helical higher positive cutting edges as shown in Fig.3.6 was used in the investigation with straight shank. Cutting force was measured using a dynamometer. It consists of a load cell type dynamometer with charge amplifier. The surface roughness of the machined surface after each cut was measured by a Talysurf roughness checker(Surtronic 3^+, Rank Hobson, UK) using a sampling length of 0.8mm. The width of the flank wear was measured using metallurgical microscope (Carl Zeiss, Germany) fitted with micrometer of 1µm resolution. Surface morphology of the worn out tool was carried out using Scanning Electronic Microscope (JEOL-JSM-7600F) with a magnification of 25X to 1000000X.

Fig.3.6 Photographic view of the end mill cutter

3.5 Experimental Results

In the present work, surface roughness, cutting force and flank wear have been investigated to evaluate the relative role of cryogenic cooling in compare to dry and wet milling at different cutting velocity and table feed. The cutting speed was varied from 14 m/min at 4 levels while table feed was varied from 22 mm/min at 5 levels and the depth of cut at 0.6 mm during the milling operation. Tool life tests were conducted in the three modes at a cutting velocity of 22 m/min, table feed 34 mm/min and depth of cut 0.60 mm. Measurement of surface roughness, cutting force and tool wear were done at intervals of 90 seconds during each experiment.

3.5.1. Surface Roughness

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 surface integrity of the product in respect of surface roughness, oxidation, corrosion, residual stresses and surface and subsurface microcracks.

Surface roughness is an important index of machinability which is substantially influenced by the machining environment for a given too-work combination and speed-feed conditions. Surface roughness has been measured at two stage; one after 90 seconds of milling with the sharp tool while recording the cutting force and second, with the progress of machining time while monitoring growth of flank wear with machining time.

The surface roughness attained after 90 seconds of milling of the hardened EN24 steel at various cutting speed and table feed combinations under dry, wet and cryogenic cooling conditions are shown in Fig.3.7, Fig.3.8, Fig.3.9, Fig.3.10, Fig.3.11 and Fig.3.12 respectively. The variation of roughness observed with progress of milling of EN24 hardened steel at a particular set of cutting velocity and table feed under dry, wet and cryogenic cooling conditions have been shown in Fig.3.13.

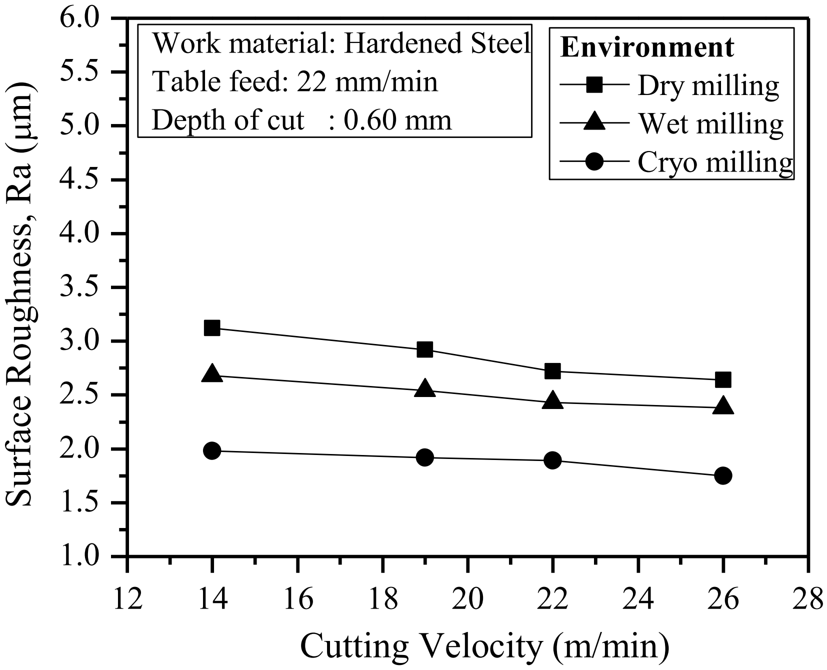


Fig.3.7 Variation of surface roughness as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **22 mm/min table feed** under different environment

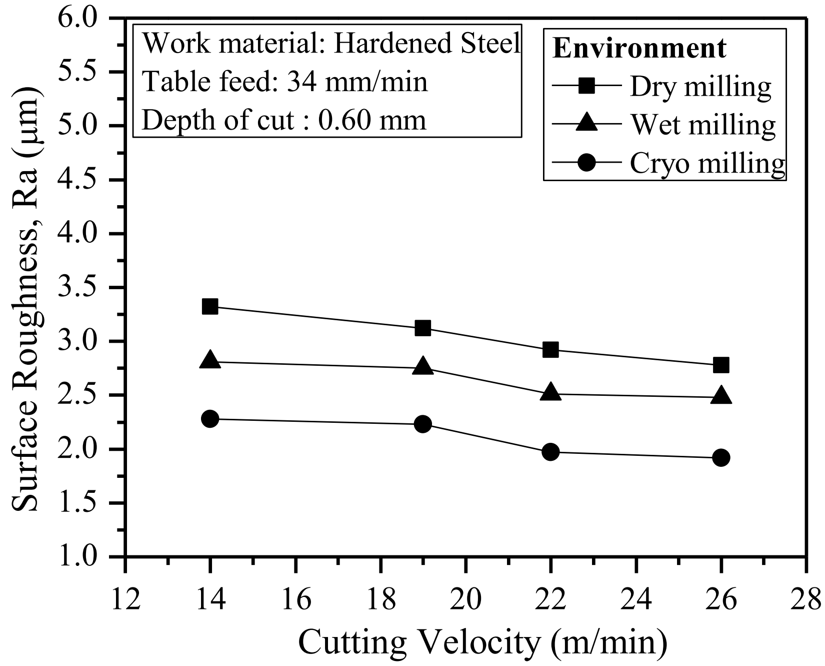


Fig.3.8 Variation of surface roughness as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **34 mm/min table feed** under different environment

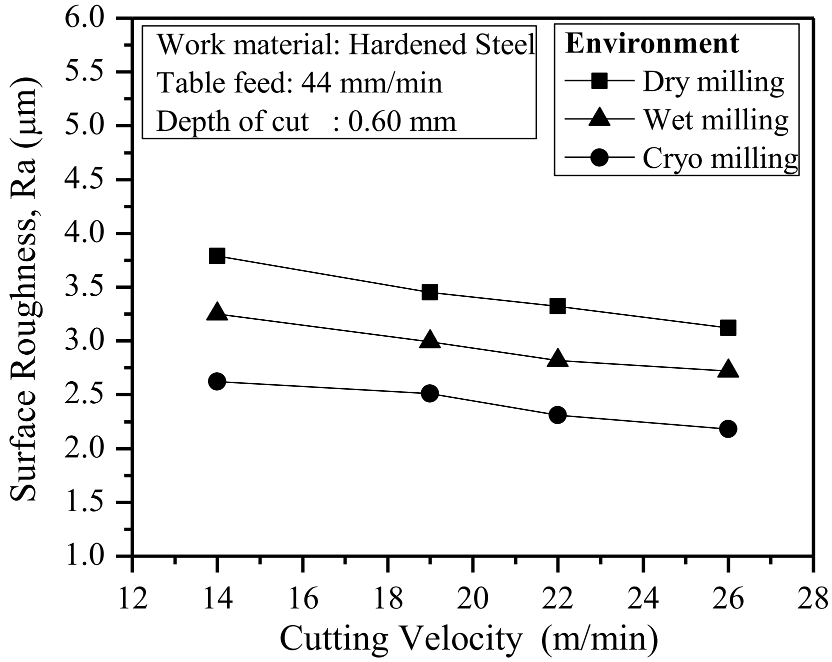


Fig.3.9 Variation of surface roughness as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **44 mm/min table feed** under different environment

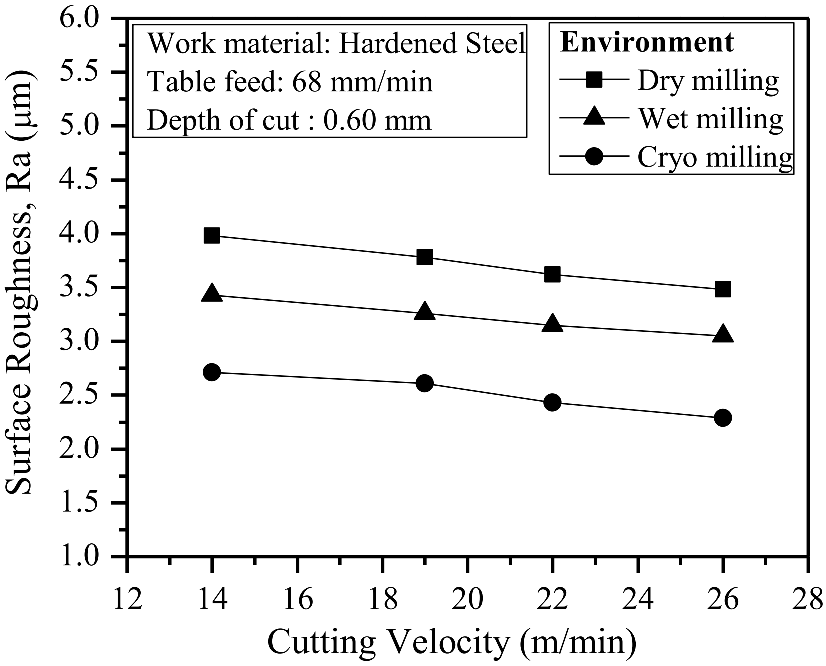


Fig.3.10 Variation of surface roughness as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **68 mm/min table feed under** different environment

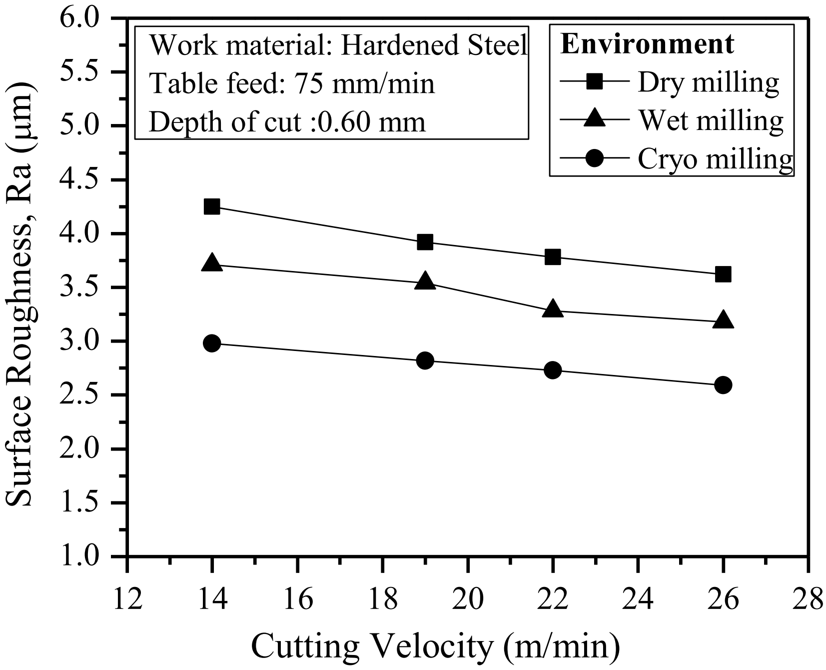


Fig.3.11 Variation of surface roughness as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **75 mm/min table feed** under different environment

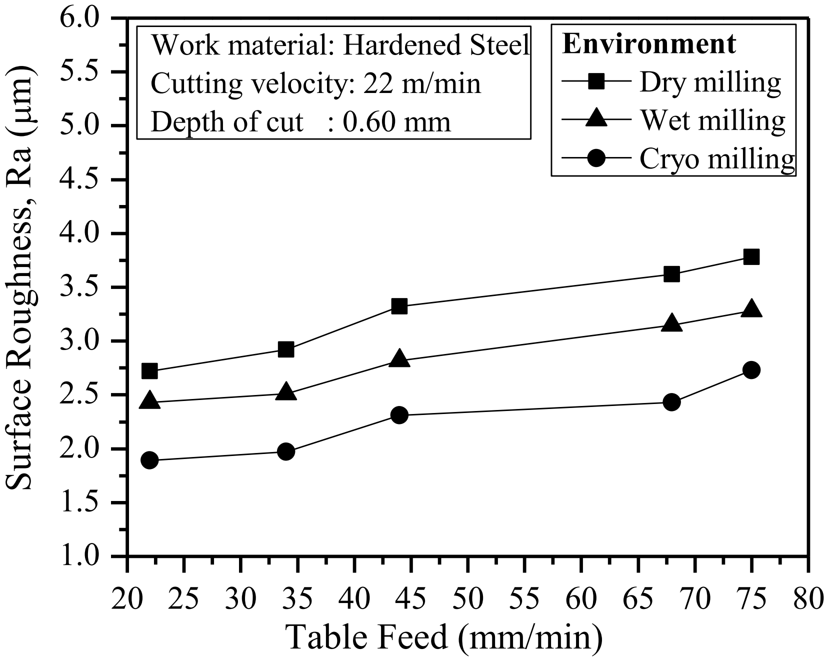


Fig.3.12 Variation of surface roughness as a function of table feed in milling EN24 hardened steel by HSS milling cutter at **22 mm/min cutting velocity** under different environment

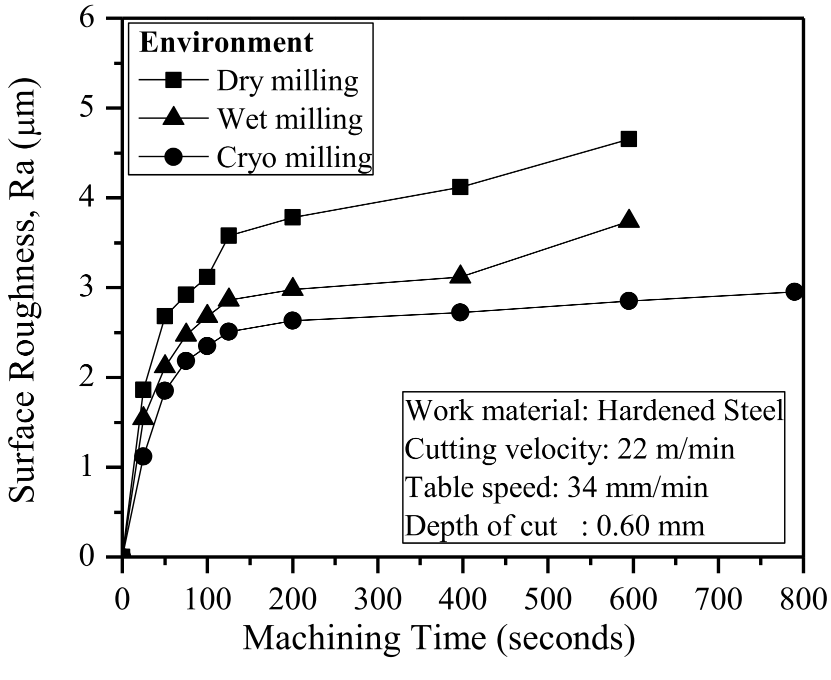


Fig.3.13 Variation of surface roughness with machining time in milling EN24 hardened steel by HSS milling cutter at under different environment

3.5.2. Cutting Force

Cutting forces are generally resolved into components in mutual perpendicular directions for convenience of measurement, analysis, estimation of power consumption and for design of machine-fixture-tool-work systems. In the present work, the magnitude of cutting force has been monitored by dynamometer at different cutting velocity and table feed combinations under dry, wet and cryogenic cooling conditions. The effects of cryogenic cooling on the cutting force under different machining conditions have been shown in Fig.3.14, Fig.3.15, Fig.3.16, Fig.3.17, Fig.3.18 and Fig.3.19 respectively. The variation of cutting force observed with progress of milling of EN24 hardened steel at a particular set of cutting velocity and table feed under dry, wet and cryogenic cooling conditions have been shown in Fig.3.20.

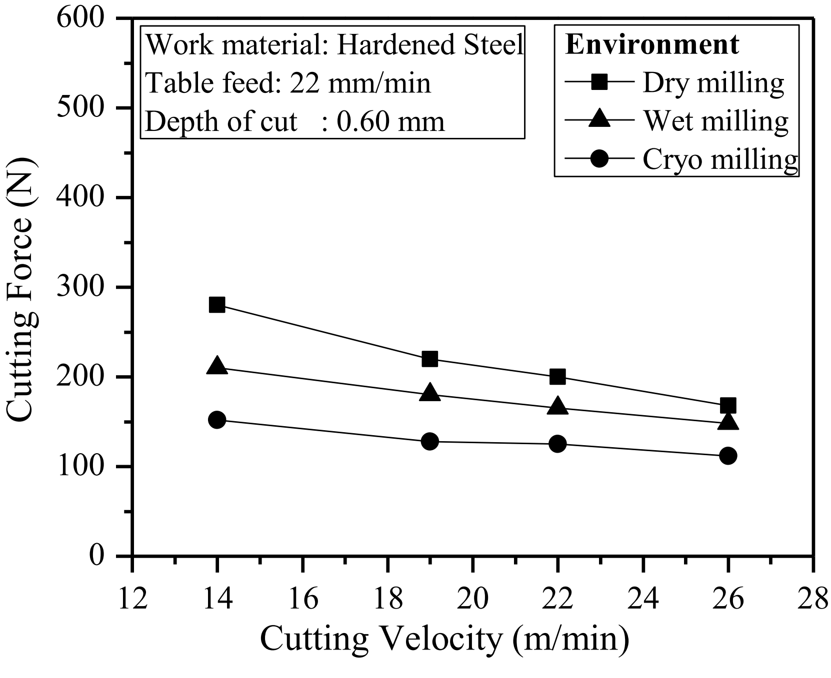


Fig.3.14 Variation of cutting force as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **22 mm/min table feed** under different environment

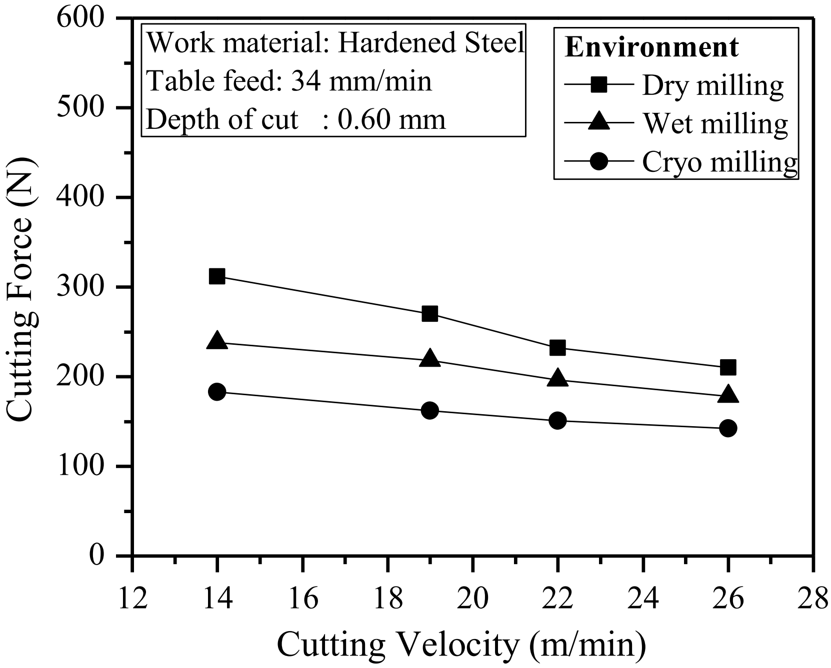


Fig.3.15 Variation of cutting force as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **34 mm/min table feed** under different environment

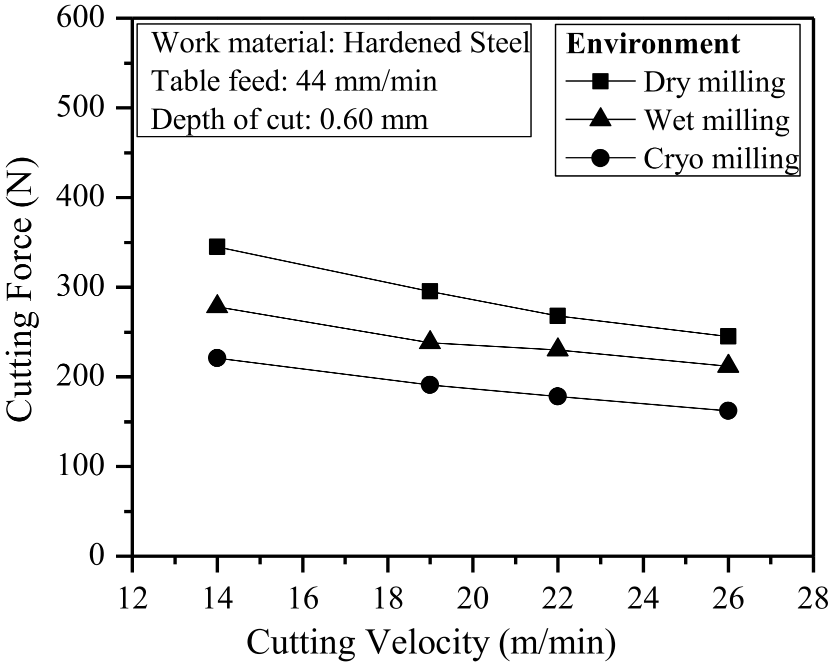


Fig.3.16 Variation of cutting force as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **44 mm/min table feed** under different environment

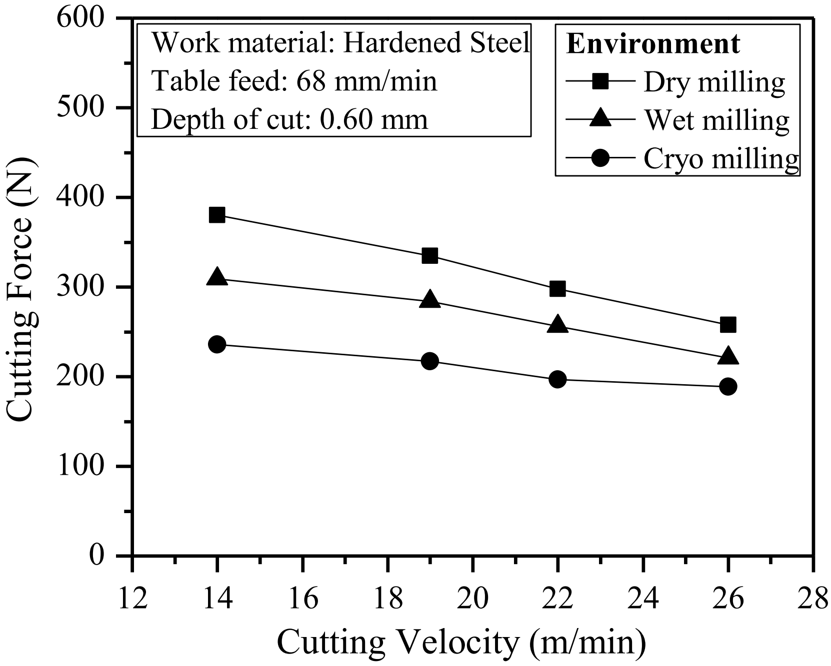


Fig.3.17 Variation of cutting force as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **68 mm/min table feed under** different environment

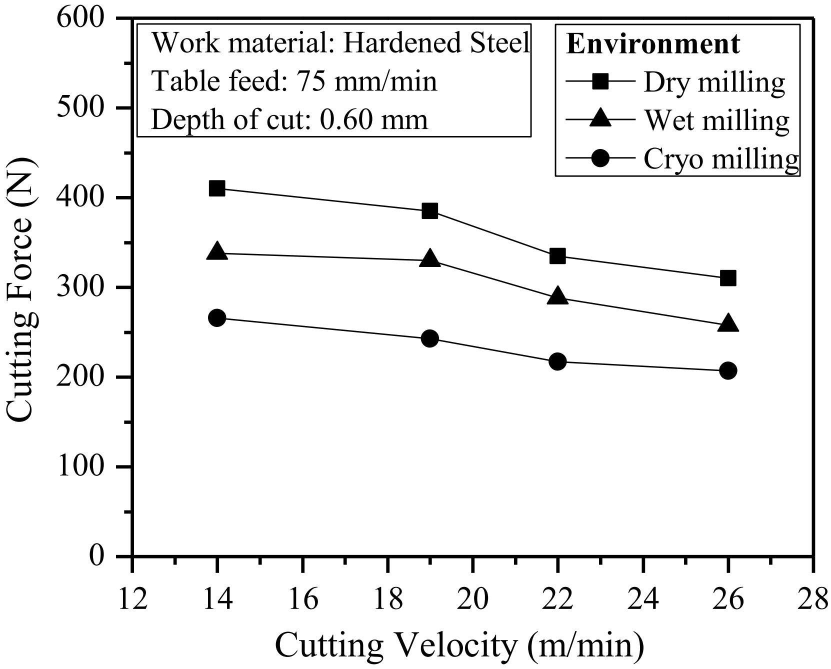


Fig.3.18 Variation of cutting force as a function of cutting velocity in milling EN24 hardened steel by HSS milling cutter at **75 mm/min table feed** under different environment

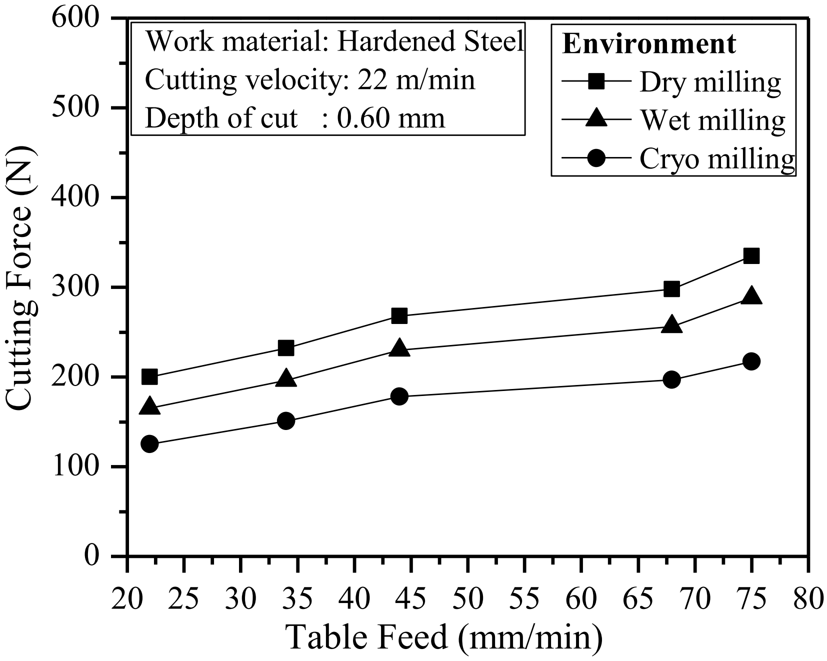


Fig.3.19 Variation of cutting force as a function of table feed in milling EN24 hardened steel by HSS milling cutter at **22 mm/min cutting velocity** under different environment

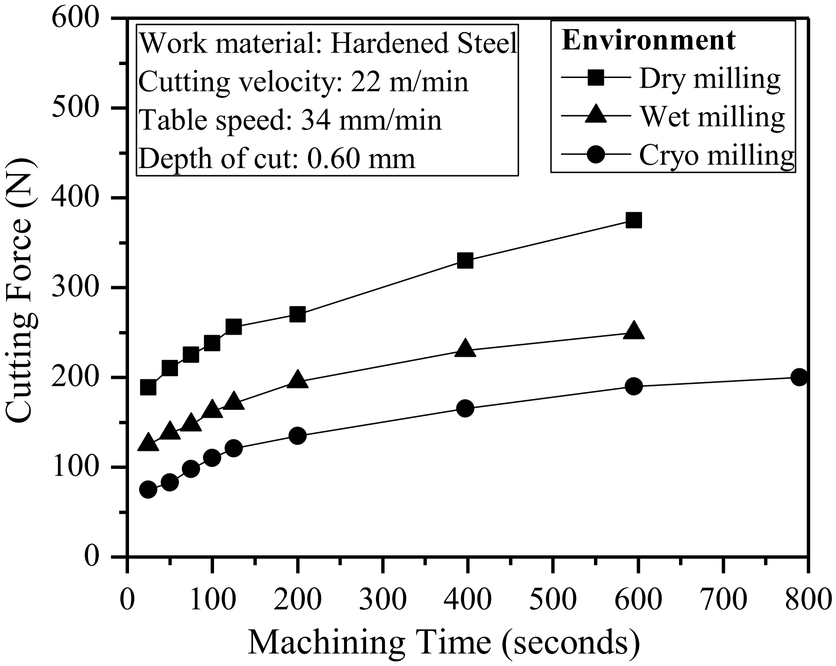


Fig.3.20 Variation of cutting force with machining time in milling EN24 hardened steel by HSS milling cutter at under different environment

3.5.3. Flank Wear

The cutting tool in conventional milling generally fails by gradual wear by abrasion, adhesion, diffusion, chemical erosion etc. depending upon the tool-work materials and milling condition. Tool wear initially starts with a relatively faster rate due to what is called break-in-wear caused by attrition and microchipping at the sharp cutting edges. Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse milling conditions caused by intensive pressure and temperature and/or dynamic loading at the tip of the milling cutter particularly if the cutter material lacks strength, hot hardness and fracture toughness. However, in the present investigations with the cutter and work material and the milling conditions undertaken, the tool failure mode has been mostly gradual wear.

The growth of flank wear has been measured at two stages; one after 90 seconds of milling with the sharp milling cutter while recording the cutting force and second, with the progress of machining time. The growth of flank wear attained after 90 seconds of milling at various cutting speed and table feed combinations under dry, wet and cryogenic cooling conditions are shown in Fig.3.21 and Fig.3.22 respectively. The growth of flank wear with progress of milling at a particular set of cutting velocity and table feed under dry, wet and cryogenic cooling conditions have been shown in Fig.3.23.

The pattern and extent of wear that developed at the surface of the milling cutter after being used for milling the EN24 hardened steel over reasonably long period have been observed under scanning electronic microscope (SEM) to see the actual effects of different environments on wear of the HSS milling cutter. The SEM views of the worn out HSS milling cutter after 790 seconds of milling of EN24 hardened steel under dry, wet and cryogenic cooling conditions has been shown in Fig.3.24.

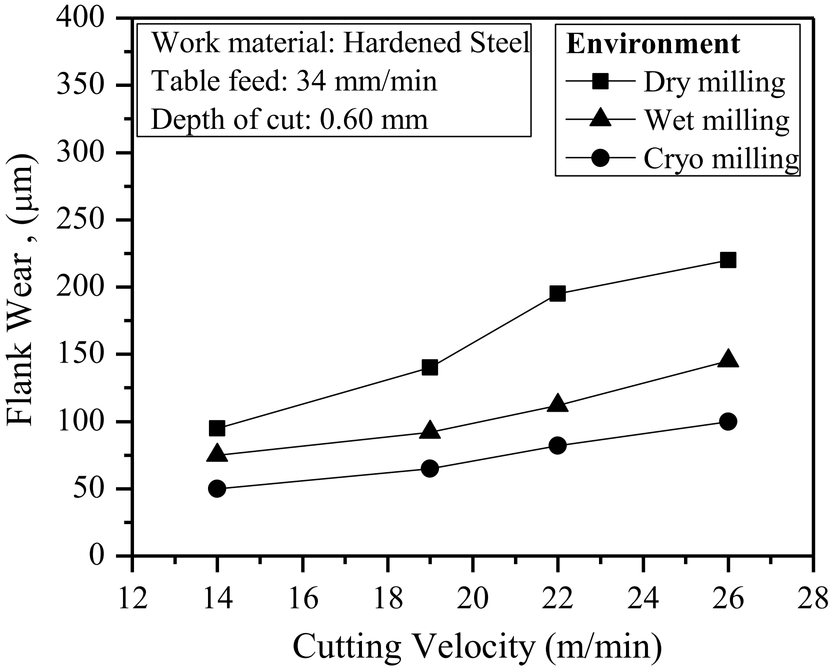


Fig.3.21 Variation of flank wear as a function of cutting velocity at 34 **mm/min table feed** while milling EN24 hardened steel by HSS milling cutter under different environment

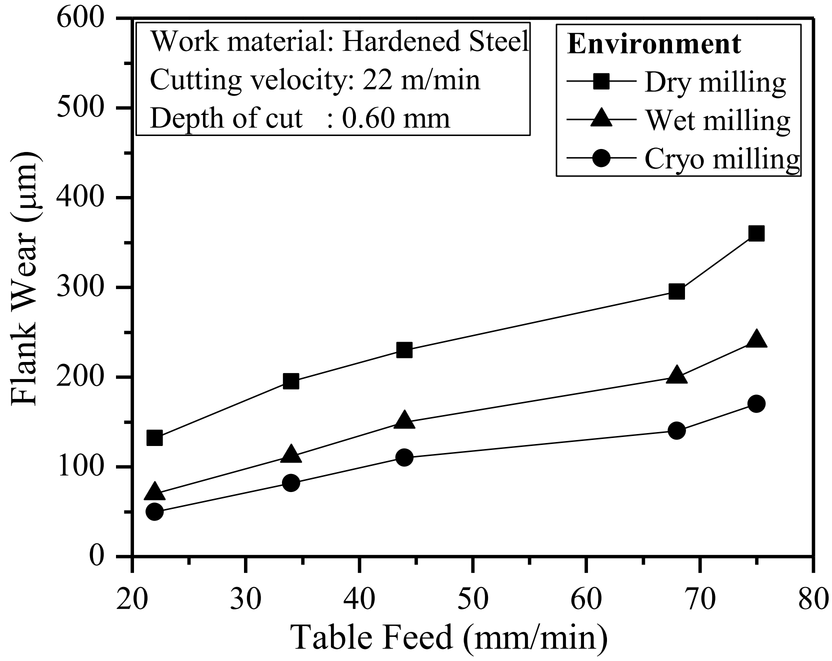


Fig.3.22 Variation of cutting force as a function of table feed at **22 mm/min cutting velocity** while milling EN24 hardened steel by HSS milling cutter under different environment

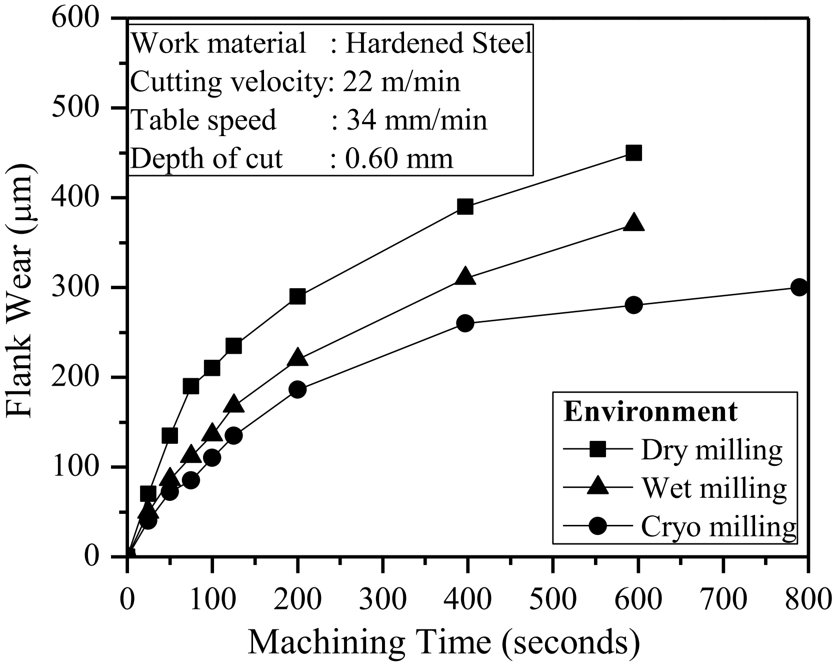
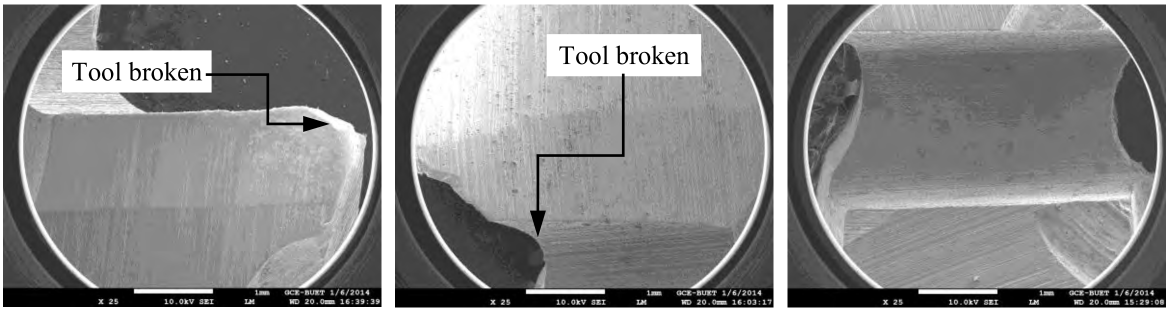


Fig.3.23 Growth of flank wear with machining time in milling EN24 hardened steel at **22 mm/min cutting velocity, 34 mm/min table feed and 0.60 mm depth of cut** under different environment



(a) Dry Milling (b) Wet Milling (c) Cryogenic Milling

Fig.3.24 SEM views of the worn out milling cutter after milling EN24 hardened steel by HSS milling cutter under (a) dry, (b) wet and (c) cryogenic cooling conditions

Chapter-4

Discussion on Experimental Results

4.1 Surface Roughness

The quality of work material‟s surfaces after undergone various manufacturing processes particularly in milling operation is very important in determining the functional performance of a component throughout the services. For the present study, only surface roughness has been considered for assessment of the quality of product under dry, wet and cryogenic cooling conditions.

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

- regular feed marks left by the tool tip on the finished surface

- irregular deformation of the auxiliary cutting edge at the tool-tip due to chipping, fracturing and wear
- vibration in the machining system
- built-up edge formation, if any

Application of cutting fluid in milling has been proven to improve the surface integrity of the work materials. The improved surface finish resulted in cryogenic machining is due to lower cutting temperature generated during the machining process, hence lowering the cutting forces and tool wear. Besides, cryogenic condition also enhances the chip breakability during machining and reduces the tendency of chip‟s adhesion to the tool resulting in less scratch on the surface finish. Surface roughness measurement, gave some improvement when milling with cryogenic application compared to dry and wet milling. Smaller roughness measurements reflect better surface quality of the workpiece. Surface finish is largely influenced by the cutting force, tool wear and chip formation.

The figures from Fig.3.7 to Fig.3.12 are showing how and to what extent surface roughness has decreased due to cryogenic application under the different experimental conditions. With the increase in cutting velocity, surface roughness decreased and with the increase in table feed, surface roughness increased as usual, even under cryogenic cooling, due to increase in energy input. The percentage reduction in surface roughness attained by wet and cryogenic cooling condition for different cutting velocity and table feed have been extracted from the previous figures and shown in Table 4.1.

It is evident in Fig.3.7 that cryogenic cooling could provide good improvement in surface finish at the beginning of machining with the fresh cutting edges. This has been more or less true for all the experimental combinations undertaken as can be seen in

Fig.3.7 to Fig.3.12. This 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.

Surface roughness for each treatment was also measured at regular intervals while carrying out machining for tool wear study. It was found that surface roughness grew substantially, though in different degree under different tool-work-environment combinations, with the progress of machining. Comparison of the Fig.3.23 with those from Fig.3.13 reveals that the pattern of growth of surface roughness bears close similarity with that of growth of flank wear in particular. Such observations indicate distinct correlation between flank wear and surface roughness. Wear at the tool flanks is caused mainly by micro-chipping and abrasion unlike crater wear where adhesive and diffusion wear are predominant particularly in machining steels by uncoated carbides. The minute grooves produced by abrasion and chipping roughen the cutting edge at the tool-tip, which is directly reflected on the finished surface. Built-up edge formation also is likely to affect surface finish directly being particularly sticked to the cutting edge as well as finished surface and indirectly by causing chipping and flaking at the tool tip. Fig.3.13 clearly shows that milling EN24 hardened steel by HSS milling cutter results sizeable surface roughness with the progress of dry milling. Wet milling, which aggravated flank wear, has further deteriorated the surface whereas, surface roughness also decreased substantially by application of liquid nitrogen.

Table 4.1 Reduction in surface roughness due to wet and cryogenic cooling in milling EN24 hardened steel

Table Feed (mm/min)	Cutting Velocity (m/min)	Environment			Percentage Reduction in Surface Roughness	
		Dry	Wet	Cryogenic	Wet Milling	Cryogenic Milling
		Surface Roughness (µm)				
22	14	3.12	2.68	1.98	15	37
	19	2.92	2.54	1.92	14	35
	22	2.72	2.43	1.89	11	31
	26	2.64	2.38	1.75	10	34
34	14	3.32	2.81	2.28	16	32
	19	3.12	2.75	2.23	12	29
	22	2.92	2.51	1.97	15	33
	26	2.78	2.48	1.92	11	31
44	14	3.79	3.25	2.62	15	31
	19	3.45	2.99	2.51	14	28
	22	3.32	2.82	2.31	16	31
	26	3.12	2.72	2.18	13	31
68	14	3.98	3.43	2.71	14	32
	19	3.78	3.26	2.61	14	31
	22	3.62	3.15	2.43	13	33
	26	3.48	3.05	2.29	13	35
75	14	4.25	3.71	2.98	13	30
	19	3.92	3.54	2.82	10	29
	22	3.78	3.28	2.73	14	28
	26	3.62	3.18	2.59	13	29

4.2 Cutting Force

It is already mentioned in the previous chapters that the magnitude of the cutting force is a major index of machinability which governs productivity, product quality and overall economy in machining. The cutting forces increase almost proportionally with the increase in chip load and shear strength of the work material. Apart from chip load and strength of the work material there are some other factors which also govern magnitude of the cutting forces. However, attempt should always be made to minimise the magnitude of the cutting forces without sacrificing material removal rate and product quality. The figures from Fig.3.14 to Fig.3.19 are showing how and to what extent surface roughness has decreased due to cryogenic application under the different experimental conditions. With the increase in cutting velocity, cutting force decreased and with the increase in table feed, cutting force increased as usual, even under cryogenic cooling, due to increase in energy input. The percentage reduction in cutting force attained by wet and cryogenic cooling condition for different cutting velocity and table feed have been extracted from the previous figures and shown in Table 4.2. It is also evident from Fig.3.14 to Fig.3.19 that cryogenic application provided more significant reduction in cutting force in compare to dry and wet milling. Fig.3.14 to Fig.3.19 and Table 4.2 reveal that the cryogenic cooling had more favourable effect on cutting force expectedly because chip-tool friction and configuration of the tool rake surface and any change in them have physically more influence on cutting force the direction of which is almost parallel to the rake surface. The figures from Fig.3.14 to Fig.3.19 as well as the tables from Table 4.2 clearly visualise that reduction in the cutting forces by liquid nitrogen happened to be much high in compared to wet condition. Fig.3.20 shows the variation of cutting force with machining time while milling EN24 hardened steel by HSS milling cutter at under different environment. It is evident from the figure that under cryogenic cooling condition, the cutting forces decreases more in compare to wet milling.

Table 4.2 Reduction in cutting force due to wet and cryogenic cooling in milling EN24 hardened steel

Table Feed (mm/min)	Cutting Velocity (m/min)	Environment			Percentage Reduction in Cutting Force	
		Dry	Wet	Cryogenic	Wet Milling	Cryogenic Milling
		Cutting Force (N)				
22	14	280	210	152	25	46
	19	220	180	128	19	42
	22	200	165	125	18	38
	26	168	148	112	12	34
34	14	312	238	183	24	42
	19	270	218	162	20	40
	22	232	196	151	16	35
	26	210	178	142	16	33
44	14	345	278	221	20	36
	19	295	238	191	20	36
	22	268	230	178	15	34
	26	245	212	162	14	34
68	14	380	309	236	19	38
	19	335	284	217	16	36
	22	298	256	197	15	34
	26	258	221	189	15	27
75	14	410	338	266	18	36
	19	385	330	243	15	37
	22	335	288	217	15	36
	26	310	258	207	17	34

4.3 Flank Wear

The milling cutter selected and used attained flank wear progressively in varying pattern and magnitude while machining the EN24 hardened steel under dry, wet as well as cryogenic cooling condition undertaken for the present investigations. Premature and catastrophic type of tool failure by plastic deformation or macro fracture was not found to occur expectedly within the present experimental domain. The SEM views of the worn out milling cutter after milling EN24 hardened steel at a particular speed-table-depth of cut combination under different environments are shown in Fig.3.24 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, both flank and crater wear have been much uniform and much smaller in magnitude and without any notch wear. Only a small 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.

It is also evident from Fig.3.24 that usual wet milling by cutting oil could not reduce flank wear appreciable while milling EN24 hardened steel. Such wet milling 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 milling cutter expected due to cooling and lubrication by the cutting fluid in intermittent cutting like milling of steel. But applications of cryogenic cooling by liquid nitrogen have substantially reduced growth of flank wear as can be seen in Fig.3.24. Such improvement by liquid nitrogen 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 flank wear by flaking and chipping.

Chapter-5

Conclusions and Recommendation

5.1 Conclusions

- Surface milling of EN24 hardened steel with liquid nitrogen has been investigated in depth and its performance is evaluated on the basis of roughness, cutting force and tool wear.
- Surface finish also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of liquid nitrogen. Surface roughness value substantially reduced from 3.12 µm to 1.98 µm i.e. 37% improvement in surface finish with the use of liquid nitrogen but under wet condition, the improvement is 15%.
- Cryogenic cooling reduced the cutting force by about 27% to 46%. Such reduction has been more effective for those tool-work combination and cutting conditions, which provided lower value of cutting temperature and favourable chip-tool interaction. 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 liquid nitrogen jets.
- The most significant contribution of application of liquid nitrogen in milling steel by the high speed steel milling cutter undertaken has been the high reduction in flank wear, which would enable either remarkable improvement in tool life or enhancement of productivity (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.

5.2 Recommendations

- Liquid nitrogen applicator may be further studied to optimize its performance. Special type of cryogenic bearing and teflon seals may be tried for much better performance.
- Consumption of liquid nitrogen during particular time of operation in milling or related operations may be studied further. Experimental investigations may be carried out for analyzing the economical aspect of liquid nitrogen as coolant and lubricant.
- A complete laboratory size portable cryogenic coolant supply system may be fabricated for any type of milling operation using the rotary applicator.
- A rotary liquid nitrogen applicator may be designed, developed with teflon and compare its performance with the developed rotary applicator.
- Liquid nitrogen applicator can be developed for other tool-work combinations during surface milling which can serve as a database for industries willing to implement this applicator.

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