ROLE OF MINIMUM QUANTITY LUBRICANT IN TURNING HARDENED AISI 1040 STEEL BY UNCOATED CARBIDE INSERT

By

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

Baishakhi Barua
This work is dedicated
to my loving

Father

&

Mother
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ABSTRACT

The generation of huge amount of heat in high production machining at high cutting velocity and feed rate shortens the tool life and deteriorates the job quality. The conventional cutting fluids are not that effective in such high production machining particularly in continuous cutting of materials like steels. Because of these some alternatives has been sought to minimize or even avoid the use of cutting fluid in machining operations. One of these alternatives is machining with minimum quantity lubricant (MQL). It is a mixture of impinging of least amount of cutting fluid along with highly compressed air through a small nozzle results in reducing the heat produced during metal cutting. The main objective of the present work is to make an experimental investigation on the role of MQL in turning hardened steel by uncoated carbide insert (SNMG 120408) in respects of chip formation, chip-tool interface temperature, tool wear and surface roughness. The result indicated that the machining with MQL performed much better than dry machining mainly due to reduction in cutting zone temperature enabling favorable chip-tool interaction. This also facilitated the reduction in tool wear in leading to enhance tool life and surface finish.
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Chapter-1

Introduction

1.1 Introduction

Any manufacturing process for its fruitful implementation essentially needs to be technologically acceptable, technically feasible and economically viable. The fourth dimension that has been a great concern of the modern industries and society is environment-friendliness in and around the manufacturing shops. The performance and service life of engineering component depends on their material, dimensional and form accuracy and surface quality. The preformed blanks are finished by machining and grinding to attain the desired accuracy and surface integrity.

The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, particularly to meet the challenges thrown by liberalisation and global cost competitiveness, insists high material removal rate and high stability and long life of the cutting tools. But high production machining and grinding with high cutting velocity, feed and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product.

A longer cut under high cutting temperature causes thermal expansion and distortion of the job which leads to dimensional and form inaccuracy. On the other hand,
high cutting temperature accelerates the growth of tool wear and also enhances the chances of premature failure of the tool by plastic deformation and thermal fracturing. The surface quality of the products also deteriorates with the increase in cutting temperature due to built-up-edge formation, oxidation, rapid corrosion and induction of tensile residual stress and surface micro-cracks. These problems are more predominant in grinding where cutting temperature is, as such, very high due to much higher specific energy requirement and cutting velocity. Such problem becomes more acute and serious if the work materials are very hard, strong and heat resistive and when the machined or ground part is subjected to dynamic or shock loading during their functional operations. Therefore, it is essential to reduce the cutting temperature as far as possible. In industries, the machining temperature and its detrimental effects are generally reduced by:

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

Cutting fluid not only cools the tool and job but also provides lubrication and cleans the cutting zone and protects the nascent finished surface from contamination by the harmful gases present in the atmosphere. But the conventional types and methods of application of cutting fluid have been found to become less effective with the increase in cutting velocity and feed when the cutting fluid cannot properly enter the chip-tool
interface to cool and lubricate due to bulk plastic contact of the chip with the tool rake surface. Besides that, often in high production machining the cutting fluid may cause premature failure of the cutting tool by fracturing due to close curling of the chips and thermal shocks. For which application of high cooling type water base cutting fluids are generally avoided in machining steels by brittle type cutting tools like carbides and ceramics. But what is of more serious concern is the pollution of the working environment caused by use of cutting fluid, particularly oil-based type.

The modern industries are, therefore, looking for possible means of dry, clean, neat and pollution free machining and grinding. Ample researches have been carried out and are still going on in this direction. Minimum quantity lubricant (MQL) appears to be a promising technique for effective cooling without the problems associated with conventional cutting fluid applications. But it is also essential to be assured that productivity and overall economy are not affected while deriving the environmental benefits. Rather it is necessary to explore the possible technological benefits of such MQL cooling and optimise it for maximum overall socio-economic benefits.
Chapter-2

Literature Review

2.1 Introduction

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

- Easy to adapt to complex part contours
- Quick change-over between components types
- Several operations performed in one setup
- 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 be integrating a number of features to increase rigidity and damping characteristics for hard machining applications. These include machine bases with polymer composite reinforcement, direct-seating colleted spindles that locate the spindle bearing close to the workpiece and hydrostatic ways. Minimizing 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 with 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. 1987, Ohama 1997, Fowler 1999]

2.2 Hard Machining

As large cutting force is associated with hard turning, rigid and precise machine tools are prime prerequisites to expel any vibration or chatter. In juxtaposition with the invention and development of new cutting tool materials and the rigid machine tools hard turning have become a practicable process. Tonshoff et al. [1986] found that the large negative rake angles on tools used for hard machining yield large dynamic thrust forces that require adequate machine rigidity, spindle power, damping characteristics, and accuracy of motion along the axes of the machine. Bossom [1990] found that tools with chamfered edges produced cutting forces twice as large as non-chamfered tools. Chryssoulouris [1982] showed that when machining in a poor stiffness setup, tools failed quickly due to edge fracture. These needs have led to recent machine tool designs that improve stiffness and damping by several methods. New machines have incorporated polymer composite materials in the machine base, reduced the number of joints in the machine, and developed improved slide ways such as hydrostatic designs [Sheehy 1997, Devitt 1998].

It would be ideal to eliminate all machining operations, including both hard turning and grinding, because they are wasteful processes that are not particularly efficient.
However, many parts specifications necessitate that finish machining be done after heat treatment. Historically this has been done by grinding, and hard turning must be capable of producing similar geometric precision and quality surfaces. Several studies have investigated the capability of the process to compete with grinding, and most have concluded that at proper conditions with a good machine, hard turning can produce dimensional accuracy and surface finishes acceptable for most applications. Matsumoto et al. [1986] were able to hard turn parts with surface finish ranging from 0.045~0.197 µm and surface waviness from 0.775~1.26 µm. Abrao and Aspinwall [1996] were able to produce a surface finish with roughness value of 0.14 µm.

A significant amount of research in hard turning has focused on understanding chip formation. The mechanics of chip formation in hard turning are very unlike chip formation in softer steels, where continuous chips have typically been observed. This type of chip formation was the basis of early machining models as shown by Merchant [1944]. However, many machining operations produce cyclic chips that can be described as the wavy chip, the catastrophic shear chip, the segmental chip, and the discontinuous chip [Komanduri et al 1981]. In hard turning, periodic saw-toothed chips have been observed by many researchers [Merchant 1944]. The periodic crack theory assumes that periodic shear cracks first develop near the surface of the work and proceed downward along the shear plane towards the tool tip. Following crack formation, bands of concentrated shear may or may not then develop [Shaw and Vyas 1998]. Elbestawi et al. [1996] developed the chip formation model, in which it starts with initiation of a crack at the free surface of the workpiece by considering the direction of crack initiation using the surface layer energy/strain energy density criterion. According to Davies et al. [1996], chip morphology
is independent of work material microstructure but is a function of tool wear during finish turning of hardened steel.

If hard turning is to replace any grinding operation, it must be capable of producing surfaces of acceptable quality. This includes both the surface topography (surface finish) and surface integrity, which is achieved when “the surface of a component meets the demands of a specific stress system and environment” [Kahles 1967]. Field et al. [1972] defined an “extended surface integrity data set” which includes: surface finish, microstructure, microhardness, fatigue resistance, residual stress state, and frictional characteristics.

There are two major types of surface damage that can be caused by hard turning. The first is white layer, which has generally been assumed to result from temperatures generated at the workpiece surface that exceed the austenitizing temperature of the material, followed by rapid cooling. The second type of damage is the formation of undesirable residual stress profiles at, and just below, the workpiece surface. Mechanical loading, plastic flow, and phase transformation can affect residual stresses, but negative effects are primarily due to the elevated temperatures during machining. Thus, the two types of damage (white layer and tensile residual stress) are related and have generally been investigated together. It is generally believed that generation of white layer requires both excessive heat at the workpiece surface and subsequent rapid cooling. Heat generation is attributed to large amounts of energy generated in the shear region during chip formation and to the frictional energy between the tool flank and workpiece surface. However, experimental results disagree about the source of rapid cooling. Tonshoff et al. [1995, 1996] performed hard turning experiments with and without coolant and found the
white layer magnitude was identical, indicating that workpiece self-cooling, and not coolant, must be responsible for quenching of the workpiece surface. This argument is reasonable because the heat-affected zone is small in hard turning, and because the cutting velocities are large enough that the contact time between the tool and workpiece is minimal. Therefore, it is possible that the bulk workpiece material acts as a heat sink and draws heat from the surface to create a self-cooling effect. However, Konig et al. [1990] found that cutting with a worn tool produced white layer, but that similar cutting conditions with the application of coolant resulted in undamaged surfaces.

Many researchers have paid considerable attention to the generation of white layer because it appears similar to thermal damage generated in grinding that is referred to as “grinding burn.” To determine the structure of white layer, Tonshoff et al. [1995] used an X-ray technique to determine the separate structures of the bulk workpiece material and the white layer region. The results showed that for 16MnCr5 steel hardened to 60-62 HRC, the bulk material was composed of approximately 75% martensite and 25% austenite. The white layer consisted of only 30% martensite and almost 70% austenite. However, inspection of chemical concentrations when machining ASTM 5115 showed no difference between the surface layer and bulk [Tonshoff et al.1995]. Apparently, the crystallographic structure may change, but there is not sufficient time for diffusion. Griffiths [1987] reported three situations where white layers have been generated: surfaces subjected to significant rubbing and wear (railroad tracks as an example), surfaces that see similar conditions resulting from pin-on-disk testing, and surfaces that undergo certain machining processes. Brinskmeier and Brockhoff [1999] presented evidence that in addition to machining conditions, material properties affect white layer generation. They attributed formation of all white layers to heating and quenching of the material, and concluded that
chemical composition of the material affects the transformation. Griffiths [1987] did not agree that all white layers are caused by a transformation, and suggested that other causes may be surface reactions with the environment and plastic flow that causes grain refinement. Several publications have proposed that white layers may have increased hardness relative to the bulk material [Tonshoff et al. 1995 and Akcan 1999]. Others have reported nearly identical hardness in the white layers compared with the bulk material [Chou et al. 1999].

Unlike residual tensile stress, reasonable levels of compressive stress are desirable. Based on the residual stress caused by mechanical loading only, hard turned surfaces should exhibit increased fatigue life compared to ground surfaces. However, the undesirable tensile stresses generated by heat are superimposed on the compressive stress [Tonshoff et al. 1996, Konig et al. 1993]. As tool flank wear increases, so does the frictional energy between the tool flank and workpiece, as well as the depth of the compressive stress induced by mechanical loading. Thus, increased tool wear results in larger tensile stresses near the surface, which is then followed by steep stress gradients with a larger compressive stress further below the surface. The stress pattern with less overall change was generated by a tool with very little flank wear compared to the other stress pattern, which was generated with a significantly worn tool. In addition to tool wear, tool edge geometry has an effect on the residual stress profiles that are generated. Kishawy and Elbestawi [1998] investigated the effect of the edge preparation in combination with cutting speed on the residual stresses of hardened D2 tool steel. Thiele et al. [2000] reported the effects of edge geometry, feed, and workpiece material hardness on subsurface deformation and residual stresses when finish machining hardened AISI 52100 steel.
While much attention has been paid to the influence of hard turning on surface integrity, surprisingly little has been done to understand the effects of resultant surface integrity on performance (wear resistance, strength, fatigue resistance, etc.). Significant concerns exist about white layer and tensile residual stresses on the workpiece surface, but most research has disputed these concerns about hard turned surface quality. Griffiths and Furze [1987] showed that white layers reduced wear when running block-on-ring tests on EN24T (similar to AISI 4340). Tonshoff and Brinksmeier [1998] attempted to use micro-hardness and residual stresses to identify mechanical and thermal influences on the workpiece and relate this to functional behavior. Matsumoto et al. [1991] fly cut AISI 4340 steel of 58 HRC and found that hard machined fatigue samples exhibited slightly increased endurance limits compared to ground samples. Rotating bending tests showed a 7% decrease in fatigue limit with increased tool wear [Tonshoff 1995]. The results also indicated that hard turned surfaces always exhibited comparable fatigue strength to ground surfaces. Abrao and Aspinwall [1996] performed axial fatigue tests on hard turned bars, and found that bars turned with PCBN tools performed better than bars machined with alumina tools and also better than ground surfaces. Matumoto et al. [1999] showed similar results, indicating that hard turned and super-finished components had comparable or improved fatigue life.

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

Tool material properties and workpiece properties obviously affect the wear behavior of tools. Several efforts have focused on tool composition, with the goal of determining optimal mixtures for the composite tools used in hard turning. Bossom [1990] showed that low CBN content tools (<70% CBN) produced better tool life and surfaces than high CBN content tools (>90%). Similar results have been cited by many others [Matsumoto et al. 1999]. Takatsu et al. [1983] performed tests on JIS SUJ2 bearing steel hardened to 62 HRC with tools that were identical other than CBN content. They found that flank wear and crater wear were both minimized at a CBN percentage of 55%. This confirms that lower CBN content tools perform better than high CBN content tools, but no consistent explanation for the improved performance has been presented. Luo et al. [1999] machined AISI 4340 steel (35-55 HRC) and found that hardness affected cutting forces and tool life. Both cutting forces and tool life were optimal (low forces, long life) at a workpiece hardness of 50 HRC. Matsumoto and Narutaki [1996] found adhesion of iron on the tool face when turning hardened steel with a high CBN content tool, and proposed that this adhered layer contributed to decreased tool life. However, they also found that adhesion of MnS on the tool face when machining a carburized bearing steel created a lubricating layer that reduced tool/chip friction and increased tool life. Barry and Byrne [2001] found a 400% difference in the wear rate of nominally similar 4340 steels with only slight differences in the workpiece inclusion content and size. The effect of tool wear on
the hard turning process especially on the quality of machined surfaces is an important parameter. Since much attention has been paid to surface integrity, the general influence of tool wear on white layer generation and residual stresses is better known than the mechanisms for tool wear itself. In general, CBN tools form scars on both the flank and rake surfaces of the cutting tool. Historically, flank wear has been studied more than crater wear because it is easier to measure and because it is believed to relate more directly to surface finish and surface integrity [Abrao 1995]. Increasing flank wear tends to increase the friction between the tool and workpiece, and the additional heating that results from friction was shown to cause white layer formation by Konig et al. [1993]. They also reported that the thermal effects from increased friction lead to more tensile residual stresses at the workpiece surface, but more compressive subsurface stress profiles. Chou and Barash [1995] suggested that flank wear is the main contributor to white layer formation. Chou and Evans [1996] showed that surface roughness and cutting forces increased significantly with flank wear when turning M50 steel. They found similar results for M50 formed by powder metallurgy and Sista et al. [1997] showed similar results when hard turning M2 tool steel.

The high specific energy required in machining under high cutting velocity and unfavorable condition of machining results in very high temperature which reduces the dimensional accuracy and tool life by plastic deformation and rapid wear of the cutting points [Chattopadhyay et al. 1968, Chattopadhyay 1982, Singh 1997]. On the other hand, such high temperature impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, surface and subsurface cracks [Chattopadhyay et al. 1982]. The mechanisms of material deformation, friction and material removal lead to the initiation of machined
components, where the temperature of the rake and flank is the most important factor to affect the chip formation, tool wear, cutting forces and surface integrity [Aronson 2004, Jaspers et al. 2002]. At elevated temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increased cutting forces and premature tool failure [List et al. 2005].

According to Muller and Blumke [2001], high speed machining for a given material can be defined as that speed above which shear-localization develops completely in the primary shear zone. Ekinovic et al. [2002] showed that when hardened steel is machined, high speed machining conditions appeared at cutting speed above 150 m/min. Ng et al. [2002] proposed that there is a peak cutting temperature at an intermediate cutting speed and when cutting speed is increased from this point, there is a reduction in temperature. Since this claim most of the literature has concluded that there is no corresponding reduction in temperature at higher cutting speeds. Conversely, Vernon and Ozel [2003] stated that the limit of cutting speed is a function of the cutting tools used. Ekinovic et al. [2005] suggested that temperature is increased with cutting speed up to maximum which is equal to the melting point of the work piece. No temperature reduction occurred at higher cutting speeds. But there is no fixed limit to the cutting speed when machining aluminum alloy because the melting point of this alloys (up to 600ºC) is lower than the temperature at which cemented carbide and ceramic tool materials begin to lose their strength and wear rapidly.

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. Tool
geometry is another important factor affecting machining forces, especially the feed (axial) and thrust (radial) force components [Thiele et al. 1999]. The use of large nose radius together with low depths of cut leads to low true side cutting edge angle values, thus resulting in high thrust forces [Ekinovic et al. 2002]. Liu et al. [2002] observed that the cutting temperature is optimum when the work piece material hardness is HRC 50. With further increase in the work piece hardness, the cutting temperature shows a descending tendency. Liu et al. [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.

According to Trent [1983], the cutting tool generally undergoes both flank wear and crater wear during machining. Flank wear generally causes an increase in the cutting forces, dimensional inaccuracy and vibration. Crater wear takes place on the rake face of the tool where the chip slides over the tool surface. Reed and Clark [1983] reported that the hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate. Moreover, thermal stresses in the tool increase with the temperature resulting in more cracks in the tool and premature failure of the tool. The amount of energy dissipated through the rake face of the tool raises the temperature at the flanks of the tool [Wu and Matsumoto 1999]. Rahman et al. [1997] discussed the machinability of Inconel 718 subjected to various machining parameters including tool geometry, cutting speed and feed rate on flank wear of the coated carbide inserts, work piece surface roughness and cutting force components as the performance indicators for tool life. They observed that tool life increases with the increase in side cutting edge angle for the inserts and the heat generated during the cutting process is distributed over a greater length of cutting edge. This improves the heat removal from the
cutting edge, distributes the cutting forces over a larger portion of the cutting edge, reduces
tool notching and substantially improves tool life.

Severe flank wear and notching at the tool nose and/or the depth of cutting line
are the dominant failure modes when machining nickel-based alloys with carbide tools
speeds range is from 10 to 30 m/min when machining nickel-based alloys with cemented
carbide tools [Fang 2002]. Cemented carbide tools cannot be used to machine nickel-
based alloys at high speed since they cannot withstand the conditions of extreme high
temperature and stress in the cutting zone. Rapid increase in notching occurs on carbide
tools at higher cutting speed. This usually leads to the premature fracture of the entire
insert edge [Ezugwu et al. 2004]. Flank wear generally causes an increase in the cutting
force and the interfacial temperature, leading normally to dimensional inaccuracy in the
work pieces machined and to vibration which makes the cutting operation less efficient
[Bouzid et al. 2004].

2.3 Cutting Fluids in Machining

Traditionally, the manufacture of a product had been attempted to be done as
quickly and inexpensively as possible. Now that more environmental regulations are being
put in place, manufacturers are forced to re-evaluate their manufacturing processes and
reduce or eliminate their waste streams. The waste streams present in machining include
cutting fluid flow, chip flow, and cutting tool usage. The application of cutting fluid may
not always reduce the cutting tool wear as is commonly believed. Rather some conditions
like machining steels by carbide tools, the use of coolant may increase tool wear. It has
been experienced [Shaw et al. 1951] that there was more tool wear when cutting with
coolant than cutting dry in case of machining AISI 1020 and AISI 4340 steels by M-2 high speed steel tool cutting. Seah et al. [1995] also reported that at the first stage of machining (first 40 seconds or so), tool wear was faster in wet cutting than in dry cutting. Later on, the wear rate stabilized and was somewhat the same for both dry and wet cutting. During machining, the cutting tool generally undergoes [Trent 1983] both flank wear and crater wear. Flank wear generally causes an increase in the cutting forces, dimensional inaccuracy and vibration. Crater wear takes place on the rake face of the tool where the chip slides over the tool surface.

Another experimental investigation was conducted [Cozzens et al. 1995] on single point boring. This was aimed to study the role of cutting fluid, tool and workpiece material, tool geometry and cutting conditions on machinability. The results indicated that the cutting fluid conditions had no significant effect on surface texture, forces and built-up edge. Since boring is a high-speed operation and lubrication is ineffective, no effect was seen on the forces. However, the cutting fluid was found to have a significant effect on surface integrity. Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained [Satoshi et al. 1997] by such cutting fluid. But surface finish did not improve significantly.

Wearing of cutting tools not only causes loss of the cutting edges or tips of the inserts but loss of the entire insert after wear of all the corners. From an environmental perspective, therefore, the significant waste is not the portion of the tool worn away by the tool-work contact, but the remaining portion of the tool that is disposed after its useful life [Sheng and Munoz 1993].
Manufacturing by machining constitutes major industrial activities in global perspective. Like other manufacturing activities, machining also leads to environmental pollution [Ding and Hong 1998 and Hong et al. 1999] mainly because of use of cutting fluids. These fluids often contain sulfur (S), phosphorus (P), chlorine (Cl) or other extreme-pressure additives to improve the lubricating performance. These chemicals present health hazards. Furthermore, the cost of treating the waste liquid is high and the treatment itself is a source of air pollution. The major problems that arise due to use of cutting fluids are [Aronson 1995]:

- environmental pollution due to breakdown of the cutting fluids into harmful gases at high cutting temperature and biological hazards to the operators from the bacterial growth in the cutting fluids
- requirements of additional systems for pumping, local storage, filtration, temporary recycling, cooling and large space requirement
- disposal of the spent cutting fluids which also offer high risk of water pollution and soil contamination.

Since beginning of twentieth century people [Peter et al.1996, Welter 1978, Kennedy 1989 and Thony et al. 1975] were concerned with possible harmful effects of various cutting fluid application. It has been estimated [Bennett 1983] that about one million workers are exposed to cutting fluids in the United States alone. Since cutting fluids are complex in composition, they may be more toxic than their constituents and may be irritant or allergenic. Also, both bacteria and fungi can effectively colonize the cutting fluids and serve as source of microbial toxins. Hence significant negative effects, in terms of environmental, health, and safety consequences, are associated with the use of cutting
fluids. The effects of exposure to the fluids on health have been studied for over 50 years; beginning with the concern that cutting fluid (oil) is a potential etiologic factor for occupational skin cancer. The international Agency for Research on Cancer has concluded that there is “sufficient evidence” that mineral oils used in the workplace are carcinogenic [Peter et al. 1996]. Basically, workers are exposed to metal cutting fluids via three routes [Bennett et al. 1985]; skin exposure, aerial exposure and ingestion.

Skin exposure is the dominant route of exposure, and it is believed that about 80 percent of all occupational diseases are caused by skin contact with fluids [Bennett et al. 1985]. Cutting fluids are important causes of occupational contact dermatitis, which may involve either irritant or allergic mechanisms. Water mixed fluids generally determine irritant contact dermatitis and allergic contact dermatitis when they are in touch with workers skin. Non-water-miscible fluids usually cause skin disorders such as foliculitis, oil acne, keratoses and carcinomas.

Iowa Waste Reduction Centre [1996] reported that besides potential skin and eye contact, inhalation is also a way to occupational exposure. Mists are aerosols comprised of liquid particles (less than 20 μm). During machining process, a considerable amount of heat is generated for which the cutting fluid may attain a temperature sufficiently higher than the saturation temperature. The vapour is produced at the solid liquid interface as a result of boiling. Vapour may be generated also at the liquid air interface when the fluid vapour pressure is less than the saturation pressure, namely as evaporation phenomena. Vapour generated then may condense to form mist. The non-aqueous components of the cutting fluid, such as the biocide additives, appear as fine aerosol that can enter the workroom air. Additionally, the cutting fluids impact with both stationary and rotating
elements within the machine tool system, which leads to mechanical energy being transmitted to the fluid. Thus, the cutting fluid has higher surface energy and becomes less stable and disintegrates into drops (atomization). The spray from the fluid application also may generate mist. A total fluid loss of 5 to 20 percent may occur due to evaporation, atomization, splashing and dragout processes. Whether formed by atomization or evaporation/condensation, small droplets may be suspended in the air for several hours even several days in the workers breathing zones. These drifting droplets tend evaporate further. Inhaled particles (with aerodynamic diameters less than 10 μm) deposit in the various regions of the respiratory system by the complex action of the different deposition mechanisms. The particulates below 2.5 μm aerodynamic diameter deposit primarily in the alveolar regions, which is the most sensitive region of lung. The particulates in size ranging from 2.5 μm to 10 μm deposit primarily in the air-ways. The potential health effects of exposure to cutting fluid mists have been the subjects of epidemiological studies in the automotive industry. The mist droplets can cause throat, pancreas, rectum, and prostate cancers, as well as breathing problems and respiratory illnesses. One acute effect observed is mild and reversible narrowing of airways during exposure to cutting fluid mist [Kennedy 1989].

Several other epidemiological studies have also suggested that exposure to fluid mist may be associated with increased risk of airway irritation, chronic bronchitis, asthma and even laryngeal cancer [Bennett et al. 1985 and Eisen et al. 1994]. The Occupational Safety and Health Administrations (OSHA) standard for airborne particulate (largely due to fluid mist) is 5 mg/m³, and the United Auto Workers (UAW) has proposed a reduction in the standard to 0.5 mg/m³. The oil mist level in a plant ranged from 4.2 to 15.6 mg/m³.
but fell to between 0.47 to 1.68 mg/m$^3$ when a different cutting fluid was substituted in the system [Welter 1978]

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

Pollution free manufacturing is increasingly gaining interest due to recent development of pollution-prevention legislation, European initiatives on product take-back or recycling, which affect many export industries in the US, and a growing consumer, demand for green products and production processes. Concern for the environment, health and safety of the operators, as well as the requirements to enforce the environmental protection laws and occupational safety and health regulations are compelling the industry to consider a cryogenic machining process as one of the viable alternative instead of using conventional cutting fluids.
Cutting fluids are widely used in machining operations to obtain accuracy of part dimensions, longer tool life and in some cases better surface finish. The research literature identifies two primary functions of cutting fluids in machining operations: lubrication to reduce process friction and cooling to remove process generated heat. A secondary function of the cutting fluid is to transport the chips from the cutting zone. Cutting fluid systems are used in industry to deliver fluid to the cutting process, recirculate fluid, separate chips, and collect fluid mists. The machining costs (labour and overhead) in the US alone are estimated to be $300 billion/year [Komanduri and Desai 1983]. The costs associated with the use of cutting fluids is estimated to be about 16% of the manufacturing costs [Byrne and Scholta 1993] which is many more times than the labour and overhead figures quoted above. A recent study in Germany found that 16% of machining cost in the high volume manufacturing industries is associated with the use of cutting fluids (procurement, maintenance and disposal) while only 4% of the cost was associated with cutting tools [Aronson 1995]. The use of cutting fluids also requires additional equipment for plant housekeeping.

2.4 Minimum Quantity Lubricant (MQL) Machining

The concept of minimum quantity lubricant (MQL), sometimes referred to as near dry machining refers to the use of a small amount of cutting fluid, typically in the order of 100 ml/hr or less, which is about ten-thousandth of the amount of cutting fluid used in flood-cooling machining [Klocke and Einesblatter 1999]. The concept of near dry machining is based on the principle of less lubrication with dry surface after the machining process. MQL is a method of supplying lubrication in machining to achieve both environmental and economic benefits. Typically, an MQL system supplies 0.3~0.5 ml/min
of a metal working fluid (MWF) with pressurized air or other supplemental gases, whereas a conventional system supplies about several thousand ml/min of MWF. The conventional flood supply system demands more resources for operation, maintenance, and disposal, and results in higher environmental and health problems. MQL machining has many advantages in this regard [Heisel et al. 1994].

Machado and Wallbank [1997] applied 200-300 ml/hr of lubricant when turning steel bars. The lubricant was delivered in a flowing air stream at a pressure of 29-34 psi. The experimental results showed that surface roughness, chip thickness and cutting forces variations were improved compared to the conventional flood cooling situation. The authors found that the cutting and feed forces were reduced with the use of cutting fluids when turning medium carbon steel bars under low cutting speeds and high feed rates. In some cases, cutting with near dry lubrication had better results than conventional flood cooling. Near dry machining reduced variation in cutting forces and extended the tool life. The effect of near dry lubrication on surface finish and chip thickness was only noticeable at low cutting speeds and high feed rates. Application of near dry lubrication reduced the cost of cutting fluids and related equipments. However, the aerosol concentration increased compared with traditional flood cooling case.

Varadarajan et al. [2002] performed experiments in the area of hard turning AISI 4340 with 2 ml/hr oil in a flow of high pressure air at 20 MPa. It was found that cutting under near dry lubrication had better performance than that in dry or wet cutting in terms of cutting forces, cutting temperatures, surface roughness, tool life, cutting ratio and tool-chip contact length. Lower cutting forces, lower cutting temperatures, better surface finish, shorter tool-chip contact length, larger cutting ratio and longer tool life were observed in
near dry turning compared with those in dry or wet cutting. The method to estimate the cutting temperature was also provided but there was not any comparison between predicted cutting temperatures and measurements. Chen et al. [2001] investigated the effects of oil-water combined mist on turning stainless steel with the use of 17 ml/hr oil and 150 ml/hr water mixture. The use of oil-water combined mist could prevent the production of built-up edge (BUE) while BUE was observed when cutting dry or with oil mist. BUE is an important factor of workpiece surface roughness. Therefore the workpiece surface finish under oil-water combined mist was better than that under dry, oil mist or water soluble oil applications. Lower cutting temperatures were also observed with the use of oil-water combined mist compared to cutting dry or with oil mist.

Dhar et al. [2006] investigated the influence of near dry lubrication on cutting temperature, chip formation and dimensional accuracy when turning AISI 1040 steel. The lubricant was supplied at 60 ml/hr through an external nozzle in a flow of compressed air (7 bar). Based on the machining tests, the authors found that near dry lubrication resulted in lower cutting temperatures compared with dry and flood cooling. The dimensional accuracy under near dry lubrication presented a notable benefit of controlling the increase of the workpiece diameter when the machining time elapsed where tool wear was observed. Dimensional accuracy was improved with the use of near dry lubrication due to the diminution of tool wear and damage. Rahman et al. [2001, 2002] performed experiments in end milling with the use of lubricant at 8.5 ml/hr oil flow rate. The oil was supplied by the compressed air at 0.52 MPa. The workpiece material was ASSAB 718HH steel. The experimental results showed that:
The tool wear under near dry lubrication was comparable to that under flood cooling when cutting at low feed rates, low speeds and low depth of cuts.

The surface finish generated by near dry machining was comparable to that under flood cooling.

The cutting forces were close in both near dry machining and flood cooling;

The fewer burrs formed during near dry machining compared to dry cutting and flood cooling application.

The tool-chip interface temperature under near dry lubrication was lower than in dry cutting but higher than that in flood cooling.

Lopez et al. [2006] studied the effects of cutting fluid on tool wear in high speed milling. Both near dry lubrication and flood cooling were applied when cutting aluminum alloys. In addition to experiments, they also performed computational fluid dynamics (CFD) simulations for estimating the penetration of the cutting fluid to the cutting zone. The oil flow rates of 0.04 and 0.06 ml/min were studied. The pressurized air was applied at 10 bars. The results showed that (i) with the help of compressed air, the oil mist could penetrated the cutting zone and provide cooling and lubricating while the CFD simulation showed that the flood coolant was not able to reach the tool teeth; (ii) the nozzle position relative to feed direction was very important for oil flow penetration optimization.

Braga et al. [2002] investigated the cutting forces, tool wear and hole quality when drilling aluminum-silicon alloys with a small amount of cutting fluid. The near dry lubrication was 10 ml/hr oil in a flow of 4.5 bar compressed air. The experiments showed the following trends when comparing the cutting performance between near dry lubrication and flood cooling. (i) The power consumed under near dry lubrication was lower than the
power required in flood cooling, regardless of the tool material. It was inferred that with flood cooling, the workpiece did not heat as much and it required more power to cut the aluminum-silicon alloys. (ii) The holes obtained with near dry lubrication offered either similar or better quality than those obtained with flood cooling. (iii) The flank wear behavior was similar for these two lubrication conditions. (iv) The hole roundness improvement was significant by introducing the near dry lubrication for the diamond coated drill and negligible for the uncoated drill.

Heinemann et al. [2006] investigated the effect of minimum quantity lubricant on tool life when drilling carbon steels with high speed steel twist drills. The cutting fluid flow rate was 18 ml/hr. It was found that a continuous supply of minimum quantity lubricant conveyed a longer tool life while a discontinuous supply of lubricant resulted in a reduction of tool life. A low-viscous and high cooling-capable lubricant provided a longer tool life when different lubricants were used for an external MQL-supply in the tests.

Hafenbraedl and Malkin [2000] evaluated the near dry lubrication with ester oil based on internal cylindrical grinding tests. These tests were performed when cutting AISI 52100 hardened steel with the oil flow rate of 12 ml/hr mixing with 69 kPa compressed air. The experimental results showed that with the application of near dry lubrication, lower specific cutting energy, better surface finish and higher G-ratio were observed when comparing with cutting completely dry or under flood cooling. However, the elevated bulk temperature was observed as well as thermal distortion of the workpiece for near dry grinding. This indicated that the cooling from the mixture of ester oil and cold air was not sufficient. The size accuracy would be a problem due to the thermal distortion.
Brinksmeier et al. [1997] applied minimum quantity lubrication in grinding. Two different work materials were used: hardened steel (16MnCr5) and tempered steel (42CrMo4V). MQL was implemented under 0.5 ml/min oil flow rate and 6 bar pressurized air. With reference to the grinding tests, the following results were observed: (i) both dry and near dry grinding would cause thermal damage on the hardened material with the creep feed grinding operation; (ii) acceptable surface finish was obtained under minimum quantity lubrication if the material removal rate was low; (iii) the type of lubricant used in minimum lubrication had a significant influence on the surface finish. The analysis of the cooling effect of cutting fluid for both minimum quantity lubrication and flood cooling was also presented. However, there was not a comparison between predicted and measured cutting temperatures.

2.5 Summary of the Review

A review of the literature on hard turning shows that several researchers highlight the economic justification for replacing grinding operations with hard turning. To become a realistic replacement for grinding operations, hard turning must prove its ability to create equivalent finished surfaces. In recent years, hard turning has become an attractive and effective solution of finish machining process because it has many advantages, such as higher process flexibility, shorter cycle times, lower cost, higher material removal rate, part longevity, and less environmental impact. The machining of hardened steel has become possible due to the development of a new generation of tool materials and machine tools. The turning of these materials demands the use of cutting tools with a high degree of hardness, mainly at high temperatures, and also the use of machine tools with high rigidity and very good accuracy. For machining hardened steel, advanced tool
materials, such as cubic boron nitride, polycrystalline cubic nitride, or with multilayer coated carbide tools are used. The potential economic benefits of hard turning can be offset by rapid tool wear or premature tool failure. Even, progressive tool wear can result in significant changes in cutting forces, residual stresses, and microstructural changes in the form of a rehardened surface layer. Therefore, the permissible speed, feed and depth of cut have to be restricted. Currently this problem is tried to be controlled by reducing heat generation and removing heat from the cutting zone through optimum selection of process parameters, proper cutting fluid selection and application. Minimum quantity lubricant (MQL) is a promising new technology in high production machining and grinding, which economically addresses the current processes' environmental and health concerns. In this process, MQL is impinged through a nozzle precisely at the narrow cutting zone with a spray of air and cutting oil. Significant progress has been made in dry and semidry machining recently and MQL machining in particular has been accepted as a successful semidry application because of its environmentally friendly characteristics.

### 2.6 Objectives of the Present Investigation

The present work studies some aspects on turning hardened steel using uncoated carbide insert at different speed-feed combinations under MQL condition. The influence of process parameters (speed, feed and depth of cut) on chip, chip-tool interface temperature, tool wear and surface roughness has been analysed. The current literature review reports many studies using CBN tools in machining hardened steels but it is also important to know the results when using carbide insert, mainly for economic reasons. The main objective of the present work is to make an experimental investigation on the role of
minimum quantity lubricant in turning hardened steel by uncoated carbide insert in respects of

i) chip morphology

ii) cutting temperature

iii) tool wear and

iv) surface roughness

2.7 Scope of the Thesis

Minimum quantity of lubricant (MQL) is a potential technique especially where the cutting temperature is a major constraint in achieving high productivity and job quality. The present research work has been taken up to explore the role of MQL on the major machinability characteristics in turning hardened AISI 1040 steel by uncoated carbide insert at different speed-feed combinations.

Chapter 1 presents the general requirements in machining industries, benefits of hard-turning over grinding process, role of cutting tools and technological-economic-environmental problems associated with the high cutting temperature and the conventional cooling practices and expected role of minimum quantity of lubricant (MQL) in hardened steel. Survey of previous work and objectives of the present work are also presented in Chapter 2.

Chapter 3 also presents the procedure and conditions of the machining experiments carried out and the experimental results on the effects of MQL, relative to dry machining on chip morphology, cutting zone temperature, cutting tool wear, surface roughness in turning hardened steel at different speed-feed combinations. Chapter 4
provides comparisons of cutting performance under different cutting environment at
different cutting conditions. Studies on cutting temperature, chip morphology, tool wear
and surface roughness are discussed. This chapter contains the detailed discussions on the
experimental results and possible interpretations on the results obtained. Finally, a
summary of major conclusions and references are provided at the end.
Chapter-3

Experimental Investigations

3.1 Material Preparation

The material used in the thesis was AISI 1040 steel (85-90 HRB) with approximately 0.41% carbon content. It was a hollow cylindrical bar of length 190 mm with external and internal diameters of 104 mm and 50 mm respectively. Fig. 3.1 shows the photographic view of the work piece used in this investigation. A test sample made from the same material (25 mm×104 mm×50 mm) was also prepared for the hardness test.

Electric furnace of high heating element (RG-3000°C) 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 (7.0 l/min
and 130 bar) 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. The 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 and test sample was pulled quickly but carefully out from the
furnace and was immersed vertically into the oil quenching tank. The work piece is stirred
at oil tank 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 tank
following same manner. Quenched AISI 1040 steel always required to temper because of
steels are often more harder than needed and too brittle for most practical uses. It was done
by heating the workpiece and test sample to a specific temperature (300°C), holding it at
that temperature for two hour and then cooling it instill air. 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 after heat treatment it became around 45 HRC. The hardness distribution within the
sample is shown Fig.3.2.
3.2 Experimental Procedure and Conditions

The concept of minimum quantity lubricant (MQL) presents itself as a possible solution for hard turn machining in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, provided that the MQL parameters can be strategically tuned. It has the benefits of a powerful stream that can reach the cutting area, it provides strong chip removal, and in some cases enough pressure to deburr. MQL technique not only provided reduction in temperature but also reduced the consumption of cutting fluid. The aim of the present work is primarily to explore and evaluate the role of MQL on machinability characteristics of hardened AISI 1040 steel mainly in terms of cutting temperature and chip-forms, which govern productivity, product quality and overall economy.

The machining was carried out on lathe, which has a 7.5 kW main spindle power. The photographic view of the experimental set-up is shown in Fig.3.3. The work material was AISI 1040 steel, hardened to nominal values of 45±2 HRC. Nozzle is placed 20.0 mm away from the tool tip to minimize the interference of the nozzle with the flowing chips.
and to reach quite close to the chip-tool contact zone without avoiding of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes. The positioning of the nozzle tip with respect to the cutting insert has been set after a number of trials. The final arrangement made and used has been shown in Fig. 3.4. The MQL is directed along the auxiliary cutting edge at an angle $20^\circ$ to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges.

Fig. 3.3 Photographic view of experimental set-up

Fig. 3.4 Photographic view of Minimum Quantity Lubricant delivery nozzle
Table 3.1 Experimental conditions

<table>
<thead>
<tr>
<th>Machine tool</th>
<th>Lathe Machine(China), 7.5 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work materials</td>
<td>Hardened AISI 1040 steel</td>
</tr>
<tr>
<td>Hardness</td>
<td>45 ±2 HRC</td>
</tr>
<tr>
<td>Size</td>
<td>Length= 190, External diameter =104 mm and Internal diameter = 50 mm</td>
</tr>
<tr>
<td>Cutting tool</td>
<td>SNMG 120408, Widia (Uncoated)</td>
</tr>
<tr>
<td>Geometry</td>
<td>-6°,-6°,6°,6°,15°,75°,0.8 mm</td>
</tr>
<tr>
<td>Tool holder</td>
<td>PSBNR 2525 M12 (ISO specification), Widia</td>
</tr>
<tr>
<td>Process parameters</td>
<td></td>
</tr>
<tr>
<td>Cutting velocity, $V_c$</td>
<td>72, 103 and 145 m/min</td>
</tr>
<tr>
<td>Feed rate, $S_o$</td>
<td>0.12, 0.14 and 0.16 mm/rev</td>
</tr>
<tr>
<td>Depth of cut, $t$</td>
<td>1.0 mm and 1.50 mm</td>
</tr>
<tr>
<td>Environment</td>
<td>Dry and Minimum Quantity Lubricant (MQL) condition</td>
</tr>
</tbody>
</table>

The cutting tool used was uncoated carbide insert (ISO specification: SNMG 120408 Widia). The tool holder provided negative 6° side and back rake angles and 6° side cutting-edge and end cutting-edge angles. The ranges of the cutting velocity ($V_c$) and feed rate ($S_o$) were selected based on the tool manufacturer’s recommendation and industrial practices. Keeping in view less significant role of depth of cut ($t$) on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.0 mm, which would adequately serve the present purpose. And for measuring surface roughness with machining time the depth of cut kept fixed to 1.50 mm. The conditions under which the machining tests have been carried out are briefly given in Table 3.1.

For the improvement of cutting performance, the knowledge of temperature at the chip-tool interface with good accuracy is essential. Several experimental and analytical techniques have been developed for this issue has arisen due to a difference in method of
calculation of weight at your end and ours or the measurement of temperatures generated in cutting zone. The average chip-tool interface cutting temperature was measured under both dry and MQL conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration.

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

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

During machining under each condition, the cutting insert was withdrawn at regular intervals and then the salient features like, VB, VS etc. were measured under a optical microscope (Carl Zeiss, Germany) fitted with a precision micrometer. After
machining the hardened steel rod by the SNMG insert, at different $V_c$-$S_o$ combinations under both dry and MQL conditions, the surface finish was measured by a Talysurf (Surtronic 3+, Rank Taylor Hobson Limited).

### 3.3 Experimental Results

#### 3.3.1 Machining Chips

The chip samples collected while turning the hardened steel by the insert of configuration SNMG at different $V_c$-$S_o$ combinations under both dry and MQL conditions have been visually examined and categorized with respect to their shape and color. The results of such categorization of the chips produced at different speed-feed combinations and environments have been shown in Table 3.2.

<table>
<thead>
<tr>
<th>$S_o$ (mm/rev)</th>
<th>$V_c$ (m/min)</th>
<th>Environment</th>
<th>Shape</th>
<th>Color</th>
<th>Shape</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.12</td>
<td>72</td>
<td>long tabular</td>
<td>burnt blue</td>
<td>long tabular</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>ribbon</td>
<td>burnt blue</td>
<td>ribbon</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>ribbon</td>
<td>burnt blue</td>
<td>ribbon</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td>0.14</td>
<td>72</td>
<td>ribbon</td>
<td>burnt blue</td>
<td>long tabular</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>long tabular</td>
<td>burnt blue</td>
<td>long tabular</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>ribbon</td>
<td>burnt blue</td>
<td>ribbon</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td>0.16</td>
<td>72</td>
<td>long tabular</td>
<td>burnt blue</td>
<td>long tabular</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>spiral</td>
<td>burnt blue</td>
<td>ribbon</td>
<td>gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>long tabular</td>
<td>burnt blue</td>
<td>ribbon</td>
<td>gray</td>
<td></td>
</tr>
</tbody>
</table>

The variation in value of chip reduction coefficient ($\xi$) with cutting speed and feed as well as machining environment evaluated for hardened steel have been plotted and shown in Fig.3.5.
3.3.2 Cutting Temperature

High production machining associated with high velocity and feed rate inherently generates high heat as well as high cutting zone temperature. The cutting temperature if not controlled properly, cutting tools undergo severe flank wear and notch wear, lose sharpness of the cutting edge by either wearing or become blunt by welded built-up edge and weaken the product quality. In normal cutting condition all such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode; cutting forces, tool life and product quality. High production machining needs to increase the process parameters further for meeting up the growing demand and cost competitiveness. Cutting temperature is increased with the increase in process parameter as well as with the increase in hardness and strength of the work material. Therefore, attempts are made to reduce this detrimental cutting temperature.
In the Present work, the average cutting temperature was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. The evaluated role of MQL on average chip-tool interface temperature in turning hardened steel at different $V_c-S_o$ combinations in compare to dry condition have been shown in Fig.3.6.

![Figure 3.6](image)

**Fig.3.6** Variation in average cutting zone temperature with increase in $V_c$ at different feeds during turning of hardened steel under dry and MQL conditions

### 3.3.3 Cutting Tool Wear

The cutting tools in conventional machining, particularly in continuous chip formation processes like turning, generally fails by gradual wear by abrasion, adhesion, diffusion, chemical erosion, galvanic action etc. depending upon the tool-work materials and machining condition. Tool wear initially starts with a relatively faster rate due to what is called break-in wear caused by attrition and microchipping at the sharp cutting edges.
Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature and/or dynamic loading at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness. However, in the present investigations with the tools and work material and the machining conditions undertaken, the tool failure mode has been mostly gradual wear. The geometrical pattern of tool wear that is generally observed in turning by carbide inserts is schematically shown in Fig.3.7. The major features that characterize flank wear and crater wear are also indicated in that figure.

![Fig.3.7 Schematic view of general pattern of wear](image)

The growth of flank wear, \( V_B \) with progress of machining recorded while turning hardened steel by the SNMG insert under dry and MQL conditions have been shown in Fig.3.8. The auxiliary flank wear which affects surface finish have also been recorded at regular intervals of machining under all the conditions undertaken. The growth of average auxiliary flank wear, \( V_S \) with time of machining of hardened carbon steel under dry and MQL conditions have been shown in Fig.3.9.
Fig. 3.8 Growth of average principal flank wear ($V_B$) with time recorded during turning hardened steel by SNMG insert under dry and MQL conditions.

Fig. 3.9 Growth of average auxiliary flank wear ($V_S$) with time recorded during turning hardened steel by SNMG insert under dry and MQL conditions.
3.3.4 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 dimensional and form accuracy and surface integrity of the product in respect of surface roughness, oxidation, corrosion, residual stresses and surface and subsurface microcracks. In the present work, only surface roughness and dimensional deviation on diameter have been investigated to evaluate the relative role of MQL on those two major aspects. Surface roughness is an important index of machinability which is substantially influenced by the machining environment for given tool-work pair and speed-feed conditions. Surface roughness has been measured at two stages; first, after a few seconds of machining with the sharp tool while recording the cutting temperature and second, with the progress of machining while monitoring growth of tool wear with machining time.

The surface roughness attained after 50 seconds of machining of the hardened steel by the sharp SNMG insert at various \( V_c-S_o \) combinations under dry and MQL conditions are shown in Fig.3.10. The variation in surface roughness observed with progress of machining of the hardened steel by SNMG insert at a particular set of \( V_c, S_o \) and \( t \) under dry and MQL conditions have been in shown in Fig.3.11.
Fig. 3.10  Variation in surface roughness ($R_a$) with that of $V_c$ and $S_o$ in turning hardened steel by SNMG insert under dry and MQL conditions.

Fig. 3.11  Surface roughness ($R_a$) developed with progress of machining of the hardened medium carbon steel under dry and MQL conditions.
Chapter-4

Discussion on Experimental Results

4.1 Machining Chips

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

Table 3.2 shows that under dry condition the shape of the most of the chips are ribbon. But under MQL condition, the shape of the chips is long tubular which indicate the lower in cutting temperature due to MQL condition. Again from Table 3.2 it is clear that when $V_c$ and $S_o$ increase, the chip-tool interaction temperature increases. Thus chip become burnt blue which indicate the higher cutting temperature. Again the colour of the chips have also become much lighter (gray) depending upon $V_c$ and $S_o$ due to reduction in cutting temperature by MQL condition. At dry condition the colour of the chips are very deeper, i.e. burnt blue due to high temperature. It is important to note in Table 3.2 that the role of MQL has been more effective in respect of form (shape) and colour of the chips.
when the hardened steel was machined by the groove type SNMG insert. Such improvement can be attributed to effectively larger positive rake of the tool and better cooling by the jet coming along the groove parallel to the cutting edges. However, the colour of the chips of the alloy steels significantly changed with the application of MQL comparing to dry condition. The colour of the chips is lighter in MQL condition than dry machining. This seemingly happened due to reduction in chip-tool and work-tool interface temperature.

The chip reduction coefficient ($\xi$) is an important index of chip formation and specific energy consumption for a given tool-work combination. It is evaluated from the ratio,

$$\xi = \frac{a_2}{a_1} = \frac{a_2}{S_o \sin \phi}$$

Where,

$\xi$ = Chip reduction coefficient

$a_1$ = Chip thickness before cut = $S_o \sin \phi$

$a_2$ = Chip thickness

$S_o$ = Feed rate

$\phi$ = Principal cutting edge angle

During the machining of the metals and alloys, continuous chips are produced and the value of $\xi$ is generally greater than 1.0 because chip thickness after cut ($a_2$) becomes greater than chip thickness before cut ($a_1$) due to almost all sided compression and friction at the chip-tool interface. Larger value of $\xi$ means larger cutting temperature and friction and hence is undesirable.
Chip thickness depends on almost all the parameters involved in machining. The degree of chip thickness which is measured by chip thickness ratio, plays an important role on cutting forces and hence on cutting energy requirements and cutting temperature. The effect of increase in $V_c$ and $S_o$ and the change in environment on the value of chip-reduction coefficient ($\xi$) obtained during turning hardened steel are shown in Fig.3.5 which depict some significant facts;

- values of $\xi$ has all along been greater than 1.0
- the value of $\xi$ has decreased by the application of minimum quantity of lubricant
- the value of $\xi$ decreases with increase in $V_c$ and $S_o$

Fig.3.5 shows that MQL has decreased the value of chip reduction coefficient for all $V_c$-$S_o$ combinations due to reduction in friction at the chip-tool interface, reduction in built-up-edge formation and wear at the cutting edges. Fig.3.5 clearly shows that throughout the present experimental domain the value of $\xi$ gradually decreased with the increase in $V_c$ and $S_o$ in different degree under both dry and MQL conditions. The value of $\xi$ usually decreases with the increase in $V_c$ particularly at its lower range due to plasticization and shrinkage of the shear zone for reduction in friction and built-up edge formation at the chip-tool interface due to increase in temperature and sliding velocity. In machining steels by tools like carbide, usually the possibility of built-up edge formation and size and strength of the built-up edge, if formed gradually increase with the increase in temperature due to increase in $V_c$ and also $S_o$ and then decrease with the further increase in $V_c$ due to too much softening of the chip material and its removal by high sliding speed. The percentage reduction in chip-reduction coefficient, $\xi$ attained by MQL for different
cutting velocity and feed have been calculated from the previous figures and shown in Table 4.1 for hardened steel. It is seen that the percentage reduction in chip reduction coefficient due to MQL varies 5.56 to 10.91. It can also show that at low feed and low cutting speed reduction in chip $\xi$ is more.

Table 4.1 Reduction in chip reduction coefficient, cutting temperature and surface roughness in turning hardened steel by SNMG insert

<table>
<thead>
<tr>
<th>Feed rate (mm/rev)</th>
<th>Cutting velocity (m/min)</th>
<th>Chip reduction coefficient</th>
<th>Cutting Temperature ($^\circ$C)</th>
<th>Surface Roughness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>MQL</td>
<td>%</td>
</tr>
<tr>
<td>0.12</td>
<td>72</td>
<td>2.95</td>
<td>2.63</td>
<td>10.85</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>2.75</td>
<td>2.45</td>
<td>10.91</td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>2.45</td>
<td>2.21</td>
<td>9.80</td>
</tr>
<tr>
<td>0.14</td>
<td>72</td>
<td>2.87</td>
<td>2.70</td>
<td>5.92</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>2.58</td>
<td>2.35</td>
<td>8.91</td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>2.36</td>
<td>2.14</td>
<td>9.32</td>
</tr>
<tr>
<td>0.16</td>
<td>72</td>
<td>2.70</td>
<td>2.55</td>
<td>5.56</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>2.41</td>
<td>2.25</td>
<td>6.64</td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>2.25</td>
<td>2.06</td>
<td>8.44</td>
</tr>
</tbody>
</table>

4.2 Cutting Temperature

During hard turning the maximum heat generated at the chip-tool interface, as a result temperature of chip-tool interface is increased quickly. This machining temperature at the cutting zone needs to be controlled as far as possible. Cutting temperature increases with the increase in specific energy consumption and material removal rate. Such high
cutting temperature adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products. That is why, attempts are made to reduce this detrimental cutting temperature. In some cases dry cutting is preferable in machine to hard materials at low speed. But in case of high speed machining cutting fluids may apply. Conventional cutting fluid application may, to some extent, cool the tool and the workpiece in bulk but cannot cool and lubricate expectedly and effectively at the chip-tool interface where the temperature is maximum. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in \( V_c \) when the chip-tool contact becomes almost fully plastic.

Therefore, application of MQL at chip-tool interface is expected to improve machinability characteristics that play vital role on productivity, product quality and overall economy in addition to environment-friendliness in machining particularly when the cutting temperature is very high. The average chip-tool interface temperature has been determined by using the tool work thermocouple technique and plotted against different cutting velocity, \( V_c \) under dry and MQL environment in turning hardened steel by uncoated SNMG insert.

The variation in average chip-tool interface temperature at different cutting velocity, feed and environment combinations are shown Fig.3.6. The cutting temperature generally increases with the increase in \( V_c \) and \( S_o \) though in different degree due to
increased energy input. So, for high-speed machining it is very important to control the cutting temperature. It could be expected that MQL would be more effective at higher values of $V_c$ and $S_o$. Fig.3.6 shows that MQL is better than dry machining for all the $V_c$-$S_o$ combinations. It is evident from Fig.3.6 that as the cutting velocity and feed rate increases, the percentage reduction in average cutting temperature decreases. It may be for the reasons that, the bulk contact of the chips with the tool with the increase in $V_c$ and $S_o$ do not allow significant entry of coolant jet. Only possible reduction in the chip-tool contact length by the MQL coolant jet particularly that which comes along the auxiliary cutting edge can reduce the temperature to some extent particularly when the chip velocity is high due to higher $V_c$. So, at industrial speed-feed conditions, this amount of reduction in average cutting temperature is quite significant in pertaining tool life and surface finish. The percentage saving in average chip-tool interface temperature attained by MQL for different $V_c$-$S_o$ combinations have been extracted from the previous figures and shown in Table 4.1 for hardened steel. It is seen that the percentage reduction in cutting temperature due to MQL varies 6.67 to 10.34.

### 4.3 Cutting Tool Wear

It is already mentioned that wear of cutting tools are generally quantitatively assessed by the magnitudes of $V_B$, $V_S$, $V_M$, $V_SM$ etc. shown in Fig.3.7, out of which $V_B$ is considered to be the most significant parameter at least in R&D work. It was reported earlier that application of conventional cutting fluid does not always help in reducing tool wear in machining steels by carbides rather may aggravate wear.

Among the different tool wears, the principal flank wear is the most important because it raises the cutting force and the related problems. The life of carbide tools, which
most fail by wearing, is assessed by the actual machining time after which the average value (VB) of its principal flank wear reaches a limiting value, like 300µm. Therefore attempts should be made to reduce the rate of growth of flank wear in all possible ways without sacrificing MRR. The cutting insert has been withdrawn at regular intervals to study the pattern and extent of wear on main and auxiliary flanks under both dry and MQL conditions. The gradual growth of VB, the predominant parameter to ascertain the end of tool life, has observed during turning of hardened steel by uncoated carbide (SNMG) insert at a cutting velocity 103 m/min, feed rate 0.12mm/rev and depth of cut 1.5 mm under both dry and MQL have been shown in Fig.3.8. It is clearly observed from the Fig.3.8 that the principal flank wear (VB) decreases significantly under MQL condition.

Another important tool wear criteria is average auxiliary flank wear (Fig.3.7) which governs the surface finish on the job as well as dimensional accuracy. Irregular and higher auxiliary flank wear leads to poor surface finish and dimensional inaccuracy. The growth of VS has been depicted in Fig.3.9 for different environments and here also MQL cooling permit quick reduction in VS with the progress of machining. So, it is clearly appears from Fig.3.8 and Fig.3.9 that the rate of growth of flank wears (VB and VS) decreases substantially by MQL when turning steel by SNMG inserts. Pressurized jet of MQL has easily been dragged into the plastic contact by its high energy jet, cools the interface and lubricate properly. It not only cools the interface but also reduces frictional heat generation by lubricating the friction zones.

It is also evident from Fig.3.8 that application of MQL has substantially reduced growth of VB. Such improvement by MQL can be attributed mainly to retention of hardness and sharpness of the cutting edge for their steady and intensive cooling,
protection from oxidation and corrosion and absence of built-up edge formation, which accelerates both crater and flank wear by flaking and chipping. The auxiliary flank wear, which occurs due to rubbing of the tool tip against the finished surface, causes dimensional inaccuracy and worsens the surface finish. Gradual decrease in depth of cut which is proportional to the width VS of that wear increases the diameter of the job in straight turning with the progress of machining. And the irregularity developed in the auxiliary cutting edge due to wear impairs the surface finish of the product.

4.4 Surface Roughness

The value of any machined product of given material is generally assessed by surface integrity and dimensional accuracy, which govern the performance and service life of that product. For the present study, only dimensional accuracy and surface finish have been considered for assessment of quality of product under dry and MQL machining. Surface finish is an important index of machinability or grind-ability because the quality of any machined product of given material is generally assessed by dimensional accuracy and surface integrity, which govern the performance and service life of that product. Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining.

Even in absence of all other sources, the turned surface inherently attains some amount of roughness of systematic and uniform configurations due to feed marks. The peak value of such roughness depends upon the value of feed, S, and the geometry of the turning insert. Nose radius essentially imparts edge strength and better heat dissipation at the tool tip but its main contribution is drastic reduction in the aforesaid surface roughness as indicated by the simple relationship,
\[ h_m = \frac{S_o^2}{8r} \]  \hspace{1cm} (4.2)

Where,

\[ h_m = \text{Peak value of roughness caused due to feed marks} \]
\[ r = \text{Nose radius of the turning inserts} \]
\[ S_o = \text{Feed rate} \]

In actual machining, particularly at high feed and cutting velocity, the peak value, \( h_m \), may decrease, due to rubbing over the feed mark ridges by the inner sharp edge of the flowing chips. Further deterioration of the cutting edge profile takes place due to chipping, wear etc. Formation of built-up edge may also worsen the surface by further chipping and flaking of the tool materials and by overflowing to the auxiliary flank at the tool-tip.

For the present study, only surface finish has been considered for assessment of quality of product under dry and MQL machining. Surface roughness is an important measuring criterion of machinability because performance and service life of the machined component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface micro-cracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part. However, it is evident that MQL improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.

Chip reduction coefficient is responsible for surface roughness along the longitudinal direction of the turned job. Usually surface roughness decreases with the increase in cutting velocity as cutting force decreases and chip reduction coefficient
decreases with the increase in cutting speed. Fig 3.10 shows the variation of the values of surface roughness, Ra attained of machining of hardened steel by the sharp uncoated SNMG insert at various $V_c$-$S_o$ combinations under both dry and MQL conditions. The surface roughness increases with the increase in feed, $S_o$ and decreases with the increase in $V_c$. Increase in $S_o$ raises Ra mainly. Reduction in Ra with the increase in $V_c$ may be attributed to smoother chip-tool interface with lesser chance of built-up edge formation in addition to possible truncation of the feed marks and slight flattening of the tool-tip. Increase in $V_c$ may also cause slight smoothing of the abraded auxiliary cutting edge by adhesion and diffusion type wear and thus reduces surface roughness. So, cutting velocity, $V_c$ influences on surface roughness under dry and MQL machining. It is clear that the surface roughness quite decreases with increasing cutting velocity under dry machining. In case of MQL machining, surface roughness decreases faster with increases cutting velocity. This is mainly because of formation of built-up edge frequently and behaviour of materials to be machined in dry machining compared that of MQL.

It appears from Fig.3.10 that surface roughness grows quite fast under dry machining due to more intensive temperature and stresses at the tool-tips. MQL condition appeared to be effective in reducing surface roughness. However, it is evident that MQL improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation. It has been also observed that the roughness of the machined surfaces is high at high feed rates and vice versa, under dry and MQL conditions. The factors influence in that phenomenon is the irregular deformation of the auxiliary cutting edge at the tool-tip due chipping, fracturing and wear.
It is evident in Fig.3.10 that MQL could provide marginal improvement in surface finish. The slight improvement in surface finish by MQL 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. The percentage saving in average surface roughness $R_a$ attained by MQL for different $V_c$-$S_o$ combinations have been extracted from the previous figures and shown in Table 4.1 for hardened steel.

Surface roughness for each treatment has been also measured at regular intervals while carrying out machining for tool wear study. It has been found that surface roughness grew substantially, though in different degree under different tool-work-environment combinations, with the progress of machining. Fig.3.11 shows the variation in surface roughness observed with progress of machining of the hardened steel by the SNMG insert at a particular set of $V_c$ (103 m/min), $S_o$ (0.12 mm/rev) and depth of cut (1.5 mm) under both dry and MQL conditions. Fig.3.11 reveals the pattern of growth of surface roughness. Such observations indicate distinct correlation between auxiliary 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 carbide insert. The minute grooves produced by abrasion and chipping roughen the auxiliary cutting edge at the tool-tip, which is directly reflected on the finished surface. Deep notching, if develops at the tool-tip would enhance surface roughness. Built-up edge formation also is likely to affect surface finish directly being particularly stacked to the cutting edge as well as finished surface and indirectly by causing chipping and flaking at the tool tip.
From the Fig. 3.11 it is clear that surface roughness gradually increases as usual with the machining time due to gradual increases in auxiliary flank wear (VS). In case of alloy steels, which as such has produced higher surface roughness under dry machining expectedly due to more intensive temperature and stresses at the tool-tips, MQL has appeared to be more effective in reducing surface roughness as it did for auxiliary flank wear. The rate of increase in surface roughness decreases to significant extent when machining has been done under MQL which not only reduced the VS but also possibly of built-up edge formation due to reduction in temperature. However, it is evident that MQL jet substantially improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasive, chipping and built-up edge formation.
Conclusions and Recommendation

Conclusions

Metal cutting fluids change the performance of machining operations because of their lubrication, cooling and chip flushing functions. But typically in the machining of hardened steel materials no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Though dry cutting of hardened steel gives low cutting forces and better surface finish, it worsens the cutting edges of the tool rapidly due to softening of the tool from the high cutting temperature. Minimum quantity lubrication (MQL) presents itself as a viable alternative for machining hardened steel with respect to chip formation, cutting temperature, tool wear surface roughness and dimensional deviation. Based on the observation and the experimental results obtained, the following conclusions are made:

(i) Application of minimum quantity lubricant (MQL) jet not only can reduce cutting fluid requirement but also substantial technological benefits as has been observed in machining hardened steel by uncoated carbide insert.

(ii) Due to the application of minimum quantity lubricant (MQL) in turning hardened steel, the shape and colour of the chips became favourable for more effective and efficient cooling and improved chip-tool interaction. Chip reduction coefficient decreases more predominantly by the use of
MQL than dry condition because MQL reduces the friction and compression of the chip ahead of the advancing tool. MQL has decreased the chip reduction coefficient by 5.56 to 10.91%.

(iii) The present MQL systems enabled reduction in average chip-tool interface temperature upto 10.34% and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.

(iv) The most noteworthy contribution of application of MQL jet in machining hardened steel by uncoated carbide insert undertaken is the high reduction in flank wear, which would permit either remarkable improvement in tool life or enhancement of productivity 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 thermally sensitive wear at the flanks and reduction of built-up edge formation which accelerates wear at the cutting edges by chipping and flaking. Cutting tool wear, flank wear in particular have decreased substantially due to the retardation of the temperature sensitive wear, like diffusion and adhesion when turning hardened steel under MQL.

(v) The surface finish obtained with the use of MQL is better than that obtained in the case of dry machining because MQL reduced auxiliary flank wear that is responsible for surface roughness, also reduced or eliminated the formation or possibility of formation of built-up edge due to reduction in flank temperature. MQL not only enhanced tool life but also improved
surface finish mainly by reducing the damage of the tool nose in machining the hardened steels.

Recommendations

(i) In this research only one MQL jet is applied along the rake surface. Other application methods, for example, along the main cutting edge and flank surface, can be further investigated in the future. The best solution of application methods to control tool wear and air quality can be offered through studying those configurations.

(ii) All testing presented in this work used uncoated carbide (SNMG) insert geometry, although it is not expected that this geometry is optimal for any or all cases. Previous work has shown that tool geometry affects nearly everything about the process: chip formation mode, cutting temperature, tool wear and failure, surface finish, residual stresses, and white layer generation. So experimental work should be used to identify the best tool geometry for different materials, cutting conditions, and applications.

(iii) This research work only focused on the effect of MQL on tool performance and product dimension accuracy. To achieve a better understanding of the machining process planning with environmental concerns as a factor of consideration, the cutting fluid atomization behavior in near dry turning process in order to estimate the resulting air quality can be further investigated in the future.
(iv) In this work, the pattern of flow is not considered. So for future investigations the pattern of flow of jet can be measured, i.e., whether it is laminar or turbulent. Though turbulent flow is able to transport more heat in comparison to laminar jet, but for more thinning of jet lamina flow jet is preferable. With increase in air pressure and nozzle tip diameter, the effective laminar flow pattern for more effective and efficient cooling can be easily maintained.


References


