EFFECTS OF CUTTING FLUIDS ON THE MACHINING OF HARDENED AISI 4320 STEEL

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Declaration

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.

Maisha Tabassum

This work is dedicated to my loving

Father

Aminul Islam

&

Mother

Mahbuba Rahman

Table of Contents

List of Tables

List of Figures

List of Symbols

MQL	Minimum Quantity of Lubricant
r_c	Chip-thickness ratio
a_1	Chip thickness before cut
a_2	Chip thickness
f	Feed rate
V	Cutting velocity
d	Depth of cut
ϕ	Principal cutting edge angle
BUE	Built up edge
CBN	Cubic boron nitride
PCBN	Polycrystalline cubic boron nitride
VB	Average flank wear
VM	Maximum flank wear
VS	Average auxiliary flank wear
VSM	Maximum auxiliary flank wear
VN	Flank notch wear
R_a	Surface roughness
h_m	Peak value of roughness caused due to feed marks
r	Nose radius of the turning inserts

MRR	Material removal rate
SEM	Scanning electron microscope
θ	Average chip-tool interface temperature

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Abstract

Hard turning is a profitable alternative to finish grinding in respect of dimensional accuracy and surface finish to fulfill functional requirement. improved performance and prolonged service life of the product. Hard turning is able to reduce processing time, production cost, surface roughness and setup time appreciably in comparison to grinding. But high heat generation at high production machining increase tool wear and deteriorates the job quality. The conventional cutting fluids are not that effective in such situation. Minimum quantity lubrication (MQL) is a suitable alternative in this regard.

In this research work, the effects of MQL on cutting performance of hardened AISI 4320 steel in respect of chip formation, chip-tool interface temperature, tool wear and product quality have been studied using coated carbide insert (SNMG-TN 4000). Three types of cutting fluids (soluble oil, vegetable oil and VG 68 cutting oil) have been used to compare the relative performance of those cutting fluids with each other as well as with that of dry condition.

Compared to dry condition, MQL performed better mainly due to substantial reduction in cutting temperature that enabling favorable chip-tool interaction. This also facilitated the substantial reduction in tool wear. dimensional inaccuracy and surface roughness. The results indicated that the use of minimum quantity lubrication (MQL) by VG 68 cutting oil performed better in comparison to other cutting fluids in respect of chips formation mode. cutting temperature, tool wear. surface roughness and dimensional deviation.

Chapter 1

Introduction

1.1 Introduction

Parts manufactured by casting, forming, or shaping processes often require further operations before the product is ready for use. These operations are done by machining processes. Machining is the broad term which describes the removal of material from a workpiece. Machining system covers cutting, abrasive operations such as grinding, nontraditional machining processes using electrical, chemical and optical sources of energy. The present and future manufacturing industries are essentially required to address different challenges and needs, such as high production rate, high quality and development of advanced materials, cost competitiveness and environment friendliness. All manufacturing industries and activities need to plan their strategies and resources in light of these factors.

The requirement of manufactured parts in terms of complexity, shape, material, size, etc. inevitably enforces the manufacturing firms to adapt new optimization strategies for the manufacturing processes, allowing the use of latest manufacturing techniques. The part sequences in the manufacturing process, are generally diverse, and are directly linked to the part shaping process. A process can include sequences of molding, forming, shearing, thermal treatment and finish machining process. Optimization strategies can avoid or delete certain sequences, according to the initial shapes and the necessary requirement of the final part. The actual optimization strategies aim at increasing the productivity, quality, or the cost reduction by searching

i. optimal material removal;
ii. improving machining accuracy;
iii. reduction of the number of operations and the machining allowances; and
iv. introducing of efficient and flexible sequences

Producers of machined components and manufactured goods are continually challenged to reduce cost, improve quality and minimize setup times in order to remain competitive. Frequently the answer is found with new technology solutions. Such is the case with grinding where the traditional operations involve expensive machinery and generally have long manufacturing cycles, costly support equipment, and lengthy setup times. The newer solution is a hard turning process, which is best performed with appropriately configured turning centers or lathes [1].

The conventional method for producing precision products has been soft machining and heat-treatment, finishing with rough and fine grinding, and finally honing the heat-treated component. In order to increase flexibility of production and make it more agile, manufacturers have realized the potential of replacing the grinding operations with hard turning. The turning lathe can incorporate more operations, making it easier to reset, and it has fewer type-dependent tools than a grinding machine. In short, the hard turning of components is a more suitable technology for the production of small lots than grinding.

In order to change from grinding to hard turning, three levels of substitution can be recognized: the first level substitutes rough grinding; the second level substitutes fine grinding; and the last level includes substitution of the honing operation. The more grinding and honing can be substituted, the greater are the benefits of hard turning. In order to accomplish this, it is necessary to have good knowledge of the surface integrity created by hard turning [2]. Hard machining makes a major contribution to search flexibility during the machining of hard alloys or high mechanical strength materials. In fact, intermediate operations such, as grinding operations can be eliminated. This, in most cases, leads to substantial cost reduction in manufacturing, and therefore hard turning operations are developing wide applications in industry.

Hard turning is an emerging technology that can potentially replace many grinding operations due to improved productivity, increased flexibility, decreased capital expenses, and reduced environmental waste. The ultimate aim of hard turning is to remove work piece material in a single cut rather than a lengthy grinding operation in order to reduce processing time, production cost, surface roughness, and setup time, and to remain competitive. So hard turning is a developing technology that offers many potential benefits compared to grinding, which remains the standard finishing process for critical hardened steel surfaces. High material removal rate and relatively low tool cost are some of the economical benefits. To increase the implementation of this technology, questions about the ability of this process to produce surfaces that meet required surface finish and integrity requirements must be answered. Additionally, the economics of the process must be justified, which requires a better understanding of tool wear patterns and life predictions. The potential economic benefits of hard turning can be offset by rapid tool wear or premature tool failure if the brittle cutting tools required for hard turning are not used properly. Even steady, progressive tool wear can result in significant changes in cutting forces, residual stresses, and micro-structural changes in the form of a rehardened surface layer (often referred to as white layer) [3].

The machining of hardened steel is almost always cited in literature using dry cutting, because the increase of the temperature makes chip deformation and shearing of the hardened material, easier. Nevertheless, high temperatures cause an inconvenience such as workpiece amendment, which affects dimensional and geometric accuracy and runs the risk of surface integrity. On the other hand, in complete absence of coolant, chip transportation causes an increase of tool-chip and tool-workpiece friction, as a result increased cutting force as well as abrasive wear and attrition. Currently, this problem is tried to be controlled by reducing heat generation and removing heat from the cutting zone through optimum selection of machining parameters, proper selection and application of cutting fluid. Some recent techniques have enabled partial control of the machining temperature by using heat resistant tools like coated carbides, CBN etc. Nevertheless, the drive to minimize the use of coolant whenever feasible has advantaged hard turning which has been successfully performed. Now a days, due to technological innovations, machining without cutting fluid, i.e. dry cutting, is already possible, in some situations. During dry cutting operations, the friction and adhesion between chip and tool tend to be higher, which causes higher temperature, higher wear rate and, consequently, shorter tool life.

During hard turning, generated heat is mainly dissipated in the chip and in the workpiece, a rather small part of heat flows to the tool. However, the highest temperature is obtained at the tool–chip interface that leads to diffusion wear and cutting edge degradation. The heat generated usually alters the microstructure of the alloy and induces residual stresses. Residual stresses are also produced by plastic deformation without heat. Heat and deformation generate cracks and micro structural changes, as well as large micro hardness variations.

Applying cutting fluids in the metal cutting process is the most common strategy to improve tool life, product surface finish, size accuracy and make chip-breaking and chip-transport easier. The conventional cutting fluids utilized in machining cause several negative effects, since these fluids can seriously damage human health and environment. Environmental concerns have become increasingly important to production processes, allied with their economic and technological aspects. These combined factors have driven the industrial sector, research centers and universities to investigate alternative production processes, to create technologies that minimize or avoid the production of environmentally aggressive residues. Large quantities of emulsion-based cutting fluids for machining are still widely used in the metal working industry, generating high costs of consumption and disposal and affecting the environment. The increasing need for environmentally friendly production techniques and the rapid growth of cutting fluid disposal costs have justified the demand for an alternative to machining processes using fluids [4, 5]. Over the last decade, however, the goal of research in this field has been to restrict as much as possible the use of cooling fluids and/or lubricants in metal-mechanical production processes. The economical and environmental concerns on the use of cutting fluids lead to the research of near dry machining several years ago [6, 7]. 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 [8, 9]. The concept of near dry machining is based on the principle of less lubrication with dry surface after the machining process. This is the minimum quantity lubrication required in the machining process. Therefore, near dry machining is also recognized as minimum quantity lubrication (MQL) machining.

Minimal quantity lubrication (MQL) is a method of supplying lubrication in machining to achieve both environmental and economical 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 [6, 10, 11].

Minimum quantity lubrication (MQL) system has long been employed successfully in various metal cutting, sawing and shaping processes. This system employs mainly cutting fluids that are non-soluble in water, especially mineral oils. Due to the very small amounts of cutting fluids used, one must consider that the costs should not prevent the use of high technology compositions in the field of additive oils. Vegetal-based materials are being increasingly used. According to Heisel et al. [12], these oils, inhaled in the form of aerosol, reduce the health hazard factor. Over the years several researchers have employed minimum quantity of lubricants in machining and grinding of steels and advanced materials and reported that if employed judiciously and effectively, minimum quantity of lubricants can effectively combat the high cutting temperature inherent in high production machining and grinding [12-16].

Machining of hardened steel and other difficult-to-cut materials requires instant heat transfer from the cutting edge of the tool to improve tool life. Supply of cutting fluid often provides the best answer. Machining by MQL condition has been widely used on so-called "hard to machine materials" such as high-temperature alloys like hardened steels and titanium. These materials cannot be cut effectively without cooling, even though dry cutting is becoming increasingly widespread. The use of cryogenic coolant easily reduces cutting temperature and chip load, provides improved tool life and surface finish as a result increase all the machinability indices. But the use of cryogenic coolant is limited due to the high cost and difficult handling of cryogen.

The knowledge over the performance of cutting fluids when applied to different work materials and operations is of crucial importance in order to improve the efficiency of most conventional machining processes. This efficiency can be measured, among other parameters, through cutting tool life and workpiece surface finish. However, the costs associated with the purchase, handling and disposal of cutting fluids are leading to the development of tool materials and coatings which do not require their application. In this work, the performance of three types of cutting fluids (two emulsions and one synthetic fluid) will be compared to dry cutting when continuous turning hardened AISI 4320 steel using coated carbide insert (SMNG-TN 4000). The following parameters will be evaluated: cutting temperature, chips form, tool wear mechanism, surface finish and dimensional accuracy.

1.2 Survey of the Previous Work

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

This chapter is intended to provide background information relevant to this research. Because hard turning requires advanced cutting tool materials, descriptions of several candidate materials are presented with arguments for or against their selection for machining hardened steels. Next, a brief introduction to tool wear is given. After the introductory material, recent research in hard turning is reviewed so that the importance of this research in the context of other work will be evident. The literature review is categorized into the following areas: machine tool requirements, dimensional accuracy, chip formation mechanism, surface integrity, effects of surface integrity on performance and tool wear.

1.2.1 Hard Turning

The manufacture of a product had been attempted to be done as rapidly and inexpensively as possible. Now that more environmental regulations are being put in place, manufacturers are forced to re-evaluate their manufacturing processes and reduce or eliminate their waste streams. The waste streams present in machining include cutting fluid flow, chip flow, and cutting tool usage. The machining temperature could be reduced to some extent by improving the machinability characteristics of the work material and surface integrity minimized by optimizing the tool geometry and by proper selection of the process parameters. Hard turning of machine parts is a production process that holds considerable promise for the future since it is an effective means of increasing productivity. In recent years hard turning become an attractive and effective solution of finish machining process because it has many advantages, such as higher flexibility, shorter cycle times, lower cost, and a higher material removal rate [17].

Precision hard turning applications have increased drastically in manufacturing industry because it potentially provides an alternative to conventional grinding in machining hardened components. This new technology significantly reduces the production time, tooling costs and the capital investment [18], especially for low volume production. Koning [19] also presented that turning of hardened steels have been an attractive alternative to costly, yet environmentally harmful, grinding processes. Benefits of hard turning over grinding have been reported including short cycle time, process flexibility, part longevity, and less environmental impact. Scientific and engineering issues of hard- turning, been frequently investigated, range from cutting mechanics, tool wear surface integrity, to part accuracy [20].

Tonshoff et al. [21] found numerous advantages to replacing grinding with hard turning operations. Even though small depths of cut and feed rates are required for hard turning, material removal rates in hard turning can be much higher than grinding for some applications. It has been estimated that resulting reduction in machining time could be as high as 60% [22]. This would facilitate flexible manufacturing systems and reduced batch sizes, which are becoming more important in industry. Aside from decreases in machining time, a reduction in the number of required machine tools may also be observed as a result of the increased flexibility of the turning process as compared to grinding [19, 21]. A reduction in the number of machine tools would also be likely to reduce part handling costs and the cost associated with multiple operators and machine setups. Another cost and environmental advantage of hard turning is the possible elimination of cutting coolant.

It seems obvious that hard turning is an attractive replacement for many grinding operations, but implementation in industry remains relatively low, particularly for critical surfaces. This is because hard turning is a relatively new processing technique, and several questions remain unanswered. Hard turning can influence the workpiece surface microstructure by generating undesirable residual stress patterns and over-hardened surface zones that are referred to as "white layers" [22, 23]. The cause and effect of these residual stress patterns and white layer generation are not fully understood. Also, because cutting tools required for hard turning are much more expensive than tools for conventional turning, tool life must be investigated to assure the economic justification for replacing grinding operations with hard turning. To become a realistic replacement for many grinding operations, hard turning must prove its ability to create equivalent finished surfaces. Geometric tolerances must be held, and undamaged surfaces that conform to surface roughness requirements must be generated.

Auschner [24] and Konig et al. [23] have shown that under ideal conditions, part geometry and surface finish comparable to those generated by grinding can be hard turned with extremely rigid machine tools and new cutting insert materials. However, with less rigid machines and improper cutting conditions, tool wear becomes excessive and eliminates any cost savings associated with hard turning. Worn cutting tools have also been found to increase the magnitude of surface damage observed on hard turned components. White layer and residual tensile stresses have been found to exist, and are expected to reduce fatigue life. However, Abrao and Aspinwall [25] in their research comparing the fatigue lives of hard turned and ground surfaces found the hard turned surfaces to have increased lives despite the existence of brittle white layers. Compressive stresses have also been found on hard turned surfaces that improve fatigue lives [26, 27] Thiele et al. [28] reported that residual stresses on the machined surface are known to influence the service quality of the component, such as fatigue life and tribological properties, and distortion. The profile (magnitude and direction along the depth) of the residual stresses can greatly enhance or reduce the fatigue life of a bearing. It is believed that compressive residual stresses are more favorable for rolling contact fatigue life than tensile residual stresses.

1.2.2 Tool Wear with Heat Resistance Tools

Hard turning is a turning operation performed on high strength alloy steels ($45<HRC<65$) in order to reach surface roughness close to those obtained in grinding.

Extensive research being conducted on hard turning has so far addressed several fundamental questions concerning chip formation mechanisms, tool-wear, surface integrity and geometric accuracy of the machined components. The major consideration for the user of this relatively newer technology is the quality of the parts produced. A notable observation is that flank wear of the cutting tool has a large impact on the quality of the machined parts (surface finish, geometric accuracy and surface integrity). For components with surface, dimensional and geometric requirements (e.g. bearing surfaces), hard turning technology is often not economical compared with grinding because tool-life is limited by the tolerances required (i.e. high flank wear rate). Poulachon et al. [29] present the various modes of wear and damage of the polycrystalline cubic boron nitrides (PCBN) cutting tool under different loading conditions, in order to establish a reliable wear modeling. Flank wear has a large impact on the quality of the parts produced and the wear mechanisms have to be understood to improve the performance of the tool material, namely by reducing the flank wear rate. The wear mechanisms depend not only on the chemical composition of the PCBN, and the nature of the binder phase, but also on the hardness value and above all on the microstructure (percentage of martensite, type, size, composition of the hard phases, etc.) of the machining work material.

The potential economic benefits of hard turning can be offset by rapid tool wear or premature tool failure if the brittle cutting tools required for hard turning are not used properly. Even steady, progressive tool wear can result in significant changes in cutting forces, residual stresses, and microstructural changes in the form of a rehardened surface layer (often referred to as white layer). Research in this area has often focused on the choice of appropriate cutting tool materials, with results typically indicating that CBN tools perform better than carbides or alumina based tools [17, 30-32]. Under proper conditions, CBN tooling can easily pay for its expensive initial cost with substantial tool life. However, short tool life is not the only result of rapid tool wear. Flank wear has been found to be the most significant factor affecting the depth of white layer [33]. Similar detrimental effects on residual stresses and white layers have been found by others [17, 22, 25, 34]. Thus, even acceptable wear rates can lead to tools that produce unacceptable surface integrity. Without a better understanding of the wear behavior of CBN tools and the effects of worn tools on workpiece surface quality, implementation of hard turning will remain limited.

High flexibility and the ability to manufacture complex workpiece geometry in a single step represent the main advantage of hard turning in comparison to grinding. Furthermore, Liu and Mittal [35] concluded that the substitution of the grinding processes with hard turning enables the avoidance of coolants and it is a green machining technology. Despite these advantages, not many developments have been sees in recent years. There has been very little research to help to understand the interaction between the workpiece hardness and PCBN tool under comfortable cutting condition [36]. Udea et al. [37] investigated the influence of the cutting temperature and the workpiece material of the cutting edge. From two-color pyrothermal radiation of the tool conducted through a hole of an internally turned tube, it can be clearly stated that the temperature increases with the cutting speed and with the hardness of the work piece. Elbestawi et al. [38] experimentally found that the cutting performance of PCBN tools during the high speed finish milling of H13 tool steel of hardness up to HRC 55 their experimental result show that the wear on high CBN tools decrease as the workpiece hardness increase. Fleming and Valentine [39] estimated that the self induced heat generation at the cutting zone is up in the range of 650-750°C, and is enough to reduce the hardness of the material in contact with the cutting tool. The heat induced soft cutting means that the PCBN is not in contact with the workpiece in its hard state, thus giving the PCBN a longer tool life compared with that of other cutting materials. Liu et al. [40] showed that, the changing role of cutting temperature is not in accord with the traditional metal cutting theory. When the workpiece material hardness is HRC 50, the cutting temperature is optimum. With further increase in the workpiece hardness, the cutting temperature shows a descending tendency. Again it is found that the effects of cutting speed on the PCBN tool are much less than the carbide tool and the ceramic tool.

Balzers [41] showed about 80% of all machining operations are now performed with coated tools, Among the coating systems available on the market, titanium-based hard thin films have found the widest acceptance. They tend to improve the wear resistance in many cutting applications [42, 43], by reducing friction, adhesion, diffusion and to relieve thermal and mechanical stresses on the substrate. Grzesik [44] studied the cutting mechanics of various coated carbide tools. He shows that depending on the coating, the tool–chip contact area and the average temperature at the tool–workpiece interface are modified, without proving that coatings are able to insulate the substrate.

According to Ko¨nig et al. [30], for turning hardened steels, cutting tools must be made of materials which fulfill the following requirements: high degree of hardness at low and high temperatures: high transverse rupture strength (higher than 390 N/mm2); high toughness; high compression strength, high resistance to thermal shock and high resistance to chemical reactions. Tonshoff and Amor [45] observed that the improved hard tool materials like PCBN, uncoated carbide, ceramics, and more rigid machine tools provide high flexibility and ability to manufacture of complex workpiece geometry in a single step which also represents the main advantage of hard turning. Furthermore, the hard turning enables the avoidance of coolants and it is a green machining technology.

Machining hardened steels using advanced tool materials, such as PCBN, or with multilayer coated carbide tools at high cutting speeds has certain advantages compared to the traditional machining sequence of processes, i.e., soft machining, heat treatment and grinding. Lower cutting force, residual stress, reduced cycle time and mainly low energy consumption, are some of those advantages, [46-48]. According to Ezugwu et al. [49] and Coelho et al. [50], PCBN tools offer excellent performance when machining hardened steels; however, their costs are still relatively high. Therefore, it becomes interesting some studies on machining hardened steels using multilayer-coated carbide tools, which appear to be the best choice for carbide. This work assesses some aspects of turning hardened AISI 4340 (48-50HRC) using TiCN-Al2O3-TiN. Some heat also arises on the tertiary zone, where the tool relief face slides on the newly machined surface. This last source is, however, not considered in most cases, either for simplicity, or because the heat generated is very small when using sharp cutting edges. The heat generated in those zones is distributed among the tool, the workpiece, the chip, and after that to the environment. Heat generated at the shearing plane can make the cutting action easy, but it can flow into the cutting edge and that will negatively affect tool life by shortening it. In general, the most important point in machining processes is the productivity, achieved by cutting the highest amount of material in the shortest period of time using tools with the longest lifetime. Combining all the parameters involved in the machining process to maximize productivity is, nevertheless, a very complex task and becomes much more difficult when working at high speed cutting in hardened steels. In general, when machining steel with coated carbide tools different tool wear mechanisms occur, such as: abrasion, adhesion, oxidation and even some diffusion, which act simultaneously and in proportions depending mainly on the temperature, [51].

Machining of hardened steel components using geometrically defined cutting tools have been researched by [19] and developed to replace some grinding operations that are costly, yet degrade the environment due to coolant needed in grinding. Ceramic materials with high hardness, in particular, cubic boron nitride (CBN), have been employed in machining hardened steel [22, 24]. Even though there have been reports of successful examples of using CBN tools for hard turning, the practices in the industry are still not widespread. One challenge is tool and work material selections at different conditions, e.g. continuous versus intermittent cutting. CBN tool materials have different compositions and can be significantly different in performance. High CBN content tools with metallic binder (CBN-H) are recommended for roughing, but low CBN content tools with ceramic binder (CBN-L) are more appropriate for finishing. Furthermore, microstructures of the work material can also remarkably affect the hard turning process.

In hard turning, Frederick Mason [52] conclude that the temperatures generated by the cutting speeds of today's advanced tooling can actually prevent low pressure flood coolant from entering the cutting zone. The majority of the cooling and lubricating aspects of a flood coolant stream are lost as the coolant is vaporized prior to entering the cutting zone.

Aneiro et al. [53] stated that by measuring the temperature underneath the carbide insert and using the gradient to calculate values near the rake face, in real machining conditions, has shown reasonable values. Some resulted relatively low, compared to some other previous works, although within the same range. Temperature near the rake face increases significantly when the doc changes from 0.2 to 0.4 mm. The increase in contact length between chip and rake face can be responsible, since it grows, together with uncut chip cross section. The results obtained, show that only the doc is significant within 95% confidence interval, for the temperature, in the range tested. Tool life was particularly long for the coated carbide tested, yielding around 7,000 m of cutting length with relatively low flank wear. If that is compared to PCBN tool at similar cutting conditions, it is about half tool life, but PCBN prices are, probably, more then twice coated carbide price. Surface roughness values were all below 0.9 mm Ra and at the best cutting conditions, it could be kept below 0.4 mm Ra. Those values are inside the range normally obtained by grinding operations at normal cutting conditions.

1.2.3 Surface Integrity during Hard Turning

A large number of theoretical and experimental studies on surface roughness of hard turned products have been reported. These studies show that cutting conditions such as cutting speed, feed rate, depth of cut, tool geometry, and the material properties of both the tool and workpiece significantly influence surface finish of the machined parts. In some studies, roughness has been measured directly with a stylus to obtain the surface profile. Thus, a stylus can be used for in-process measurement [54]. However, use of a stylus results in destruction of the sensor head due to high surface speeds of the workpiece. Tracing has also been accomplished by using a vibratory stylus [55]. Real-time measurement of roughness implies assessing the conditions of the workpiece just behind the cutting edge of the tool. Surface inspection has been conducted typically as a post process operation, which is both time consuming and uneconomical since a number of non-conforming parts can be produced prior to inspection. However, since the workpiece rotates at relatively high speeds in turning operations, in-process measurements should be taken with non-contact transducers. Optical reflection has been restricted to measurements of relatively smooth surfaces generated by lapping, grinding and other fine machining. This technique is based on the principle that reflected light from the relatively smooth surface exhibits an exponential distribution with regard to the detecting angle. A definite relation has been found by Sathyanarayanan and Radhakrishnan [56] between the average inclination of roughness profile and the surface roughness, providing that a limited range of the finishing operation remains consistent..

Surface properties such as roughness are critical to the functionality of machined components. Increased understanding of surface generation mechanisms can be used to optimize machining processes and to improve component functionality. As a result, numerous investigations have been conducted to determine the effect of parameters such as feed rate, tool nose radius, cutting speed and depth of cut on surface roughness in turning operations [57-60]. These investigations show consistently that the surface roughness is predominantly a function of the feed rate. However, these investigations are unable to explain and predict the surface roughness at low feed rates typical of finish machining. Because the results from prior investigations of surface roughness do not sufficiently account for the behavior at low feed rates, motivation exists to study the effects of additional factors largely neglected in previous studies. These factors include the tool cutting edge geometry and the workpiece material properties. The cutting edge geometry, commonly referred to as edge preparation, is particularly significant in finish turning because the feeds used for finish cuts are often of the same order of magnitude as the edge geometry. Therefore, much of the tool-workpiece interaction occurs along the cutting edge. Workpiece properties are significant because the plastic deformation of the workpiece contributes to the surface generation process and these properties can be modified to vary the plastic deformation characteristics. Hard turning serves as an ideal process to examine the effects of workpiece properties and tool edge geometry on the surface roughness and on additional responses such as the cutting forces. Workpiece properties such as hardness are significant in hard turning because this process is defined by a characteristic type of chip formation (segmented), resulting typically from the machining of high-hardness materials [61, 62]. Additionally, hard turning encompasses a relatively wide range of workpiece hardness values (45-70 HRC). Cutting tool edge geometry is critical in hard turning because tools with superior edge strength are required to withstand the large tool stresses produced. As a result, various types of edge configurations such as hones and chamfers are applied to the insert [19]. Furthermore, when hard turning is typically used as a finishing process, the un-deformed chip thickness is the same order of magnitude as the cutting edge geometry.

In a study related to hard turning of bearing races, Liu and Mittal [27] found that the integrity of the hard turned surface is better than that generated by abrasive super finishing processes. The microprofile of the turned surface has a lower root mean square surface roughness for equivalent average surface roughness. Rech and Moisan [63] presented that finishing cutting processes, such as grinding or hard turning, have a great influence on the surface integrity, because of the thermomechanical material removal mechanisms. The hard turning process is interesting with regard to its capacities to produce a low surface roughness (*Ra* is less than 0.2 μm) during a long cutting time and also to induce compressive residual stresses when machining at low feed rate and low cutting speed. Feed rate is the major parameter that influences the surface roughness, whereas cutting speed is the major parameter that influences the residual stress level.

Thiele and Melkote [26] published the results of an investigation concerning the effect of cutting edge geometry and workpiece hardness on surface generation in finish hard turning. They found that increasing the edge hone radius tends to increase the average surface roughness. They attributed this to the increase in the ploughing component compared to the shearing component of deformation. The effect of edge hone on the surface roughness decreased with increase in workpiece hardness. However, Thiele and Melkote did no refer to the effect of edge hone when tool wear starts to occur. Elbestawi and Kishawy [38] published in 1999 their conclusions regarding the effects of process parameters on material side flow during hard turning. They noted that even a small feed should improve the surface finish, it could actually lead to more material side flow on the machined surface and hence, to a deterioration of the surface quality. In addition increasing the tool nose radius led to ploughing of a larger part of the chip, hence, a severe material side flow exists on the machined surface. Their experiments were carried out on bars of carbon nitride case hardened steel AISI 4615 (60HRC) using BZN 8100 PCBN cutting inserts.

Ko and Kim [64] instigated the surface integrity and machinability in intermittent hard turning considering a ball bush made of AISI 52100 as workpiece. The conclusions were that the low content CBN tool is superior to a high content CBN tool in terms of tool wear and surface integrity for intermittent hard turning. However, they concentrated their attention on the so-called white layer and the characteristics of the residual stresses. Not many authors specifically concentrated their research on the effect of tool wear to surface roughness evolution in hard turning. Their findings and area of investigation are still reduced to a restricted number of machining conditions.

El-Wardany et al. [65, 66] studied the quality and integrity of the surface produced and the effects of cutting parameters and tool wear on chip morphology during high-speed turning of AISI D2 cold work tool steel in its hardened state (60–62 HRC). The metallographic analysis of the surface produced illustrates the damage surface region that contains geometrical defects and changes in the sub surface metallurgical structure. The types of surface damage are dependent on the cutting parameters, tool geometry and the magnitude of the wear lands. Kishawy and Elbestawi [67] investigated the tool wear characteristics and surface integrity during high-speed turning of AISI D2 cold work tool steel. A wide range of residual stress distributions beneath the machined surface was obtained depending on the cutting parameters and edge preparation. The unfavorable tensile residual stresses were minimized at high cutting speeds and high depths of cut.

Hard turning is also very attractive to manufacturers because this process is possible without the use of cutting fluid or other lubricants. Dry cutting is beneficial because of the elimination of the cost of the cutting fluid as well as the high cost of fluid disposal [68]. As the environmental impact of manufacturing processes is under more scrutiny today than ever, manufacturers may find it advantageous to use dry cutting processes [69].

In hard turning, cutting forces and heat generation are higher in hard turning since cutting speeds are relatively low, a greater fraction of the heat generated during chip formation will be conducted into the part. Coolants are often not used in hard turning in order to reduce costs and to prevent tool breakage from thermal shock. According to Reach and Moisan [63] finishing cutting processes, such as grinding or hard turning, have a great influence on the surface integrity, because of the thermomechanical material removal mechanisms. The hard turning process is interesting with regard to its capacities to produce a low surface roughness (Ra< 0.2 μm) during a long cutting time and also to induce compressive residual stresses when machining at low feed rate and low cutting speed. Feed rate is the major parameter that influences the surface roughness, whereas cutting speed is the major parameter that influences the residual stress level.

1.2.4 Hard Turning with MQL

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

Vleugels et al. [70] observed that the contact length between the tool and chip has a direct influence on the cutting temperatures and the amount of heat energy that is dissipated in the tool which enhances thermally activated chemical wear. Maximum temperature is found to develop on the rake face of the tool. at a certain distance from the cutting edge, where crater wear occurs. The amount of energy dissipated through the rake face of the tool also raises the temperature at the flanks of the tool. Reed et al. [71] reported that the hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate. Moreover, thermal stresses in the tool increase with the temperature resulting in more cracks in the tool and premature failure of the tool. The high cutting temperature also causes mechanical and chemical damage of the finished surface. Machining involves extensive plastic deformation ahead of the tool in a narrow shear zone and friction between the rake face and the chip; high tool temperatures; freshly generated, chemically active surfaces that can interact extensively with the tool material and high mechanical and thermal stresses on the tool [72].

The current trend in machining practice is higher material removal rates and or higher cutting speeds. The cutting tool must resist these severe conditions and provide a sufficiently long economical tool life. Often, a cutting fluid is used to reduce the tool temperatures by cooling and reduced the heat generated due to friction by acting as a lubricant. In high speed machining conventional types and methods of application of cutting fluid have been found to become less effective. With the increase in cutting velocity and feed, 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.

Usually the high cutting temperature is controlled by profuse cooling [73-75]. But such profuse cooling with conventional cutting fluids is not able to solve these problems fully even when employed in the form of jet or mist. With the advent of some modern machining process and harder materials and for demand for precision machining, the control of machining temperature by more effective and efficient cooling has become extremely essential. Generally, suitable cutting fluid is employed to reduce this problem through cooling and lubrication at the cutting zone. But it has been experienced [76] that lubrication is effective at low speeds when it is accomplished by diffusion through the workpiece and by forming solid boundary layers from the extreme pressure additives, but at high speeds no sufficient lubrication effect is evident. The ineffectiveness of lubrication of the cutting fluid at high speed machining is attributed [77] to the inability of the cutting fluid to reach the actual cutting zone and particularly at the chip-tool interface due to bulk or plastic contact at high cutting speed.

Enormous efforts to reduce the use of lubricant in metal cutting are being made from the viewpoint of cost, ecological and human health issues [6-7, 78-79]. Minimal quantity lubrication (MQL) can be considered as one of the solutions to reduce the amount of lubricant. Again 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 Minimum Quantity Lubricant (MQL) machining process as one of the viable alternative instead of using conventional cutting fluids. In some applications the consumption of cutting fluids has been reduced drastically by using mist lubrication. However, mist in the industrial environment can have a serious respiratory effect on the operator [80]. Consequently, high standards are being set to minimize this effect. Use of cutting fluids will become more expensive as these standards are implemented leaving no alternative but to consider environmentally friendly manufacturing.

An experiment was preformed in the area of hard turning AISI 4340 with 2 ml/hr oil in a flow of high pressure air at 20 MPa by Varadarajan et al. [81] 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.

Apart from the cost aspects, Heisel et al. [82] found that cutting fluids represents a serious problem to the preservation of the environment and to human health. Therefore, Minimum volume of oil (MOV) technique may represent a compromise between the advantages and disadvantages of completely dry cutting and cutting with abundant soluble oil. MVO is a technique, which consists of the application of a very small volume of cutting oil (usually less than 100 ml/h), in a flow of compressed air. This small amount of oil, most of the time is enough to substantially reduce friction and to avoid the adhesion of the chip on the tool. When abundant cutting fluid is used, the machined surface is flooded, while when MVO is used the lubricant is placed just in the contact area of the tool-chip and tool-workpiece. In this technique, the lubrication function is carried out by the oil and cooling is provided mainly by compressed air. Comparing the above to wet cutting, Heisel et al. [83], pointed out some advantages: (a) the amount of fluid used is much lower; (b) reduction of costs with oil maintenance, recycling and rejection; (c) the workpieces remain almost dry, eliminating washing operation; (d) the low content of oil which stays on the chips makes their drying unnecessary.

An experiment was done to investigate 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 [84]. 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. 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. Diniz et al. [85] applied 10 ml/hr oil in turning AISI 52100 steel with CBN tools. The supplied air pressure was 4.5 bars. According to the experimental data, the following conclusions were drawn. (i) Dry and near dry machining had similar performance in terms of CBN tool flank wear, always better than the tool life under flood cooling. (ii) The workpiece surface roughness measured in near dry cutting was close to that obtained from dry cutting.

When turning AISI 1040 steel the influence of near dry lubrication on cutting temperature, chip formation and dimensional accuracy was investigated by Dhar et al. [15]. 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.

The effects of cutting fluid on tool wear in high speed milling were studied by Lopez et al. [86]. 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. Sasahara et al. [87] reported that in the case of helical feed milling for boring aluminum alloy, cutting forces, cutting temperature and dimension accuracy under near dry lubrication were close to those under flood cooling condition. Rahman et al. [9, 88] 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: (1) 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; (2) the surface finish generated by near dry machining was comparable to that under flood cooling; (3) cutting forces were close in both near dry machining and flood cooling; (4) fewer burrs formed during near dry machining compared to dry cutting and flood cooling application; (5) the tool-chip interface temperature under near dry lubrication was lower than in dry cutting but higher than that in flood cooling.

The effect of minimum quantity lubricant on tool life when drilling carbon steels with high speed steel twist drills was investigated by Heinemann et al. [89]. 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. Brinksmeier et al. [14] applied minimum quantity lubrication in grinding. Two different work materials were used: hardened steel (16MnCr5) and tempered steel (42CrMo4V). The minimum quantity lubrication 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

Itoigawa et al. [90] investigated the effects and mechanisms in minimal quantity lubrication by use of an intermittent turning process of aluminum silicon alloy. Especially a difference between minimal quantity lubrication (MQL) and MQL with water is inspected in detail to elucidate boundary film behavior on the rake face. He concluded that MQL with water droplets gives good lubrication performance if the appropriate lubricant, such as synthetic ester, is used. MQL with synthetic ester, without water, shows a lubrication effect. However, tool damage and material pick-up onto the tool surface cannot be suppressed.

1.2.5 Summary of the Review

A review of the literature on machinability of different commercial hardened steel shows that several researchers highlights the economic justification for replacing grinding operations with hard turning. To become a realistic replacement for many grinding operations. hard turning must prove its ability to create equivalent finished surfaces. Hard turning of machine parts is a production process that holds considerable promise for the future since it is an effective means of increasing productivity. 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. Again this new technology significantly reduces the production time, tooling costs and the capital investment. The ultimate aim of hard turning is to reduce force, temperature, tool wear. tool life, quality of surface turned, and amount of material removed are also predicted.

According to the researchers for turning hardened steels cutting tools plays very important role. The machining of hardened materials 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. The principal properties expected from any tool material are high hot hardness, toughness and chemical stability. For machining hardened steels advanced tool materials, such as cubic boron nitride (CBN), polycrystalline cubic nitride (PCBN), or with multilayer coated carbide tools are used.

Through reviewing the literature it is investigated that the control of machining temperature and its detrimental effects. It is realized that the machining temperature has a critical influence on chip formation mode, tool wear, tool life, surface roughness and dimensional deviation. All these responses are very important in deciding the overall performance of the tool. At the elevated temperature the cutting tools may undergo plastic deformation and attain rapid tool wear because by adhesive, abrasive, chemical and diffusion wear at the flanks and the crater. The dimensional accuracy and surface integrity of the workpiece also deteriorate due to high temperature. The conventional cutting fluids are not that effective in high speed machining particularly in continuous cutting of materials likes steels. Further the conventional cutting fluids are not environment friendly. The disposal of the cutting fluids often leads to local water pollution and soil contamination. Recycling and reuse of conventional cutting fluids are further problems.

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 the minimum quantity lubrication (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 minimum quantity lubrication (MQL) machining in particular has been accepted as a successful semidry application because of its environmentally friendly characteristics.

Completely dry cutting has been a common industry practice for the machining of hardened steel parts. These parts typically exhibit a very high specific cutting energy. Traditional beliefs indicate that completely dry cutting of them, as compared to flood cutting, lowers the required cutting force and power on the part of the machine tool as a result of increased cutting temperature. However, achievable tool life and part finish often suffer under completely dry condition. Therefore, the permissible feed and depth of cut have to be restricted. Under these considerations, the concept of minimum quantity lubrication (MQL) presents itself as a possible solution for hard turning in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, provided that the minimum quantity lubrication parameters can be strategically tuned. Minimum quantity lubrication (MQL) presents itself as a viable alternative for hard machining with respect to tool wear, heat dissertation, and machined surface quality. In different research the researchers compare the mechanical performance of minimum quantity lubrication (MQL) to completely dry lubrication for the turning of hardened steel materials and examine the tool temperature, white layer depth, and part finish. The results indicate that the use of minimum quantity lubrication leads to reduced surface roughness, delayed tool flank wear, develop tool life and lower cutting temperature, while also having a minimal effect on the cutting forces.

1.3 Objective of the Present Work

It is very straightforward from the previous literature survey that minimum quantity lubrication (MQL) can control remarkably the cutting temperature as compared to dry machining. MQL assisted hard turning has been widely used, because of high cutting temperature generated during machining not only reduces tool life but also impairs the product quality. The temperature becomes more intensive when cutting velocity and feed are increased for higher MRR and the work materials are relatively difficult to machine for their high strength, harden ability and lesser thermal conductivity. These materials cannot be cut effectively without cooling, even though dry cutting is becoming increasingly widespread. Cutting fluids are widely used to reduce the cutting temperature as well as reduce force and surface integrity. In this regard, it has already been observed through previous research that proper application of MQL may play vital role in providing not only environment friendliness but also some techno-economical benefits.

The main objectives of the present work is to conduct an experimental investigation on the role of three types of cutting fluids (soluble oil, vegetable oil and VG 68 cutting oil) in continuous turning of hardened AISI 4320 steel using coated carbide insert on the major machinability characteristics in respect of

i. chips form (chip shape, chip color and chip thickness ratio)
ii. cutting temperature
iii. tool wear mechanisms
    - average principal flank wear (VB)
    - maximum flank wear (VM)
    - average auxiliary flank wear (VS)
iv. surface finish (R_a) and
v. dimensional accuracy

1.4 Scope of the Thesis

Application of minimum quantity of lubricants (MQL) is a potential technique especially where the cutting temperature is a major constraint in achieving high productivity and job quality. But overall economical viability demands that such MQL application does not affect the essentially important technological requirements rather works favorable in respect of cutting power consumption, product quality and tool life. Keeping that in view, the present research work has been taken up to explore the role of different cutting fluids on the major machinability characteristics in turning hardened AISI 4320 steel by coated carbide tool (SNMG 120408-TN 4000) under different conditions.

Chapter 1 presents the general requirements in machining industries, benefits of hard-turning over grinding process, role of cutting tools and technological-economical-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 1.**

Chapter 2 deals with method of heat treatment of the given alloy steel and also design and development of the minimum quantity of lubricant (MQL) system for the present work to enable proper cooling of the cutting zone. **Chapter 2** 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 integrity and dimensional deviation in turning hardened steel under different cutting conditions. Calibration results of tool-work thermocouple are also presented in this chapter.

Chapter 3 provides comparisons of cutting performance under different cutting environment under different cutting conditions. Studies on cutting temperature, chip morphology, tool wear, surface integrity and dimensional deviation are discussed. **Chapter 3** also contains the detailed discussions on the experimental results and possible interpretations on the results obtained. Finally, a summary of major contributions and future work is given in **chapter 4** and references are provided at the end.

Chapter 2

Experimental Investigations

2.1 Introduction

The alloy steel (AISI 4320) was heat treated to produce desired hardness as well as great variety of microstructures and properties. The whole process was done in an inert environment by using continuous flow of argon gas. Generally, heat treatment uses phase transformation during heating and cooling to change a microstructure in a solid state. In heat treatment of specimen, the processing was most often entirely thermal and modifies only structure. Thermo-mechanical treatments, which modify component shape and structure, and thermo-chemical treatments which modify surface chemistry and structure, are also important processing approaches which fall into the domain of heat treatment.

The high cutting temperature generated during machining of hardened steel not only reduces tool life but also impairs the product quality. The temperature becomes more intensive when cutting velocity and feed are increased for higher MRR and the work materials are relatively difficult to machine for their high strength, harden-ability and lesser thermal conductivity. Cutting fluids are widely used to reduce the cutting temperature. But the major problems associated with the use of conventional methods. It has already been observed through previous research that proper application of MQL may play vital role in providing not only environment friendliness but also some techno-economical benefits. Again using different cutting fluids show varying performance in reducing cutting temperature.

2.2 Material Hardening

The material used in the thesis was alloy steel named AISI 4320 steel (Nickel-chromium-molybdenum steel). It was a long solid bar which had been sliced in small pieces with the help of band saw to fit into the electric furnace. The working length of the pieces was 230 mm with diameter of 74 mm as shown in Fig.2.1. To make provision for pulling the red hot metal pieces from furnace, hook had to be facilitated. Using drilling and boring tools a through hole was created in the solid shaft in radial direction. A triangular hook of mild steel was attached to the work piece so that the work-piece can be pulled out from the furnace with the help of a tong. A test sample made from the same material was also prepared. It was a rectangular block with dimension 25mm×15mm×10mm. This was made for the hardness test.

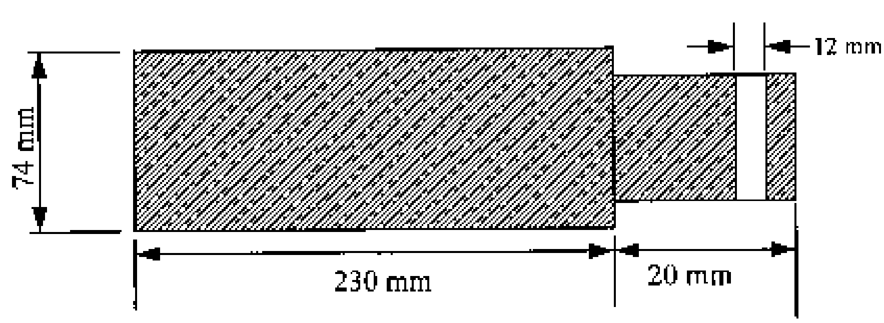


Fig. 2.1 Work material specimen for hardening

Electric furnace of high heating element 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 was formed on the surface of the work material during hardening. Due to scale forming, carbon quickly deposited from the work piece. 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 passed through the furnace chamber to drive out air as well as oxygen. It was done by high flow rate of argon gas of about 7 liters per minute at a pressure of 130 bars. After two minutes, the flow rate was slowed down and held it at 5.5 liters per minute. At this point the furnace was turned on with 5 amperes current rating. It took three hours to raise the temperature to 900°C and held the work material at that temperature for one hour. Schematic view of the heat treatment set up is shown in Fig.2.2.

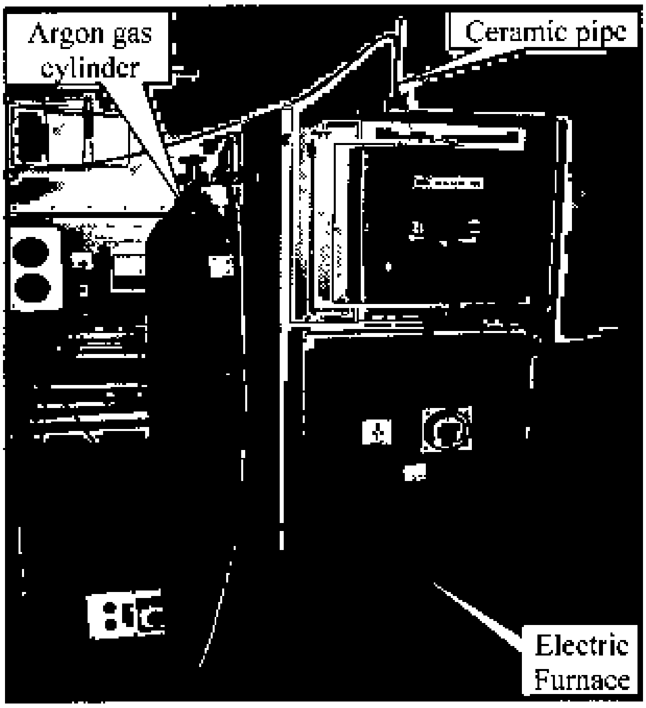


Fig.2.2 Photographic view of heat treatment set-up

A quench tank having capacity 140 liters was set up on the floor of heat treatment lab. 10 kilograms ice and 10 kilograms of sodium chloride was mixed with 120 liters of water to prepare a 10% brine solution. This mixture reduced the absorption of atmospheric gases that, in turn reduced the amount of bubbles. As a result, brine wetted the metal surface and cooled it more rapidly than water. In addition to rapid and uniform cooling, the brine removed a large percentage of any scale that may be present. The work piece was pulled quickly but carefully out from the furnace using a tong and was immersed it vertically into the brine solution. The solution was stirred vigorously for about 10 minutes and was continued the quench until the specimen was cool enough to handle using bare hands. Heat transfer was not so fast through the steam layer. On the other hand the very act of transforming the water into steam means the water has to take in enormous amounts of energy to transform the water from liquid state to gaseous state (steam). Moving the part and re-circulating the water aids in getting the best quench. The test sample was also quenched in the same solution following same manner.

Quenched carbon steels always required to temper because of steels are often more harder than needed and too brittle for most practical uses. Also, several internal stresses like residual stresses are set up during the rapid cooling from the hardening temperature. As a result, to relieve the internal stresses and reduce brittleness, tempered was done. The set-up for tempering is shown in Fig.2.3. The procedure of tempering is the re-heating of specimen below its re-crystallization temperature (160°C). Holding the specimen at that temperature for a one hour then cooled it usually in still air. The resultant strength, hardness, and ductility depend on the temperature to which the specimen is heated during the tempering process. The purpose of tempering was also to produce definite physical properties within the specimen.

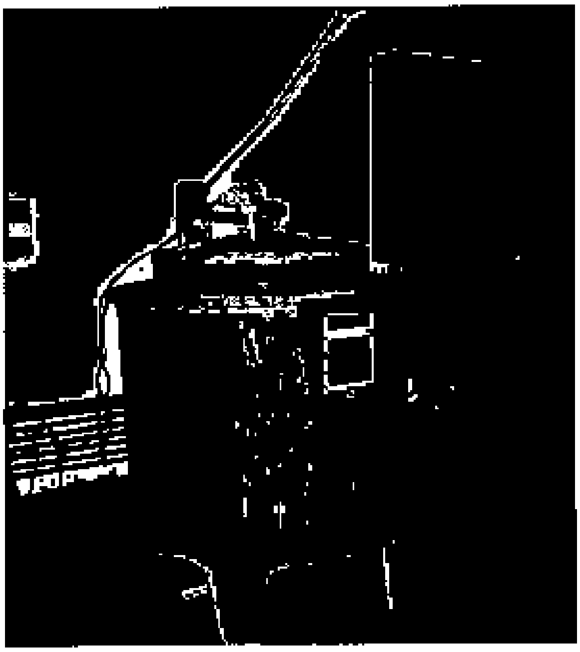


Fig. 2.3 Photographic view of tempering set-up

The sample was cleaned and ground a flat surface of 0.015 inches deep along the face of the sample. Hardness of the sample was measured on the C scale of Rock-well hardness tester. The hardness of the sample before heat treatment was 163 HRB and after heat treatment it became around 37 HRC.

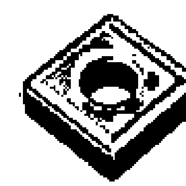
2.3 Experimental Procedure and Conditions

The machining tests have been carried out by turning a hardened AISI 4320 steel in a lathe (7.5 kW) at different cutting velocities (V) and feed rates (f) under dry and MQL (two emulsions and one synthetic fluid) condition at a constant depth of cut (d) by standard coated carbide insert (SNMG-TN 4000). Minimum quantity lubrication (MQL) machining has been accepted as a successful semidry application because MQL has positive part on environment friendliness as well as techno-economical benefit. To evaluate and explore the role of different cutting fluids on the machinability distinctiveness of a tool-work combination, frequently used in machining industries, mostly in terms of chip morphology, cutting temperature, tool wear, surface finish and dimensional deviation, which manage product quality, productivity and overall economy is endeavor of the present work.

The conditions under which the machining tests have been carried out are briefly given in Table 2.1. A number of cutting velocity, feed and depth of cut have been taken over relatively wider ranges keeping in view the industrial recommendations for the tool-work materials undertaken and evaluation of role of variation in V and f on effectiveness of MQL. Keeping in view less significant role of depth of cut (d) 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.

Effectiveness of cooling and the related benefits depend on how closely the MQL jet can reach the chip-tool and work-tool interfaces where, apart from the primary shear zone, heat is generated. Considering common interest and time constraint only coated carbide insert has been used for the present work. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view a standard tool configuration namely SNMG-TN 4000 has been undertaken for the present work. The insert has been clamped in a PSBNR 2525 M12 type tool holder. The nozzle tip orientation regarding the cutting insert has been settling after a few trials and fixing an inclined metal stripe to the insert holder and nozzle tip attaching on it. The thin but high velocity stream of MQL has been heading for along the auxiliary cutting edge of the insert, so that the coolant reaches as close to the chip-tool and work-tool interfaces as possible and cools the above mentioned interfaces and both the principal and auxiliary flanks effectively as well. Fig.2.4 shows the photographic view of the experimental set up used in the present investigation.

Table 2.1 Experimental conditions

Machine tool	: Lathe Machine(China), 7.5 kW
Work materials	: Hardened AISI 4320 steel [C 0.17-0.22, Mn 0.45-0.65, Si 0.15-0.30, Ni 1.65-2.00, Cr 0.40-0.60, P 0.035 (max), S 0.04 (max), Mo 0.20-0.30]
Hardness (HRC)	: 37
Size	: Diameter = 74 mm and length = 230 mm
Cutting tool	: Coated Carbide, SNMG-TN 4000, Widia 
Coating	: TiCN
Geometry	: -6°,-6°,6°,15°,75°,0.8 mm
Tool holder	: PSBNR 2525 M12 (ISO specification), Widia
Process parameters	
Cutting velocity, V	: 82. 114 and 163 m/min
Feed rate, f	: 0.10, 0.12 and 0.14 mm/rev
Depth of cut, d	: 1.0 mm
MQL supply	: Flow Rate 150 ml/hr, Air Pressure 23 bar, Oil Pressure 25 bar
Environment	: i. Dry ii. MQL (Soluble oil) iii. MQL (Vegetable oil) iv. MQL (VG 68 cutting oil)

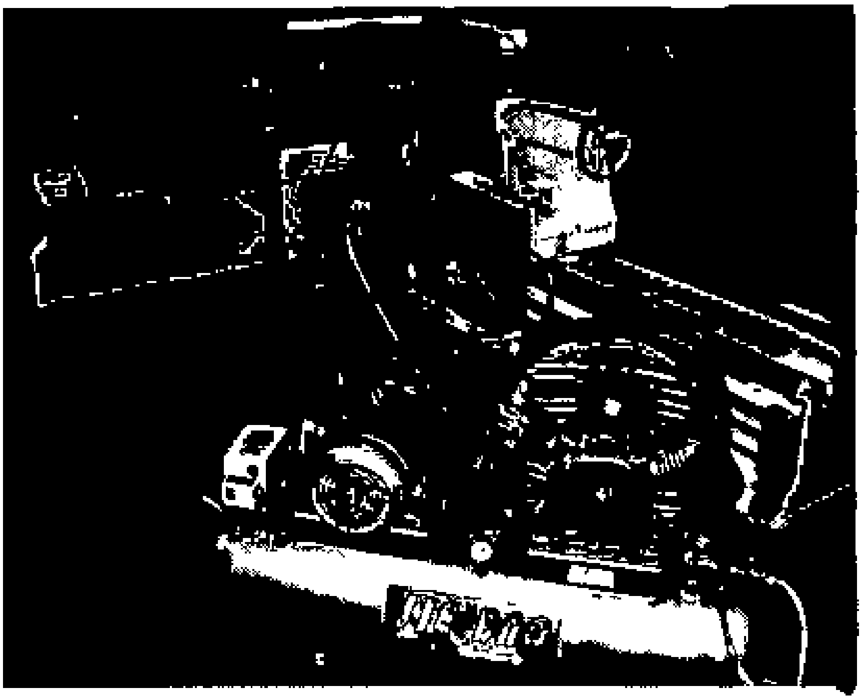


Fig.2.4 Photographic view of the experimental set-up

The MQL system needs to be properly designed for achieving substantial technological and economical benefit in addition to environmental friendliness. Following factors should be considered during the effective design of the MQL system:

i. effective cooling by enabling MQL jet reach as close to the actual hot zones as possible
ii. avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes
iii. minimum consumption of cutting fluids by pin-pointed impingement and only during chip formation
iv. pressure and flow rate of the MQL should be maintained at an optimum level and constant throughout the cut

An MQL system using cutting fluid and compressed air essentially consists of

i. compressor for compressing and delivering compressed air at the desired pressure
ii. mixing chamber for mixing cutting fluid and compressed air
iii. suitable nozzle to impinge MQL to the cutting zone
iv. pressure and flow control valves for effective economical use of cutting fluid

Compressor and MQL applicator are the two major components of MQL system. Compressor acts as air supply unit and is able to develop a maximum pressure of 23 bars. However, the main purpose of the compressor is to supply air at a pressure, which is required to set in the different components of MQL applicator. MQL applicator consists of three such components as fluid chamber, mixing chamber and a nozzle.

The fluid chamber is used to contain the cutting fluid selected for a particular machining and the fluid pump supplies the cutting fluid from the fluid reservoir. The high pressure air from the compressor enters into two chambers, one is fluid chamber and other is mixing chamber. Fluid chamber has an inlet port and an outlet port at the top and the bottom respectively. It is connected to the compressor by a flexible pipe through the inlet port to keep the fluid inside chamber under a constant pressure of 23 bars. It is required to maintain the flow of cutting fluid into the mixing chamber at constant rate over a long period of time during machining. However, based on our research requirement, fluid chamber has been designed with capacity of one liter so as to enable to supply the cutting fluid continuously for at least six hours during machining at a flow rate of 150 ml/hr. The fluid chamber is connected at the bottom with the mixing chamber by a nipple. A needle is inserted by a rubber pad to permit a little amount of fluid flow under high pressure. The compressed air through the upper inlet port creates the pressure to cause the fluid to go to the mixing chamber.

For mixing the compressed air and cutting fluid, mixing chamber is necessary. Mixing chamber has two inlet ports and an one outlet port. One of the inlet ports permits high pressure compressed air to the mixing chamber. The flow of this compressed air is controlled by a globe valve and measured by a pressure gauge. The other port permits fluid flow from the fluid chamber. The air and the cutting fluid are mixed in the mixing chamber so that the mixture contains minimum quantity of cutting fluid. The mixture of the air and cutting fluid is impinged at a high speed through the nozzle at the chip- tool interface. The mist at the cutting zone is impinged by the nozzle which is connected with the outlet port of the mixing chamber. This is worth mentioning that sudden expansion at the inlet port and contraction at the outlet port of the mixing chamber results in turbulence in the air-flow and ensures complete or proper mixing of air with cutting fluid in the chamber. Fig.2.5 shows the schematic view of the mixing chamber along with nozzle used for the present work.

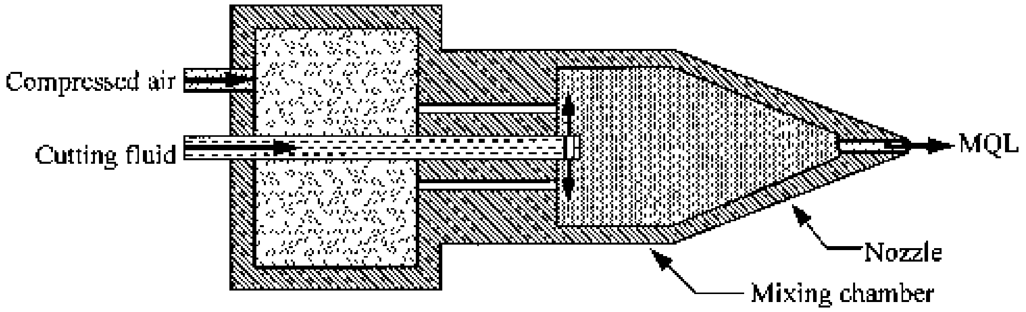


Fig.2.5 Schematic view of the mixing chamber along with nozzle

Different cutting fluids have different chemical composition. So, lubricating and cooling action vary according to the different chemical composition of cutting fluids. In this present investigation, three types of cutting fluids (soluble oil, vegetable oil and VG-68 cutting oil) were used to evaluate the performance on machinability characteristics of hardened AISI 4320 steel.

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 the measurement of temperatures generated in cutting zone. The average chip-tool interface cutting temperature was measured under dry and MQL conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. Thermocouples have always become a popular tool to be used in temperature measurements during metal cutting. This method is very useful to indicate the effects of the cutting speed, feed rate and cutting parameters on the temperature. Thermocouples are conductive, rugged and inexpensive and can operate over a wide temperature range. But proper functioning of this technique needs care about parasitic emf generation.

The set-up of the calibration technique employed for the tool-work thermocouple used in the present investigation has been prepared to be mounted on a precision lathe. The tool holder used was screw type where the coated carbide SNMG insert has been mounted. To avoid generation of parasitic emf, a long carbide rod has been used to extend the insert. The workpiece was hardened steel. Tool and workpiece have been insulated from the machine tool. A digital multi-meter (Rish Multi, India) has been used to record emf as milivolt. For thermocouple, one end of multi-meter has been connected to the workpiece and other end to the tool. During machining, the emf as milivolt has been recorded from multi-meter under dry and MQL conditions. So, to know the chip tool interface temperature we need to calibrate the emf with temperature. For calibration, tool-work has been brazed together and the insulated thermocouple has been inserted in sensitive hole in a graphite plate. A thermometer and multi-meter has been placed in another two consecutive holes of graphite plate. Heating has been done by the means of electric heater. A graphite block embedded with an electrically heated porcelain tube has served as the heat sink. A chromel-alumel thermocouple has been used as a reference in the vicinity of the tool-work thermocouple for measuring the temperature of the graphite block. Due to the heating, thermoelectric emf is generated between the tool and the workpiece. This emf has been recorded by multi-meter at the same time the junction temperature measured by the reference thermocouple has been recorded using a digital temperature readout meter (Eurotherm. UK). Corresponding emf-temperature has been recorded in the interval of heat apply. The cutting zone has formed the hot junction while a cold part of the tool and the workpiece has formed the cold junction. This technique is easy to apply but only measures the mean temperature over the entire contact area and high local temperatures which may occur for a short period of time cannot be observed.

The photographic view of calibration by tool-workpiece thermocouple technique and variation of temperature with different emf (mV) has been shown in Fig.2.6 and Fig.2.7 respectively.

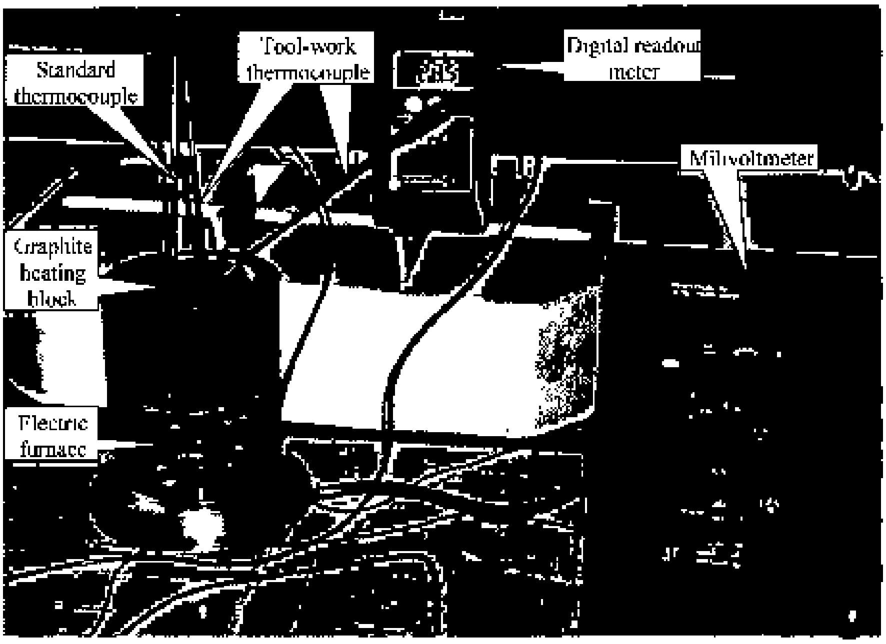


Fig.2.6 Photographic view of tool-work thermocouple calibration set up

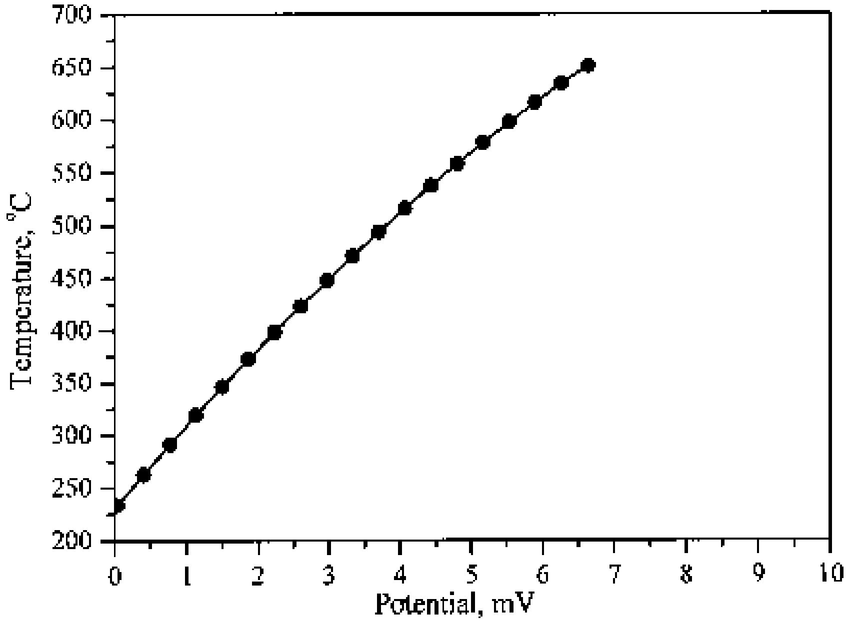


Fig.2.7 Temperature calibration curve for hardened AISI 4320 steel and carbide

2.4 Experimental Results

2.4.1 Machining Chips

The form, colour and thickness of the chips also directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples collected while turning the hardened AISI 4320 steel by the SNMG insert at different V-f combinations under dry, MQL (soluble oil), MQL (vegetable oil) and MQL (VG 68 cutting oil) conditions have been visually examined and categorized as per ISO standard 3685 [91] with respect to their shape and color. The form and colour of all those chips have been noted down. The thicknesses of the chips has been repeatedly measured by a slide calliper to determine the value of chip-thickness ratio, r_c, which is an important index of machinability. The results of such categorization of the chips produced at different V-f combinations and environments by the alloy steel have been shown in Table 2.2.

Chip thickness ratio, r_c (ratio of chip thickness before and after cut) is another important machinability index. For given tool geometry and cutting conditions, the value of r_c depends upon the nature of chip-tool interaction, chip contact length and chip form, all of which are expected to be influenced by MQL in addition to the levels of V and f. The variation in value of r_c with change in V and f and as well as machining environment evaluated for alloy steel have been plotted and shown in Fig.2.8, Fig.2.9, Fig.2.10 and Fig.2.11 respectively.

Table 2.2 Shape and color of chips produced during machining

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Different MQL environments							
		Dry		MQL (Soluble oil)		MQL (Vegetable oil)		MQL (VG 68 cutting oil)	
0.10	82	snarled ribbon	blue	snarled ribbon	metallic	snarled ribbon	metallic	snarled ribbon	metallic
	114	snarled ribbon	blue	snarled ribbon	metallic	snarled ribbon	metallic	snarled ribbon	metallic
	163	snarled ribbon	blue	snarled ribbon	golden	snarled ribbon	golden	snarled ribbon	metallic
0.12	82	snarled tubular	blue	snarled ribbon	metallic	snarled ribbon	metallic	snarled ribbon	metallic
	114	snarled ribbon	blue	snarled ribbon	metallic	snarled ribbon	metallic	snarled ribbon	metallic
	163	snarled ribbon	blue	snarled ribbon	golden	snarled ribbon	golden	snarled ribbon	metallic
0.14	82	snarled ribbon	blue	snarled ribbon	metallic	long tubular	metallic	long tubular	metallic
	114	snarled ribbon	blue	snarled ribbon	metallic	snarled ribbon	metallic	snarled ribbon	metallic
	163	snarled ribbon	blue	snarled ribbon	golden	snarled ribbon	golden	snarled ribbon	metallic

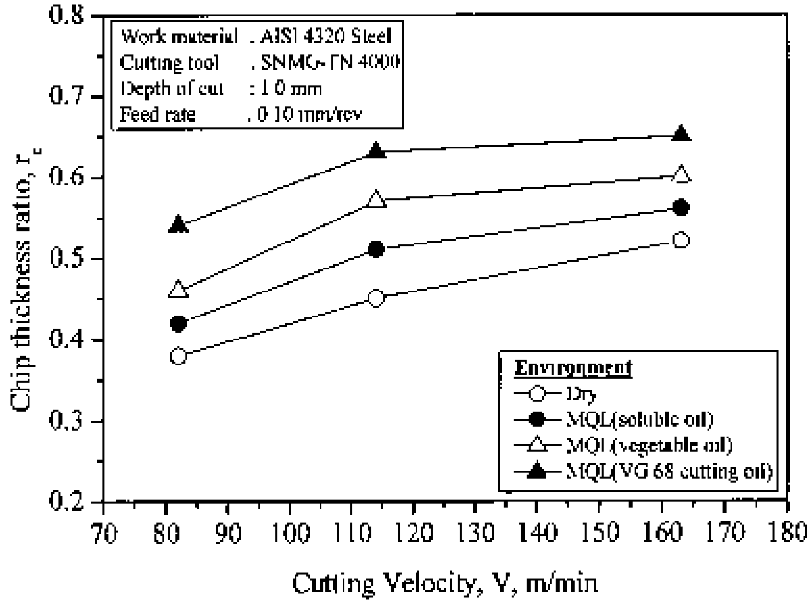


Fig.2.8 Variation of chip thickness ratio (r_c) with cutting velocity under different environments at f = 0.10 mm/rev

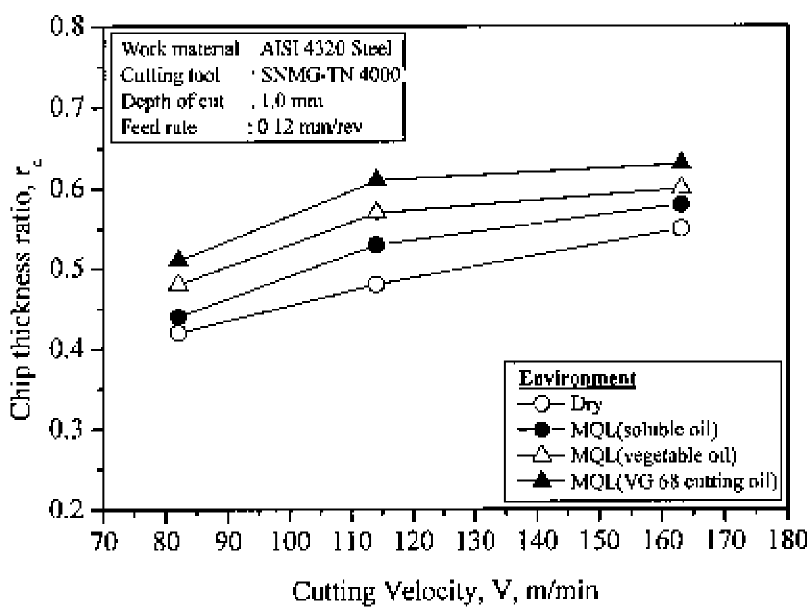


Fig.2.9 Variation of chip thickness ratio (r_c) with cutting velocity under different environments at f = 0.12 mm/rev

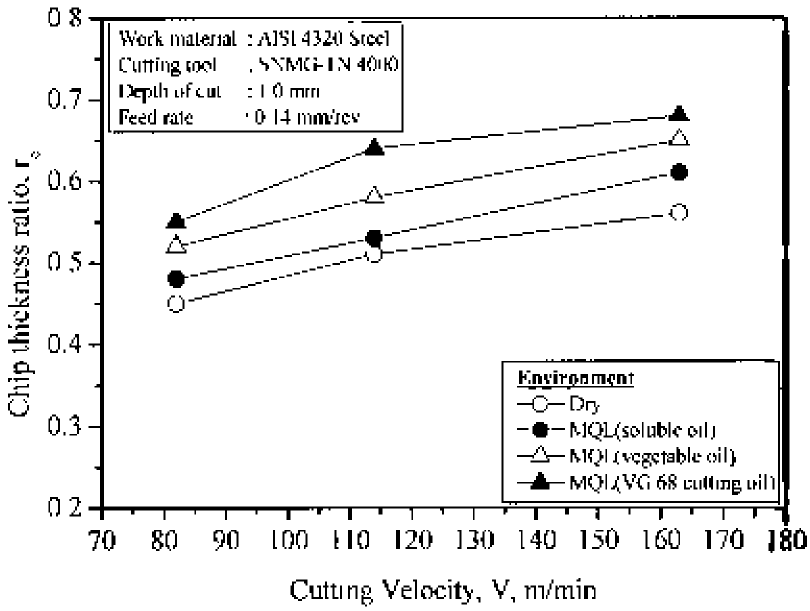


Fig.2.10 Variation of chip thickness ratio (r_c) with cutting velocity **under different** environments at f = 0.14 mm/rev

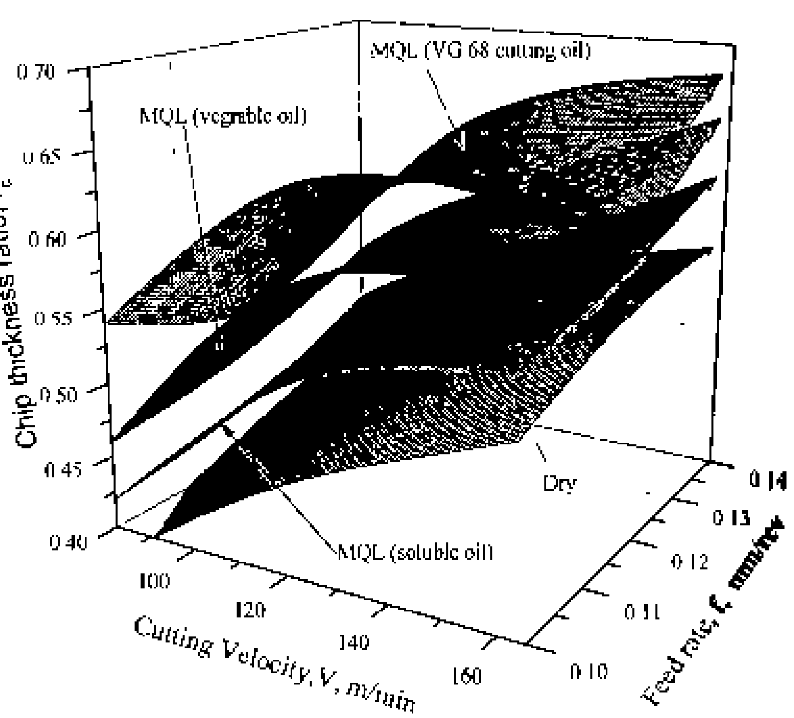


Fig.2.11 Variation of chip thickness ratio (r_c) with cutting velocity (V) and **feed rate (f)** under different environments

2.4.2 Cutting Temperature

During machining of the workpiece, the material ahead of the cutting edge is deformed plastically and removed in the form of chips. The energy required to deform the workpiece material and the chips is mainly converted into heat. Heat is generated at the (a) primary deformation zone due to shear and plastic deformation, (b) secondary deformation zone, due to the result of friction force in the tool-chip interface and (c) tertiary deformation zone due to friction between tool clearance face and newly generated workpiece surface. All such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. At elevated temperature the cutting tool if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. Again generation of heat and high cutting temperature increase with the increase in strength and hardness of the work material. To reduce this detrimental cutting temperature actions are taken. Application of conventional cutting fluid may cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface where the temperature is high. This is mainly because the flowing chips make mainly plastic contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Plastic contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V when the chip-tool contact becomes almost fully plastic.

The average chip-tool interface temperature has been measured under both dry and MQL conditions by tool-work thermocouple techniques during turning of the hardened AISI 4320 steel at different cutting velocities and feeds in the present investigation. The evaluated role of different cutting fluids on average chip-tool interface temperature in turning the given hardened steel by coated carbide (SMNG-TN 4000) insert at different V and f combinations under both dry and MQL conditions have been shown in Fig.2.12, Fig.2.13, Fig.2.14 and Fig.2.15.

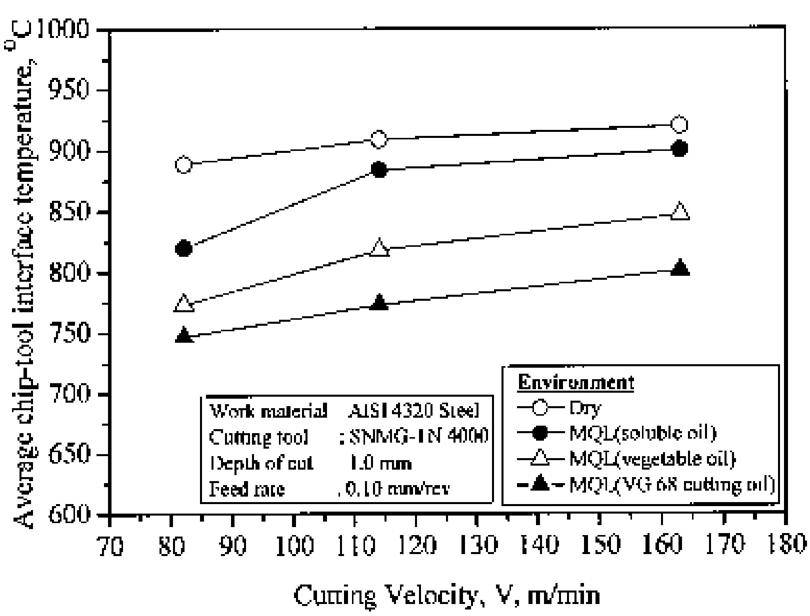


Fig.2.12 Variation of average chip-tool interface temperature with cutting velocity under different environments at f = 0.10 mm/rev

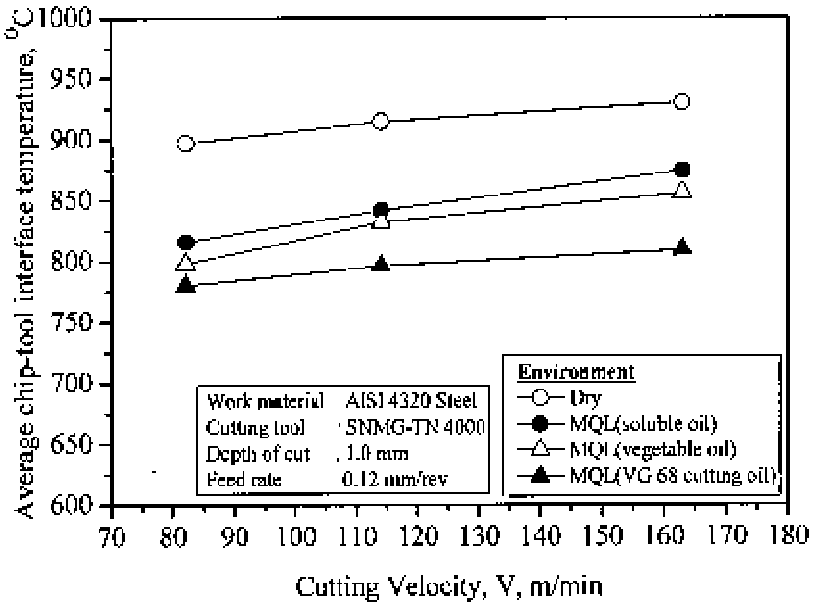


Fig.2.13 Variation of average chip-tool interface temperature with cutting velocity under different environments at f = 0.12 mm/rev

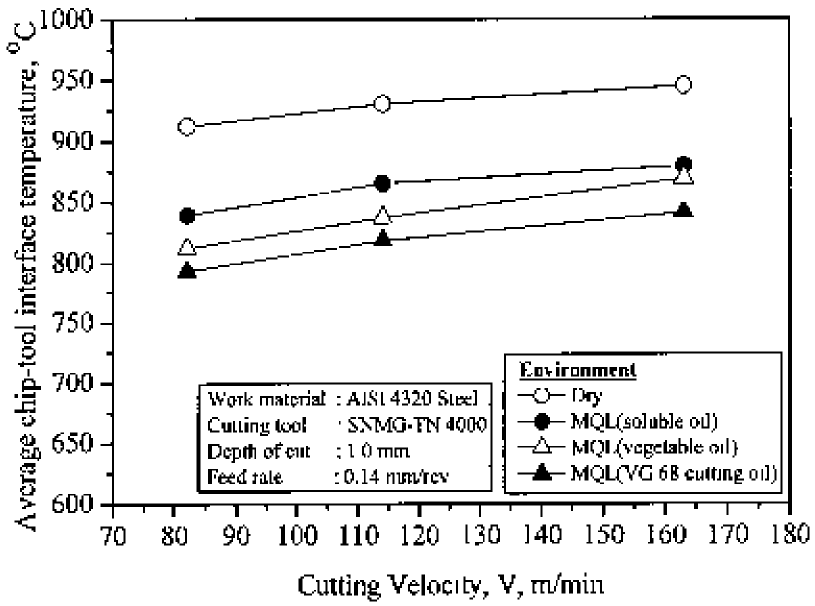


Fig.2.14 Variation of average chip-tool interface temperature with cutting velocity under different environments at f = 0.14 mm/rev

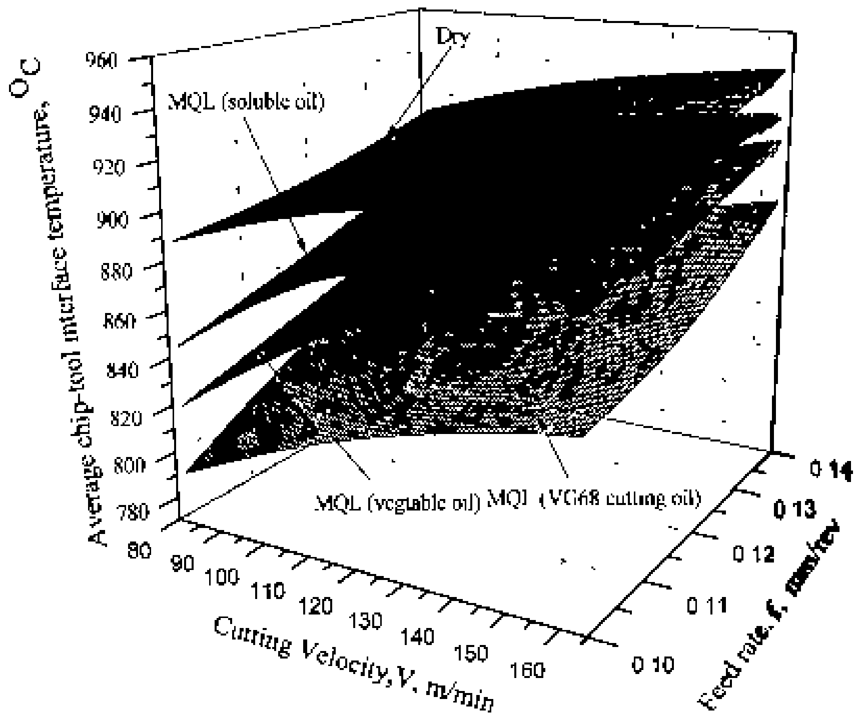


Fig.2.15 Variation of chip-tool interface temperature (θ) with change in cutting velocity (V) and feed rate (f) under different environments

2.4.3 Tool Wear

Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tools. Cutting tools may fail by brittle fracture, plastic deformation or gradual wear. In conventional machining, particularly in continuous chip formation processes like turning, generally the cutting tools fail 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 micro-chipping at the sharp cutting edges. Turning by coated carbide inserts having enough strength; toughness and hot hardness generally fail by gradual wears.

With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces due to continuous interaction and rubbing with the chips and the work surfaces respectively. The principal flank wear is the most important because it raises the cutting forces and related problems. Again the life of the tools, which ultimately fail by the 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 progress of machining. Wear may grow at a relatively faster rate at certain locations within the zones of flank wear apart from notching. The width of such excessive wear are expressed by VM (maximum flank wear), VS (average auxiliary flank wear) and VSM (maximum auxiliary flank wear). The reason of these preferential wears are the presence of some initial defect or variation in geometry, temperature and chip-tool interaction along the cutting edges depending upon the tool geometry, tool-work materials and the conditions of machining. The pattern and extent of the auxiliary flank wear (VS) affects surface finish and dimensional deviation of the machined parts. Growth of tool wear is sizeable 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. In the present investigations the given insert attained significant values of VM, VS and VSM in different degree under different conditions. Fig. 2.16 shows the schematic view of general pattern of wear.

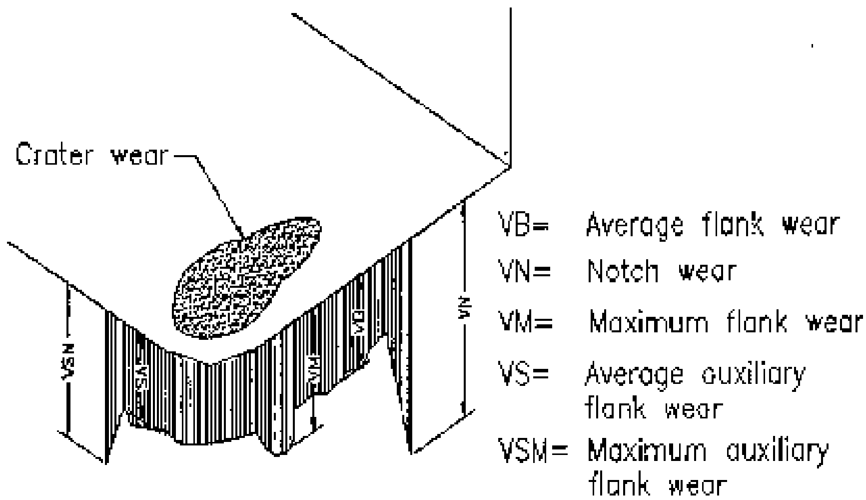


Fig. 2.16 Schematic view of general pattern of wear

During machining under each condition, the cutting insert was withdrawn at regular intervals and then the salient features like, VB, VM, VS, VSM, etc. were measured under metallurgical microscope fitted with micrometer of least count 1.0 µm. At the end of the machining and attaining sufficient wear the pattern and extent of wear of each tool was examined under Scanning Electron Microscope (SEM) and the photographs are taken for onward comparative study.

To reduce the rate of growth of VB, attempts should be made in all possible ways without much sacrifice the MRR. The growth of principal flank wear, VB with progress of machining time recorded while turning the hardened AISI 4320 steel by SNMG insert at V=114 m/min. f=0.10 mm/rev and d=1.0mm under dry. MQL (vegetable oil) and MQL (VG 68 cutting oil) conditions have been shown in Fig.2.17. Fig.2.18 shows the growth of maximum flank wear (VM) with time observed while turning the hardened AISI 4320 steel by SNMG insert at a particular V, f and d combination under dry, MQL (vegetable oil) and MQL (VG 68 cutting oil) environments.

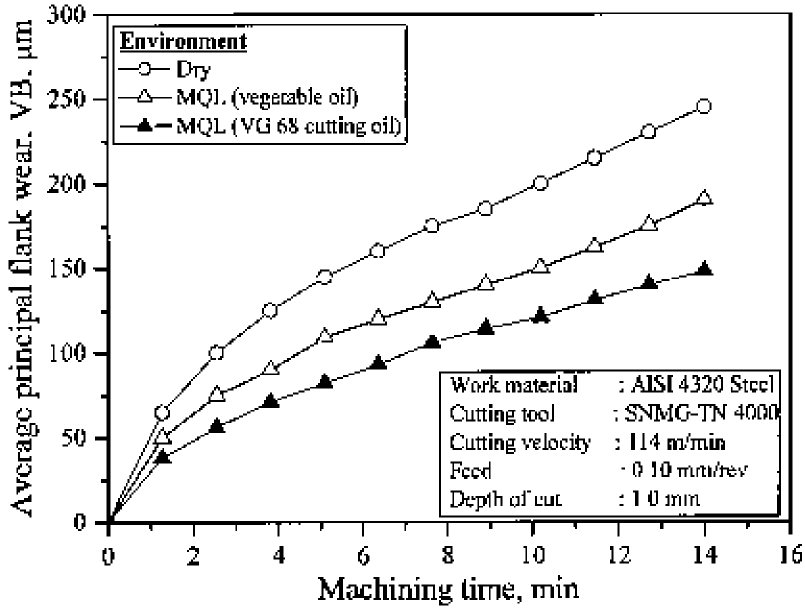


Fig.2.17 Growth of average principal flank wear (VB) with time recorded during turning AISI 4320 steel by SNMG insert under different environments

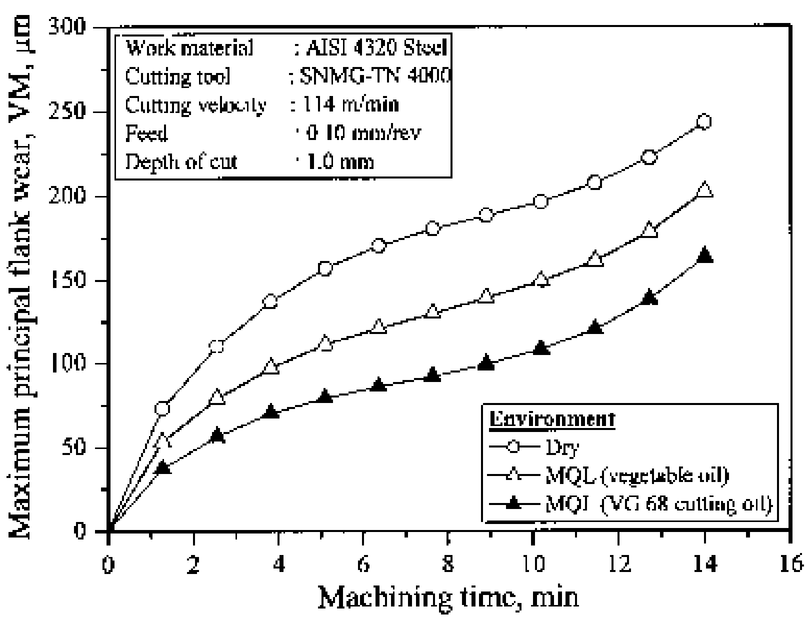


Fig.2.18 Growth of maximum principal flank wear (VM) with time recorded during turning AISI 4320 steel by SNMG insert under different environments

The auxiliary flank wear, which affects dimensional accuracy and surface finish, have also been recorded at regular intervals of machining under all the conditions undertaken. The growth of average auxiliary flank wear, VS with time of machining of the hardened AISI 4320 steel under different environments have been shown in Fig.2.19.

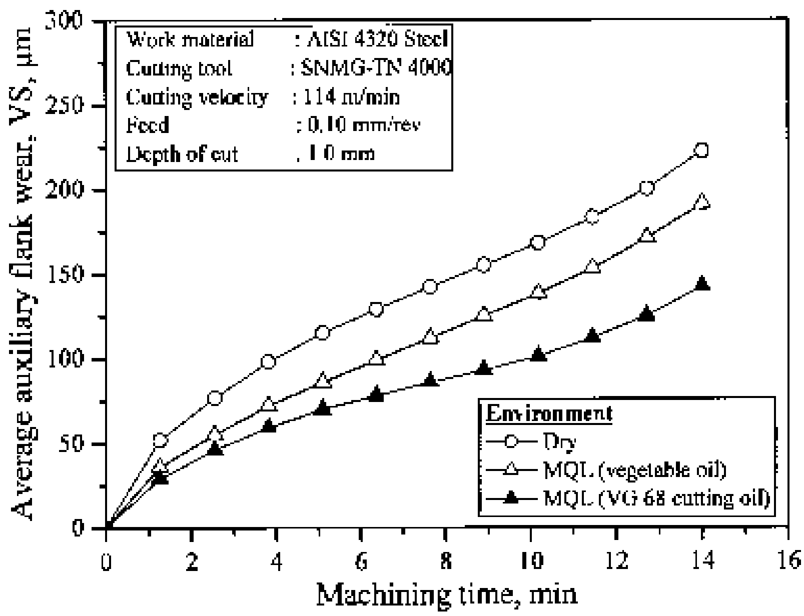
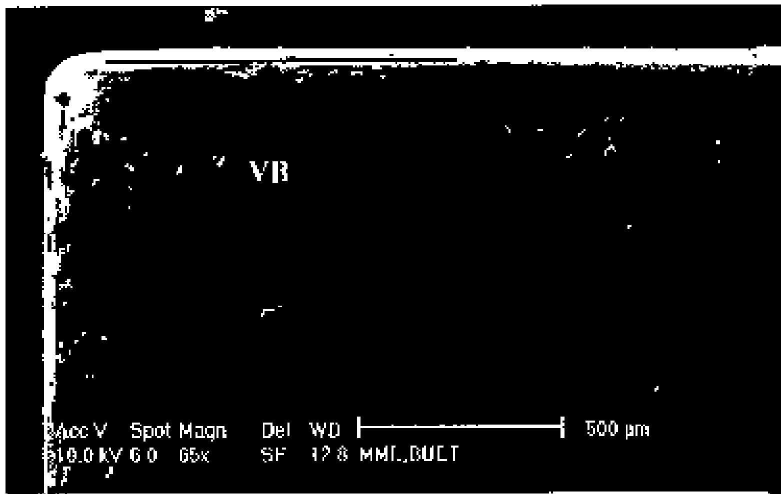
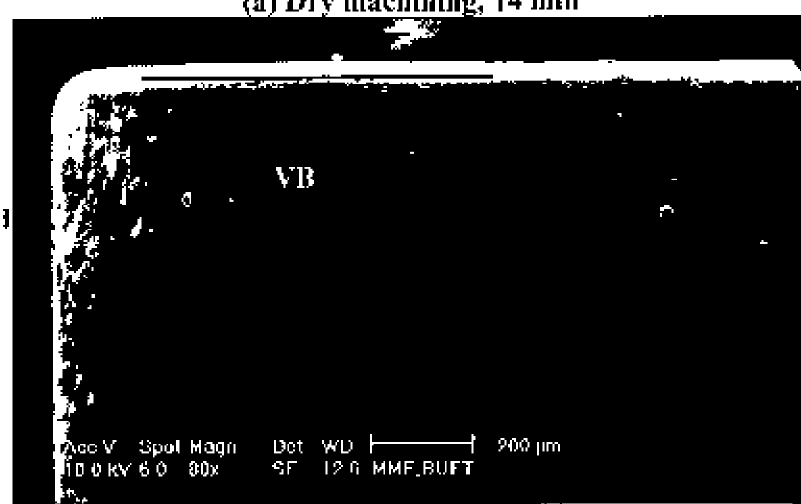


Fig.2.19 Growth of average auxiliary flank wear (VS) with time recorded during turning AISI 4320 steel by SNMG inserts under different environments

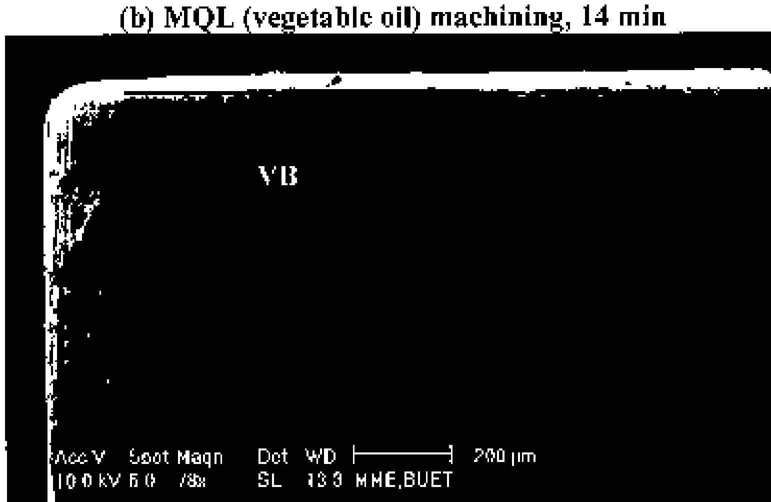
To see the actual effects of different environments on wear of the carbide insert of present configuration, the SEM views showed the pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining the hardened AISI 4320 steel over reasonably long period. The SEM views of the principal and auxiliary flank of the worn out SNMG insert after about 14 minutes of machining hardened AISI 4320 steel under dry, MQL (vegetable oil) and MQL (cutting oil) conditions have been shown in Fig.2.20 and Fig.2.21 respectively.



(a) Dry machining, 14 min

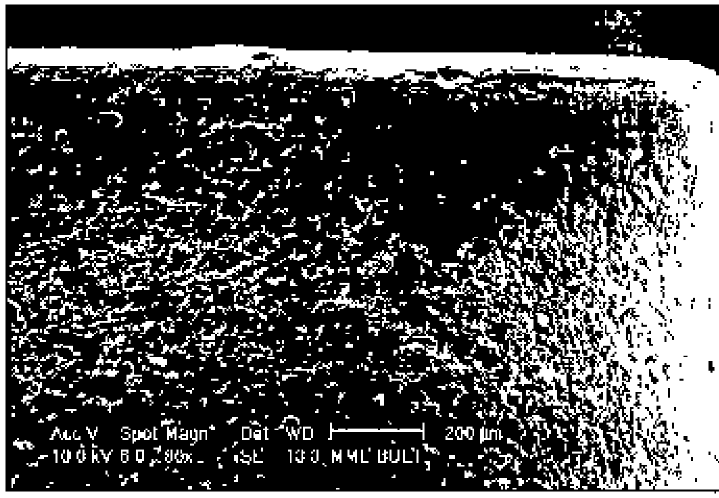


(b) MQL (vegetable oil) machining, 14 min

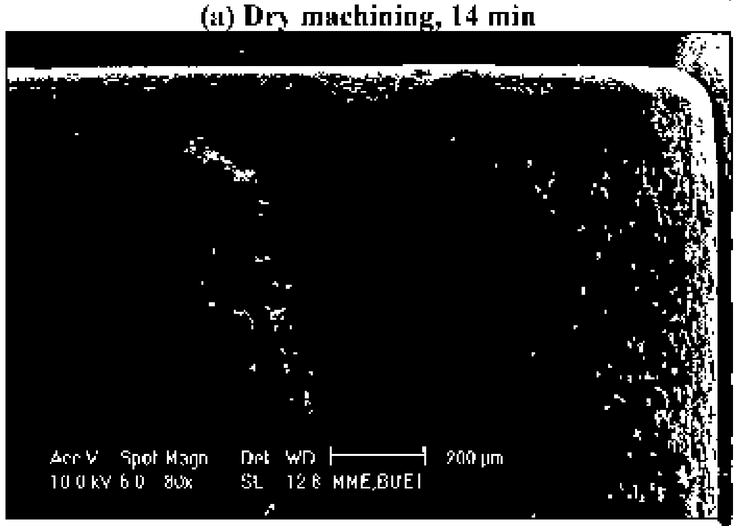


(c) MQL (VG 68 cutting oil) machining, 14 min

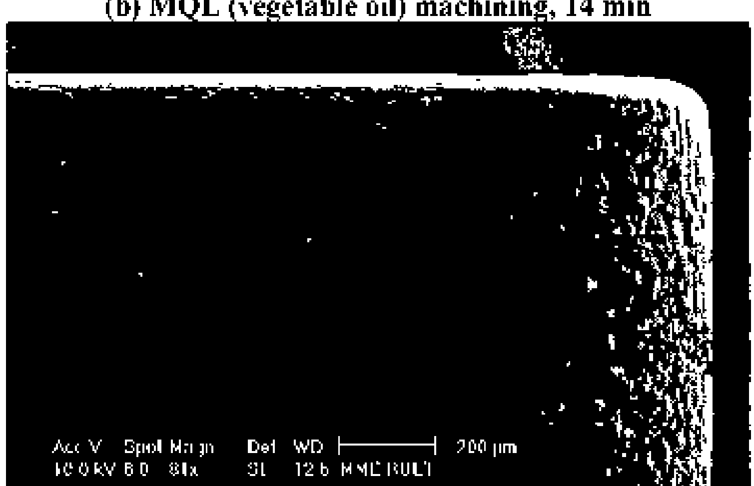
Fig.2.20 SEM views of principal flank of worn out insert under (a) dry (b) MQL (vegetable oil) and (c) MQL (VG 68 cutting oil) conditions



(a) Dry machining, 14 min



(b) MQL (vegetable oil) machining, 14 min



(c) MQL (VG 68 cutting oil) machining, 14 min

Fig.2.21 SEM views of auxiliary flank of worn out insert under (a) dry (b) MQL (vegetable oil) and (c) MQL (VG 68 cutting oil) conditions

2.4.4 Product Quality

Now-a-days quality of the product is very crucial thing. The performance and service life of any machined parts mainly vary by the quality of that product. For a given material quality 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 micro-cracks.

To evaluate the quality of the product only the surface roughness and the dimensional deviations on diameter have been investigated in this present work. This investigation is carried out under different cutting environment at various V-f combinations. But depth of cut is constant through out the experiment, i.e. 1.0 mm.

Finished Surface is a very vital consideration for product quality. This important index of machinability is substantially influenced by the machining environment for given tool-work pair and speed-feed conditions. So the development of surface roughness in continuous machining processes like turning, is caused by

i. vibration in the machining system
ii. improper machine set-up
iii. gradual wear of the cutting tool

Surface roughness has been measured at two stages. At first stage, the roughness of the surface was measured after a few seconds of machining with the sharp tool while recording the cutting temperature. Here the surface finish has been measured by a Talysurf

(Surtronic 3+, Rank Taylor Hobson Limited) by the machining of the hardened steel bar by the coated carbide insert at different V-f combination under dry. MQL (soluble oil), MQL (vegetable oil) and MQL (VG 68 cutting oil), using a sampling length of 0.10mm.

At second stage, the surface roughness has been measured with the progress of machining while monitoring growth of tool wear with machining time. In this stage the surface finish was measured by a Talysurf (Surtronic 3+, Rank Taylor Hobson Limited) by the machining of the hardened steel bar by the coated carbide insert at cutting velocity of 114 m/min, 1.0 mm depth of cut and 0.10 mm/rev feed under dry. MQL (vegetable oil) and MQL (cutting oil) conditions. As the soluble oil gave poor performance it has not been applied at second stage. Here the performance is compared among the three environments. i.e. dry. MQL (vegetable oil) and MQL (VG 68 cutting oil).

The surface roughness, Ra attained of machining of hardened AISI 4320 steel by the sharp coated carbide (SNMG-TN 4000) insert at various V-f combinations under dry, MQL(soluble oil), MQL (vegetable oil) and MQL (VG 68 cutting oil) conditions are shown in Fig.2.22, Fig.2.23 and Fig.2.24 respectively.

Fig.2.25 shows the variation in surface roughness observed with progress of machining of the hardened AISI 4320 steel by the SNMG insert at a particular set of V-f and d, i.e., 114 m/min. 0.10 mm/rev and 1.0mm respectively, under dry, MQL (vegetable oil) and MQL (cutting oil) conditions. Here the total machining time was considered as after 14 seconds.

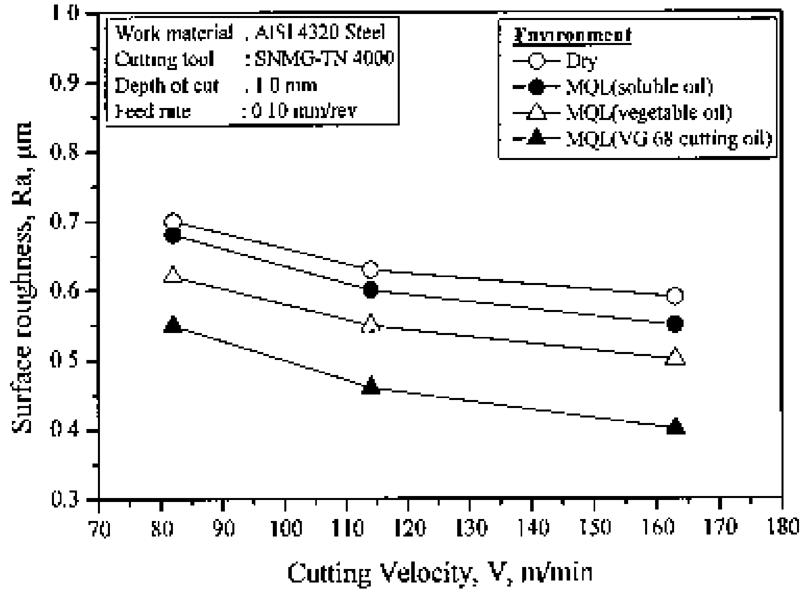


Fig.2.22 Variation of surface roughness (Ra) with cutting velocity under different environments at f = 0.10 mm/rev

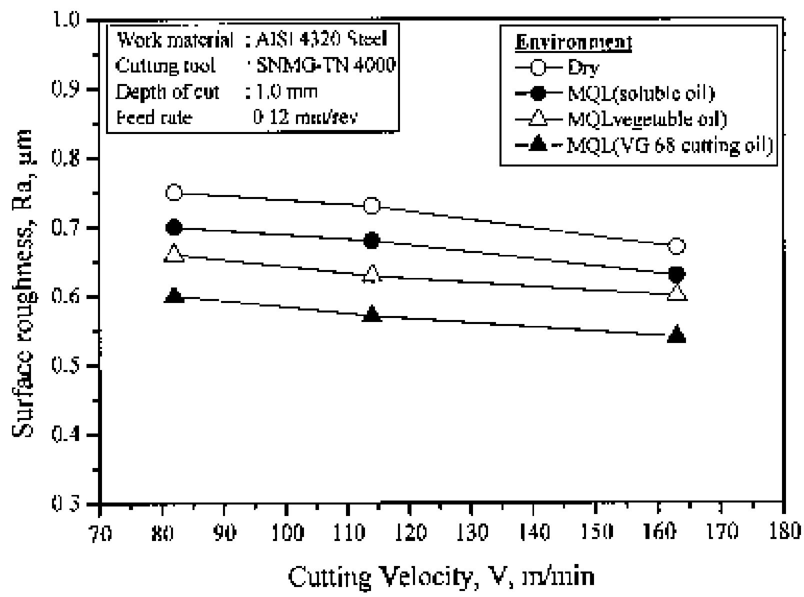


Fig.2.23 Variation of surface roughness (Ra) with cutting velocity under different environments at f = 0.12 mm/rev

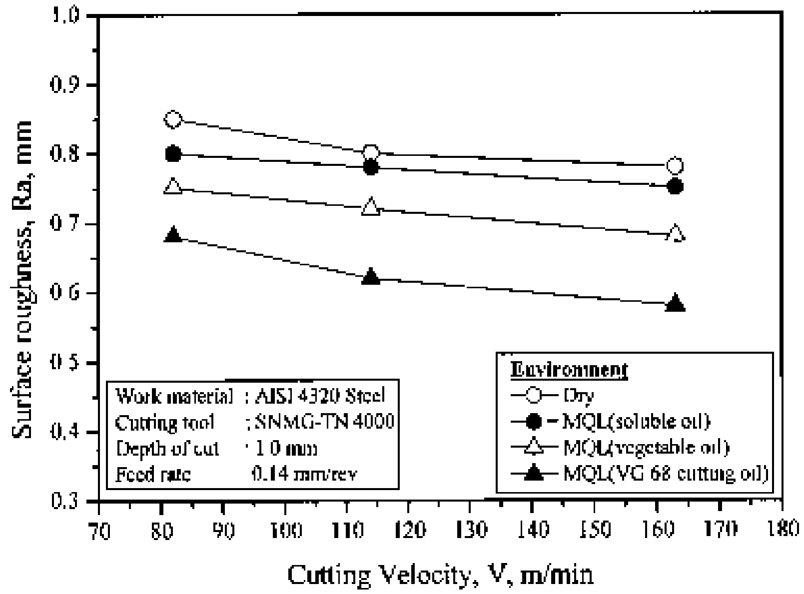


Fig.2.24 Variation of surface roughness (Ra) with cutting velocity under different environments at f = 0.14 mm/rev

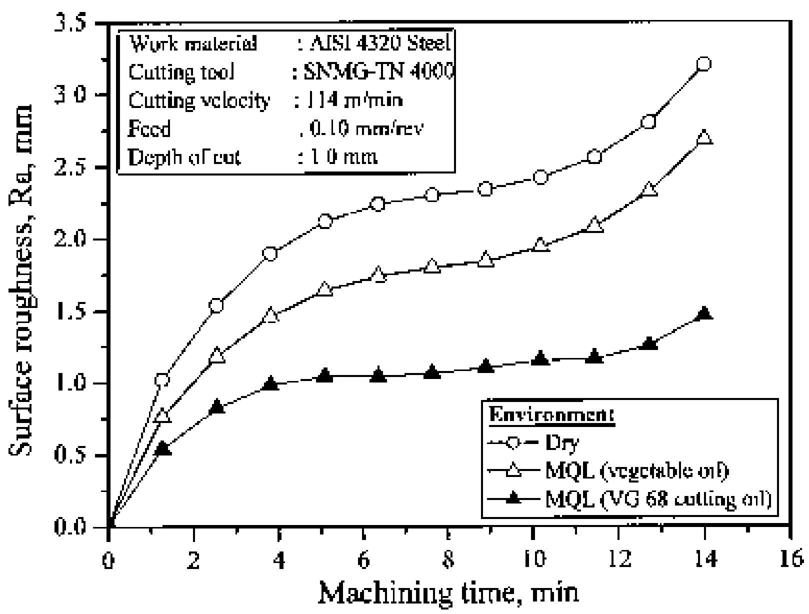


Fig.2.25 Surface roughness (Ra) developed with progress of machining under different environments

Dimensional accuracy often affects the performance and service life of the machined component. The diameter of the machined part during the straight turning in a centre lathe is generally found to increase along length of cut due to gradual wear of the tool tip; decrease due to thermal expansion and subsequent cooling of the job if the job temperature rises significantly during machining and increase due to system compliance of the machine-fixture-tool-work (M-F-T-W) system under the action of the cutting forces. So the development of dimensional deviation in continuous machining processes like turning, is caused by

i. vibration in the machining system
ii. improper machine set-up, tool
iii. excessive heat development
iv. gradual wear of the cutting tool

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

The gradual increase in dimensional deviations on diameter observed along the length of cut on the hardened AISI 4320 steel after one full pass of machining at cutting velocity of 114 m/min, 0.10 mm/rev feed and 1.0mm depth of cut under dry, MQL (vegetable oil) and MQL (Vg 68 cutting oil) conditions have been considered. For MQL environment only the vegetable oil and VG 68 cutting oil have been applied. Here the soluble oil has not been used because it has been found earlier that among the three given cutting fluids, soluble oil does not give better performance. Dimensional deviation of the machined work piece has been measured by fitting a dial gauge of least count 10 μm on the carriage of the machine tool under a complete pass of machining. During machining gauge reading has been taken in 10 mm interval and plotted in Fig.2.26.

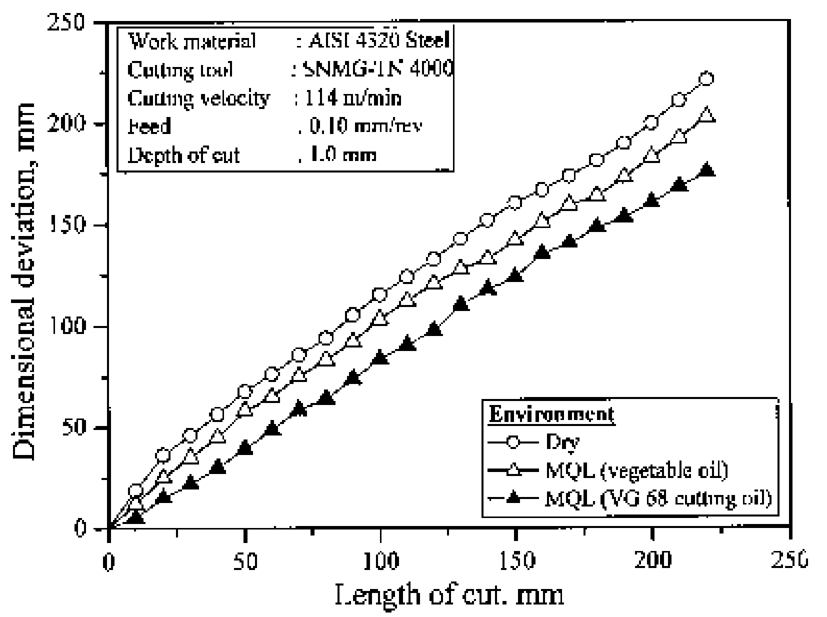


Fig.2.26 Dimensional deviation observed after one full pass turning under dry, MQL (vegetable oil) and MQL (VG 68 cutting oil) conditions

Chapter 3

Discussion on Experimental Results

3.1 Machining Chip

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 and f, 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.

From the Table 2.2 it is stated that under dry and MQL condition the shape of the most of the chips are snarled ribbon. But when V=82 m/min and f=0.14 mm/rev, the shape of the chips are long tubular under the application of vegetable oil and cutting oil. Again from Table 2.2 it is clear that when V and f increase, the chip-tool interaction temperature increases. Thus chip become much deeper, i.e. from metallic to golden. Again the colour of the chips have also become much lighter depending upon V and f due to reduction in cutting temperature by MQL condition. At dry condition the colour of the chips are very deeper, i.e. blue due to high temperature.

It is important to note in Table 2.2 that the role of MQL has been more effective in respect of form (shape) and colour of the chips when the same 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 jets 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 minimum quantity lubricant 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. But among the three types of cutting fluids the VG 68 cutting oil shows the favourable results in this regard.

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

$$r_c = \frac{a_1}{a_2} = \frac{f \sin \varphi}{a_2} \quad \text{.......} \quad (3.1)$$

Where,

r_c = Chip thickness ratio

a_1 = Chip thickness before cut = f sinφ

a_2 = Chip thickness

f = Feed rate

φ = Principal cutting edge angle

During the machining of the metals and alloys, continuous chips are produced and the value of r_c is generally less 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. Smaller value of r_c means larger cutting forces 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 and f and the change in environment on the value of chip-thickness ratio (r_c) obtained during turning hardened AISI 4320 steel are shown in figure from Fig.2.8 to Fig.2.11which depict some significant facts;

i. values of r_c has all along been less than 1.0

ii. the value of r_c has increased by the application of minimum quantity of lubricant

iii. the value of r_c increases with increase in V and f

Fig.2.8 to Fig.2.11 show that MQL has increased the value of chip thickness ratio for all V-f combinations due to reduction in friction at the chip-tool interface, reduction in built-up-edge formation and wear at the cutting edges. In all V-f combinations MQL by cutting oil and vegetable oil show more effectiveness than soluble oil. The figures from Fig.2.8 to Fig.2.11 clearly show that throughout the present experimental domain the value of r_c gradually increased with the increase in V and f in different degree under both dry and MQL conditions. Among three cutting fluids, cutting oil (VG 68) has shown the best performance, because the value of r_c has increased more than the other two fluids, i.e. vegetable oil and soluble oil. The value of r_c usually increases with the increase in V 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 and also f and then decrease with the further increase in V due to too much softening of the chip material and its removal by high sliding speed.

The percentage increment in chip-thickness ratio, r_c attained by MQL for different cutting velocity and feed have been calculated from the previous figures and shown in Table 3.1 for hardened AISI 4320 steel. For ease of comparison. the ranges and averages of percentage increment in r_c has been separately shown in Table3.2 which visualizes how the beneficial role of MQL varied with different cutting fluids.

Table 3.1 Percentage increment in chip thickness ratio (r_c) due to minimum quantity lubricant

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Percentage increment in r_c under different MQL environments		
		MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.10	82	11	21	42
	114	13	27	40
	163	8	15	25
0.12	82	5	14	21
	114	10	19	27
	163	5	9	15
0.14	82	7	16	22
	114	4	14	25
	163	9	16	21

Table 3.2 Average percentage increment in chip thickness ratio (r_c) due to minimum quantity lubricant

Savings	Average Percentage increment in r_c		
	MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
Range	4-13	9-27	15-42
Average	8.00	16.78	26.56

From Table 3.1 the percentage of increment in chip thickness ratio for the stated V-f combinations for MQL by cutting oil, vegetable oil and soluble oil over dry condition are 15~42%, 9~27% and 4~13% respectively. It can also show that at low feed and low cutting speed increase in chip thickness ratio is more. But if feed increases better result is shown at 114 m/min cutting velocity. Again Table 3.2 presents that the average value of percentage increment in chip-thickness ratio for MQL by cutting oil, vegetable oil and soluble oil are 26.56%, 16.78% and 8% respectively. So it is concluded that cutting oil (VG 68) gives best performance than other two fluids.

3.2 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 (MRR). Such high cutting temperature adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products. 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 when the chip-tool contact becomes almost fully plastic.

Therefore, application of minimum quantity lubricant (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 under dry and MQL environment in turning hardened steel by coated SNMG insert.

The variation in average chip-tool interface temperature at different cutting velocity, feed and environment combinations are shown Fig.2.12 to Fig.2.15. The cutting temperature generally increases with the increase in V and f 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 and f. Fig.2.12 to Fig.2.15 show that MQL is better than dry machining for all the V-f combinations but among three fluids used for MQL, cutting oil shows best results, secondly vegetable oil and than soluble oil.

It is evident from Fig.2.12 to Fig.2.15 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 and f 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. So, at industrial speed-feed conditions, this amount of reduction in average cutting temperature is quite significant in pertaining tool life and surface finish. Here cutting oil gives good performance among other cutting fluids.

The percentage saving in average chip-tool interface temperature θ attained by MQL for different V-f combinations have been extracted from the previous figures and shown in Table 3.3 for hardened AISI 4320 steel. For convenience of comparison, the ranges and averages of percentage savings in θ have been separately shown in Table 3.4 which visualizes how the beneficial role of MQL varied with different cutting fluids.

Table 3.3 Percentage reduction in chip-tool interface temperature (θ) due to minimum quantity lubricant

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Percentage reduction in θ under different MQL environments		
		MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.10	82	10	13	16
	114	8	10	15
	163	7	8	13
0.12	82	9	11	13
	114	8	9	13
	163	6	8	13
0.14	82	8	11	13
	114	7	10	12
	163	7	8	11

Table 3.4 Average percentage reduction in θ due to minimum quantity lubricant

Savings	Average percentage reduction in θ		
	MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
Range	7-10	8-13	11-16
Average	7.78	9.78	13.22

From the Table 3.3 and Table 3.4 it is found that, in case of MQL by cutting oil and vegetable oil among all V-f combinations the reduction in cutting temperature for V=82m/min and f=0.10 mm/rev is more. In this V-f combination temperature reduction under MQL by cutting oil, vegetable oil and soluble oil varies from 6~11%, 3~8% and 1~5% respectively. It can be noticed that with the increase in feed rate MQL becomes less effective at higher cutting velocity but it shows better performance at lower cutting velocities. This may be due to the increase in chip load and increase in plastic contact length during cutting prevents the MQL to enter into the chip-tool interface. More over, it shows best reduction at higher velocity for lower feed rate. Again Table 3.4 presents that the average percentage reduction in chip-tool interaction temperature under MQL by cutting oil, vegetable oil and soluble oil are 8.11%, 4.78% and 2.67% respectively. Therefore, in all the tests through out the entire experiment, MQL with cutting oil (VG 68) shows the best performance due to its better cooling and lubrication irrespective of speed feed and depth of cut.

3.3 Cutting Tool Wear

It is already mentioned that wear of cutting tools are generally quantitatively assessed by the magnitudes of VB, VS, VM, VSM etc. shown in Fig.2.16, out of which VB is considered to be the most significant parameter at least in R&D work. It was reported **[91,92]** 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 forces and the related problems. The life of carbide tools, which mostly fail by wearing, is assessed by the actual machining time after which the average value (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 AISI 4320 steel by coated carbide (SNMG-TN 4000) inserts at a cutting velocity 114 m/min, feed rate 0.10mm/rev and depth of cut 1.0 mm under dry and MQL have been shown in Fig. 2.17. It is clearly observed from the Fig.2.17 that the principal flank wear (VB) decreases significantly under MQL condition. As from the previous discussion it is obtained that MQL by cutting oil and vegetable oil in feed 0.10 mm/rev, cutting velocity 114 m/min and depth of cut 1.0 mm is more effective so the wear parameters are selected considering these fact. Again Fig.2.18 shows the growth of maximum flank wear (VM) with progress of machining recorded while turning the hardened AISI 4320 steel. undertaken by the SNMG inserts at the given cutting velocity (114m/min), feed (0.10 mm/rev) and depth of cut (1.0 mm) under dry and MQL conditions. MQL cooling enabled sharp reduction in VM with the progress of machining.

Another important tool wear criteria is average auxiliary flank wear (as shown in Fig.2.19) 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. 2.19 for different environments and here also MQL cooling permit quick reduction in VS with the progress of machining. So, it is clearly appears from Figures that the rate of growth of flank wears (VB, VM 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.2.17 that application of minimum quantity lubricant jet has substantially reduced growth of VB. Such improvement by MQL jet can be attributed mainly to retention of hardness and sharpness of the cutting edge for their steady and intensive cooling, protection from oxidation and corrosion and absence of built-up edge formation, which accelerates both crater and flank wear by flaking and chipping. Fig.2.17 also shows that VB decreases much faster in case of applying cutting oil than vegetable oil because of its appreciable chemical properties.

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.

The results of the experimental study have been presently carried out on tool wear in machining hardened AISI 4320 steel under different environments. Application of conventional method and type of cutting fluid like soluble oil does not help in reducing wear or improving tool life. But proper application of MQL in the form of jet provides substantial improvement. Such benefit of MQL may be attributed mainly to reduction of abrasive and chemical wear at the tool flanks and also possible control of chip-tool interaction and thereby built-up edge formation which not only adds flaking wear but also accelerates chipping of the cutting edges by inducing vibration. The cutting oil shows appreciable performance in this regard.

Application of MQL has provided substantial improvement. Both flank and crater wear have been much uniform and much smaller in magnitude and without any notch wear. In the process of systematic growth of cutting tool wear, the cutting tools usually first undergo rapid wear called break-in wear at the beginning of machining due to attrition and micro-chipping and then uniformly and relatively slow mechanical wear followed by faster wear at the end. The mechanism and rate of growth of cutting tool wear depend much on the mechanical and chemical properties of tool and the work materials and their behaviour under the cutting condition. While machining this steel, no notching has been found to develop in any of the inserts even under dry machining condition possibly for less hardenability and more chemical stability of this steel.

In uninterrupted machining of ductile metals by tools like carbides at reasonably high V and f, crater wear is governed mainly by adhesion and diffusion for rubbing at higher stresses and temperature and flank wear mainly by abrasion for lesser pressure and temperature. But adhesion and diffusion type temperature sensitive wear may also occur, in addition to abrasion wear, at the tool flanks if the flank temperature becomes high. Turning of strong metal like hardened AISI 4320 steel at reasonably high V (114 m/min) and f (0.10 mm/rev) under dry condition is expected to cause sufficiently high temperature at the tool flanks. Therefore, adhesion and diffusion are also likely to have contributed in the flank wear in the present case, and MQL seemingly prevented such temperature sensitive adhesion and diffusion as well as reduced abrasion wears. But the wear is decreased more due to the application of cutting oil than vegetable oil.

The SEM views of the worn out inserts after machining of hardened AISI 4320 steel at a particular V-f-d combination under different environments for different times spans, shown in Fig.2.20 and Fig.2.21, qualitatively indicate that MQL has provided sizeable reduction in overall wear of the insert. Fig.2.20 also show that principle flank wear occurred more or less uniformly along the main cutting edge of the SNMG tool and under different environments in machining the AISI 4320 steel. However, VM sizeably decreased due to MQL as can be seen in Fig.2.18. Substantial reduction in average auxiliary flank wear (VS) in SNMG inserts enabled by present MQL in machining AISI 4320 steel has been revealed in Fig.2.19 and Fig.2.21. So it is found that cutting oil increase tool life by decreasing tool wear.

3.4 Product Quality

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. The major causes behind development of surface roughness in continuous machining processes are:

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

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

iii. vibration in the machining system

iv. built-up edge formation, if any

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

$$h_m = \frac{f^2}{8r} \quad \text{(3.2)}$$

Where,

h_m = Peak value of roughness caused due to feed marks

r = Nose radius of the turning inserts

f = 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.

Feed force as well as chip thickness ratio 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 thickness ratio increases with the increase in cutting speed. Fig 2.22 to Fig.2.24 show the variation of the values of surface roughness, Ra attained of machining of hardened AISI 4320 steel by the sharp SNMG inserts at various V-f combinations under dry and MQL (vegetable oil, cutting oil and soluble oil) conditions. The surface roughness increases with the increase in feed, f and decreases with the increase in V. Increase in f raises Ra mainly. Reduction in Ra with the increase in V 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 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 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 faster decreases 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 2.22 to Fig.2.24 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 2.22 to Fig.2.24 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. Compared among vegetable oil, cutting oil and soluble, cutting oil gives best performance and soluble oil gives worst performance. Because at higher speed and feed rate, cutting oil gives better surface finish than other two cutting fluids.

The percentage saving in average surface roughness Ra attained by MQL for different V-f combinations have been extracted from the previous figures and shown in

Table 3.5 for hardened AISI 4320 steel For convenience of comparison, the ranges and averages of percentage savings in Ra have been separately shown in Table 3.6 which visualizes how the beneficial role of MQL varied with different cutting fluids.

Table 3.5 Percentage reduction in surface roughness (Ra) due to minimum quantity lubricant

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Percentage reduction in Ra under different MQL environments		
		MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.10	82	3	11	21
	114	5	13	27
	163	7	15	32
0.12	82	7	12	20
	114	7	14	22
	163	6	10	19
0.14	82	6	12	20
	114	3	10	23
	163	4	13	26

Table 3.6 Average percentage reduction in Ra due to minimum quantity lubricant

Savings	Average percentage reduction in Ra		
	MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
Range	3-7	10-15	19-32
Average	5.11	12.22	23.33

From the Table 3.6 it is shown that in respect of surface roughness MQL is better for f=0.10 mm/rev and V=163 m/min. The value of percentage reduction for cutting oil, vegetable oil and soluble oil are 19~32%, 10~15% and 3~7%respectively. Again the average percentage reductions are 23.33%. 12.22% and 5.11% for cutting oil, vegetable oil and soluble oil respectively. So it is clear that surface roughness is reduced under MQL condition than dry through out the V-f combinations but MQL by cutting oil and vegetable oil show better results.

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. 2.25 shows the variation in surface roughness observed with progress of machining of the hardened AISI 4320 steel by the SNMG insert at a particular set of V (114m/min), f (0.10 mm/rev) and d (1.0 mm) under dry and MQL conditions at machining time 14 seconds. Fig.2.25 reveals the pattern of growth of surface roughness. Such observations indicate distinct correlation between auxiliary flank wear and surface roughness also like dimensional deviation. 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 coated carbides. 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. 2.25 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 minimum quantity lubrication 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. Among different MQL condition cutting oil is the best performer because surface roughness decreased to a large extent by application of cutting oil (VG 68).

Fig.2.26 shows the effect of MQL by vegetable oil and cutting oil on the dimensional accuracy of the turned job. The finished job diameter generally deviates from its desired value with the progress of machining, i.e. along the job-length mainly due to change in the effective depth of cut for several reasons which include wear of the tool nose, over all compliance of the machine-fixture-tool-work system and thermal expansion of the job during machining followed by cooling. Therefore, if the machine-fixture-tool-work system is rigid, variation in diameter would be governed mainly by the heat and cutting temperature. With the increase in temperature the rate of growth of auxiliary flank wear and thermal expansion of the job will increase. MQL takes away the major portion of heat and reduces the temperature resulting from decrease in dimensional deviation Performance of cutting oil is found better than that of vegetable oil in controlling the deviation of dimension during machining hardened steel.

Fig.2.26 clearly shows that dimensional inaccuracy can be sizably reduced by the present method of MQL jet in machining hardened AISI 4320 steel rod by carbide inserts. Careful observation of the figure presenting dimensional deviations under various machining conditions and those presenting average auxiliary flank wear visualises that dimensional deviations observed have close relation with corresponding auxiliary flank wear Fig.2.26 and Fig.2.19 show that the nature of increase of dimensional deviation with the progress of machining AISI 4320 steel rod is quite similar to that of growth of auxiliary flank wear (VS). Dimensional inaccuracy has been respectively enhanced and reduced by application of MQL, expectedly, in the way VS has been respectively raised and reduced. Therefore, increase in diameter is almost directly related to that of auxiliary flank wear. However, it is clear from Fig.2.26 that the use of minimum quantity of lubricant by VG 68 cutting oil has reduced the dimensional inaccuracy remarkable in compare to vegetable oil.

Chapter 4

Conclusions and Recommendations

4.1 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 AISI 4320 steel by coated carbide insert (SNMG-TN 4000).

(ii) Due to the application of minimum quantity lubricant (MQL) in turning hardened AISI 4320 steel, the shape and colour of the chips became favourable for more effective and efficient cooling and improved chip-tool interaction. Chip thickness ratio increases 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 by VG 68 cutting oil shows the best results than vegetable oil and soluble oil in respect of chip thickness ratio. Minimum quantity lubricant by VG 68 cutting oil has increased the chip thickness ration (r_c) by 15 to 42%.

(iii) The present MQL systems enabled reduction in average chip-tool interface temperature upto 16% depending upon the types of cutting fluids and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices. MQL by VG 68 cutting oil is more effective among the three environments.

(iv) The most noteworthy contribution of application of MQL jet in machining hardened AISI 4320 steel by coated 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 minimum quantity lubricant by VG 68 cutting oil in comparison to other environments.

(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. Cutting oil is the best performer than vegetable oil and the higher value of reduction of surface roughness is observed during machining at 114 m/min with feed rate 0.10 mm/rev.

(vi) Minimum quantity lubricant (MQL) not only enhanced tool life but also improved surface finish and dimensional accuracy mainly by reducing the damage of the tool nose in machining the hardened steels. MQL by VG 68 cutting oil and vegetable oil has reduced tool wear, improved surface finish and dimensional accuracy in comparison to dry machining but MQL by VG 68 cutting oil performed better in comparison to MQL by vegetable oil.

4.2 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 SNMG tool 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 minimum quantity lubricant (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.

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Appendix

Table-1 Chip thickness ratio (r_c) under dry condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Uncut chip thickness, a_1, mm	Chip thickness, a_2, mm	Chip thickness ratio, r_c
0.1	82	0.09659	0.25	0.38
	114	0.09659	0.21	0.45
	163	0.09659	0.19	0.52
0.12	82	0.1159	0.28	0.42
	114	0.1159	0.24	0.48
	163	0.1159	0.21	0.55
0.14	82	0.1352	0.30	0.45
	114	0.1352	0.27	0.51
	163	0.1352	0.24	0.56

Table-2 Chip thickness ratio (r_c) under MQL (soluble oil) condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Uncut chip thickness, a_1, mm	Chip thickness, a_2, mm	Chip thickness ratio, r_c
0.1	82	0.09659	0.23	0.42
	114	0.09659	0.19	0.51
	163	0.09659	0.17	0.56
0.12	82	0.1159	0.26	0.44
	114	0.1159	0.22	0.53
	163	0.1159	0.20	0.58
0.14	82	0.1352	0.28	0.48
	114	0.1352	0.26	0.53
	163	0.1352	0.22	0.61

Table-3 Chip thickness ratio (r_c) under MQL (vegetable oil) condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Uncut chip thickness, a_1, mm	Chip thickness, a_2, mm	Chip thickness ratio, r_c
0.1	82	0.09659	0.21	0.46
	114	0.09659	0.17	0.57
	163	0.09659	0.16	0.6
0.12	82	0.1159	0.24	0.48
	114	0.1159	0.20	0.57
	163	0.1159	0.19	0.6
0.14	82	0.1352	0.26	0.52
	114	0.1352	0.23	0.58
	163	0.1352	0.21	0.65

Table-4 Chip thickness ratio (r_c) under MQL (VG 68 cutting oil) condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Uncut chip thickness, a_1, mm	Chip thickness, a_2, mm	Chip thickness ratio, r_c
0.1	82	0.09659	0.18	0.54
	114	0.09659	0.15	0.63
	163	0.09659	0.16	0.65
0.12	82	0.1159	0.23	0.51
	114	0.1159	0.19	0.61
	163	0.1159	0.18	0.63
0.14	82	0.1352	0.25	0.55
	114	0.1352	0.21	0.64
	163	0.1352	0.20	0.68

Table-5 Chip-tool interface temperature (^{0}C) under dry condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Milivoltmeter reading (mV)	Temperature (^{0}C)
0.1	82	12.68	889
	114	13.54	909
	163	14.06	920
0.12	82	13.02	897
	114	13.82	915
	163	14.56	930
0.14	82	13.68	912
	114	14.61	930
	163	15.56	945

Table-6 Chip-tool interface temperature (^{0}C) under MQL (soluble oil) condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Milivoltmeter reading (mV)	Temperature (^{0}C)
0.1	82	10.4	820
	114	12.48	884
	163	13.13	900
0.12	82	10.28	816
	114	11.04	842
	163	12.13	874
0.14	82	10.96	839
	114	11.82	865
	163	12.32	879

Table-7 Chip-tool interface temperature (^0C) under MQL (vegetable oil) condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Milivoltmeter reading (mV)	Temperature (^0C)
0.1	82	9.14	773
	114	10.34	818
	163	11.22	847
0.12	82	9.78	798
	114	10.74	832
	163	11.49	856
0.14	82	10.18	812
	114	10.9	837
	163	11.94	869

Table-8 Chip-tool interface temperature (^0C) under MQL (VG 68 cutting oil) condition

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Milivoltmeter reading (mV)	Temperature (^0C)
0.1	82	8.52	747
	114	9.14	773
	163	9.88	801
0.12	82	9.32	780
	114	9.74	796
	163	10.08	809
0.14	82	9.66	793
	114	10.33	818
	163	11.02	841

Table-9 Tool Wear under dry condition

Time (min)	Average principal flank wear (VB), μm	Average maximum flank wear (VM), μm	Average auxiliary flank wear (VS), μm
0	0	0	0
1.27	65	73	52
2.54	100	110	77
3.81	125	137	98
5.09	145	157	115
6.36	160	170	129
7.63	175	180	142
8.90	185	188	155
10.18	200	196	168
11.45	215	207	183
12.72	230	222	200
14	245	243	222

Table-10 Tool Wear under MQL (vegetable oil) condition

Time (min)	Average principal flank wear (VB), μm	Average maximum flank wear (VM), μm	Average auxiliary flank wear (VS), μm
0	0	0	0
1.27	50	53	36
2.54	75	79	55
3.81	90	97	72
5.09	109	111	86
6.36	120	121	99
7.63	130	130	112
8.90	140	139	125
10.18	150	149	138
11.45	162	161	153
12.72	175	178	171
14	190	202	191

Table-11 Tool Wear under MQL (VG 68 cutting oil) condition

Time (min)	Average principal flank wear (VB), µm	Average maximum flank wear (VM), µm	Average auxiliary flank wear (VS), µm
0	0	0	0
1.27	38	37	29
2.54	56	56	46
3.81	71	70	59
5.09	82	79	70
6.36	93	86	78
7.63	106	92	86
8.90	114	99	93
10.18	121	108	101
11.45	131	120	112
12.72	140	138	125
14	148	163	142

Table-12 Surface Roughness (Ra), µm

Feed rate, f, mm/rev	Cutting velocity, V, m/min	Environments			
		Dry	MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.1	82	0.7	0.68	0.62	0.55
	114	0.63	0.6	0.55	0.46
	163	0.59	0.55	0.5	0.4
0.12	82	0.75	0.7	0.66	0.6
	114	0.73	0.68	0.63	0.57
	163	0.67	0.63	0.6	0.54
0.14	82	0.85	0.8	0.75	0.68
	114	0.8	0.78	0.72	0.62
	163	0.78	0.75	0.68	0.58

Table-13 Surface Roughness (Ra) with machining time (µm)

Time (Min)	Environments		
	Dry	MQL (Vegetable oil)	MQL(VG 68 cutting oil)
0	0	0	0
1.27	1.02	0.76	0.54
2.54	1.54	1.18	0.82
3.81	1.90	1.46	0.98
5.09	2.12	1.64	1.04
6.36	2.24	1.74	1.04
7.63	2.30	1.80	1.06
8.90	2.34	1.84	1.10
10.18	2.42	1.94	1.15
11.45	2.56	2.08	1.16
12.72	2.80	2.32	1.25
14	3.20	2.68	1.46

Table-14 Dimensional Deviation (µm)

Length (mm)	Environments		
	Dry	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0	0	0	0
10	18.75	12	5
20	36.25	25	15
30	46.25	35	22
40	56.25	45	30
50	67.5	58	39.25
60	76.25	65	48.75
70	85.5	75	58.5
80	93.75	83	64
90	105	92	73.5
100	115	103	83.25
110	123.75	112	90.25
120	132.5	120.5	97.5
130	142.5	127.5	109.75
140	151.75	132.5	117.5
150	160.25	141.5	123.5
160	166.5	150.5	135
170	173.25	159	140
180	181	163.5	148
190	189.5	172.5	153
200	199.5	182.5	160
210	210.5	192	168
220	220.5	202.5	175