Effects of Minimum Quantity of Lubrication (MQL) on Tool Wear and Surface Roughness in Turning AISI-1040 Steel with Uncoated Carbide Tool

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A Project Thesis

By

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September, 2005

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Submitted to the Department of Industrial & Production Engineering, Bangladesh University of Engineering & Technology, Dhaka, in partial fulfillment of the requirements for the degree of **Master of Industrial & Production Engineering.**

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The thesis titled "**Effects of Minimum Quantity of Lubrication (MQL) on Tool Wear and Surface Roughness in Turning AISI-1040 Steel with Uncoated Carbide Tool**" submitted by Md. Abu Hayat Mithu, Student No. 040308005F, Session- April 2003, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **MASTER OF ENGINEERING** in Industrial & Production Engineering on September, 2005.

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September, 2005

Declaration

I do hereby declare that this work has been done by me and neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma except for publication.

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Abstract

Minimum quantity lubrication (MQL) refers to the use of cutting fluids of only a minute amount-typically of a flow rate of 50 to 500 ml/hour which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition. The concept of minimum quantity lubrication, sometimes referred to as near dry lubrication or micro lubrication, has been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. The minimization of cutting fluid also leads to economical benefits by way of saving lubricant costs and workpiece/tool/machine cleaning cycle time.

During machining, the cutting tool generally undergoes both flank wear and crater wear. Flank wear generally causes an increase in the cutting forces, dimensional inaccuracy and vibration. Crater wear takes place on the rake face of the tool where the chip slides over the tool surface. This was aimed to study the role of cutting fluid, tool and workpiece material, tool geometry and cutting conditions on machinability. Proper selection and application of cutting fluid generally improves tool life. But surface finish did not improve significantly. Wearing of cutting tools not only causes loss of the cutting edges or tips of the inserts but loss of the entire insert after wear of all the corners. From an environmental perspective, therefore, the significant waste

is not the portion of the tool worn away by the tool-work contact, but the remaining portion of the tool that is disposed after its useful life.

Compared to the dry and wet machining, MQL machining performed many superiors mainly due to reduction in cutting zone temperature enabling favorable chip formation and chip-tool interaction. It also provides reduction in tool wear, which enhanced the tool life, dimensional accuracy and product quality. Furthermore, it provides environment friendliness and improves the machinability characteristics.

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Chapter-1

Introduction

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 (underside of the chip and the machined surface) that can interact extensively with the tool material and high mechanical and thermal stresses on the tool [**Komanduri and Desai 1983**]. Further, the shear and friction in the cutting process interact with enabling changes in friction to be accompanied by similar changes in the shear, resulting in further reduction in the overall energy requirements. The frictional energy in machining can account for some ¼ to 1/3 of the total cutting energy, which depending on the type of cutting operation can range up to 69 x 10^3 Nm/m^3. 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. The net result is reduced tool forces or cutting energy and increased tool life.

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

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

Longer cuts under high cutting temperature cause thermal expansion and distortion of the job particularly if it is slender and small in size, which leads to dimensional and form inaccuracy. On the other hand, high cutting temperature accelerates the growth of tool wear and also enhances the chances of premature failure of the tool by plastic deformation and thermal fracturing. The surface quality of the products also deteriorates with the increase in cutting temperature due to built-up-edge formation, oxidation, rapid corrosion and induction of tensile residual stress and surface micro-cracks. Such problem becomes more acute and serious if the work materials are very hard, strong and heat resistive and when the machined part is subjected to dynamic or shock loading during their functional operations. Therefore, it is essential to reduce the cutting temperature as far as possible. In industries, the machining temperature and its detrimental effects are generally reduced by (a) proper selection of process parameters, geometry of the cutting tools and proper selection and application of cutting fluid and (b) using heat and wear resistant cutting tool materials like carbides, coated carbides and high performance ceramics (CBN and diamond are extremely heat and wear resistive but those are too expensive and are justified for very special work materials and requirements where other tools are not effective). Cutting fluid not only cools the tool and job but also provides lubrication and cleans the cutting zone and protects the nascent finished surface from contamination by the harmful gases present in the atmosphere. But the conventional types and methods of application of cutting fluid have been found to become less effective. With the increase in cutting velocity and feed, the cutting fluid cannot properly enter the chip-tool interface to cool and lubricate due to bulk plastic contact of the chip with the tool rake surface. Besides that, often in high production machining the cutting fluid may cause premature failure of the cutting tool by fracturing due to close curling of the chips and thermal shocks. For which application of high pressure cooling type water base cutting fluids are generally avoided in machining steels by brittle type cutting tools like carbides and ceramics. But what is of more serious concern is the pollution of the working environment caused by use of cutting fluid, particularly oil-based type.

The major socio-economic problems **[Aronson 1995]** that arise due to conventional type and method of application of cutting fluids are (a) inconveniences due to wetting and dirtiness of the working zone (b) possible damage of the machine tool by corrosion and mixing of the cutting fluid with the lubricants (c) environmental pollution due to break down of the cutting fluid into harmful gases and biological hazards to the operators from bacterial growth in the cutting fluids and (d) requirement of additional systems for local storage, pumping, filtration, recycling, re-cooling, large space and disposal of the cutting fluid, which causes soil contamination and water pollution.

The modern industries are, therefore, looking for possible means of dry (near dry), clean, neat and pollution free machining and grinding. Minimum Quantity Lubrication (MQL) refers to the use of cutting fluids of only a minute amount–typically of a flow rate of 50 to 500 ml/hour–which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition, where, for example, up to 10 liters of fluid can be dispensed per minute. The concept of minimum quantity lubrication, sometimes referred to as "near dry lubrication" [**Klocke and Eisenblatter, 1997**] or "micro lubrication" **[MaClure et al, 2001]**, has been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. The minimization of cutting fluid also leads to economical benefits by way of saving lubricant costs and workpiece/tool/ machine cleaning cycle time.

1.1 Literature Review

Use of cutting fluids was always considered a solution rather than a problem in machining, at least till recently. They serve many useful functions, including, cooling of the cutting tool at higher speeds, lubrication at low speeds and high loads, increasing tool life, improving the surface finish, reducing the cutting forces and power consumption, reducing the distortion due to temperature rise in the workpiece, chip handling and disposal, providing a protective layer on the machined surface from oxidation and protection of the machine tool components from rust. For a long time, because of the limitations on the tool materials available, the use of cutting fluid was considered as an essential integral part of the machine tool system. All the ill effects associated with the use of cutting fluids were considered as a price for improving productivity. Various methods were developed to minimize their adverse effects although progress was far less than desired. The detrimental effects of the cutting fluids include the cost of the cutting fluid system, *i.e.* the fluid itself, pumping systems, collection and filtration system, storage and disposal and sometimes a recalculating system etc; the physiological effects on the operator, namely, toxic vapors, unpleasant odors, smoke fumes, skin irritations (dermatitis), or effects from bacteria cultures from the cutting fluid; and its overall effect on the worker safety and on the environment. In some applications the consumption of cutting fluid has been reduced drastically by using mist lubrication. However, mist in the industrial environment can have a serious respiratory effect on the operator. Consequently, high standards are being set to minimize this effect. Until now, ample research and investigations have been done in different parts of the world on machinability of different materials mainly in respect of chip morphology, cutting forces, cutting temperature, chip tool interaction, dimensional accuracy, surface integrity (surface roughness), and wear and life of cutting tool with or without (dry machining) using cutting fluid. Environmental pollution arising out of conventional cutting fluid applications has been a serious concern of the modern machining industries. Research has also been initiated on control of such pollution by minimum quantity of lubrication (MQL) and their technological effects particularly in temperature intensive machining on tool wear and surface roughness. A brief review on tool wears and surface roughness in simple turning with uncoated carbide tools is presented in this section.

1.1.1 Effects and Control of Cutting Temperature

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

It was observed [**Jawahir and van Luttervelt 1993**] that, in machining ductile metals producing long chips, the chip-tool contact length has a direct influence on the cutting temperature and thermo-chemical wear of cutting tools. The cutting temperature becomes higher on the rake face of the tool at a certain distance from the cutting edge where cratering occurs. Such high rake face temperature can also raise the temperature at the flank of the tool.

In addition to usual flank wear and crater wear the cutting tools often attain notching on the flanks and grooving on the rake surface at the outer ends of the engaged portions of the cutting edges. On the major cutting edge, the grooving wear occurs at the extreme end of the depth of cut and is characterized by deeper abrasion of the tool edge. On the end cutting edge, the grooving wear is characterized by smaller multiple notches. Several mechanisms have been proposed [**Solaja 1958**] to explain grooving wear, such as (a) development of a work-hardened/abrasive oxide layer on the cut surface (b) formation of thermal cracks due to steep temperature gradient (c) presence of side-spread material at the edges of a newly cut surface and (d) fatigue of tool material dua to cutting force fluctuations at the free surface caused by lateral motions of the edges of the chip.

Trent [1983] also reported that in machining ductile metals, the chip contact length plays significant role on the chip and tool temperature which becomes maximum almost at the center of the chip-tool contact surface where then crater wear begins and grooves intensively.

Kosa et al [1989] suggested that in machining ductile metals, the heat and temperature developed due to plastic deformation and rubbing of the chips with tool may cause continuous built-up of welded debris which affects machining operation. Austenitic stainless steels are generally considered difficult-to-machine because of high work-hardening rate, toughness and ductility. Therefore, tools will be subjected to high frictional heat, and chips will have a tendency to stick and cause severe built-up edge formation.

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

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

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

The high specific energy required in machining under high cutting velocity and unfavorable condition of machining results in very high temperature, which reduces the dimensional accuracy and tool life by plastic deformation and rapid wear of the cutting points [**Chattopadhyay and Bhattacharya 1968, Chattopadhyay and Chattopadhyay 1982 and Singh et al. 1997**]. On the other hand, such high temperature, if not controlled, impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, micro cracks and subsurface cracks. This problem is further intensified while machining for faster material removal in bulk and finishing very hard, strong and difficult-to-machine materials that are gradually advancing with vast and rapid developments in the modern areas like aerospace technology and nuclear science.

The primary functions of cutting fluids are to reduce the cutting temperature and increase tool life **[Shaw et al. 1951]**. The cutting fluids are believed to reduce cutting temperature either by removing heat as a coolant or reducing the heet generation as a lubricant. In addition, the cutting fluid has a practical function as e chip-handling medium **[Beaubien 1964]**. Cutting fluids also help in machining of ductile materials as AISI-1040 Steel by reducing or preventing formation of a built-up edge (BUE), which degrades the surface finish [**Heginbotham and Gogia 1961**].

Usually profuse cooling [**Alaxender et al. 1998, Kurimoto and Barroe 1982 and Wrethin et al. 1992**] controls the high cutting temperature. 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 mechining process end harder meterials 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 hes been experienced **[Cassin and Boothroyed 1965]** that lubrication is effective at low speeds when it is accomplished by diffusion through the workpiece and by forming solid boundary layers from the extreme pressure additives, but at high speeds no sufficient lubrication effect is evident. The ineffectiveness of lubrication of the cutting fluid at high speed machining is attributed [**Shaw et al. 1951**] to the inability of the cutting fluid to reach the actual cutting zone and particularly at the chip-tool interface due to bulk or plastic contact at high cutting speed.

The cooling and lubricating effects by cutting fluid (flood cooling) [**Merchant 1958 and Kitagawa et al. 1997**] influence each other and diminish with increase in cutting velocity. Since the cutting fluid does not enter the chip-tool interface during high speed machining, the cutting fluid action is limited to bulk heat removal only. Mazurkiewicz et al. [**1989**] reported that a coolant applied at the cutting zone through a high pressure jet nozzle could reduce the contact length and coefficient of friction at chip-tool interface and thus could reduce cutting forces and increese tool life to some extent.

In machining ductile metals even with cutting fluid, the increase in cutting velocity reduces the ductility of the work material and causes production of long continuous chips, which raises the cutting temperature further [**Nedess and Hintze 1989**].

The effect of the heat generated at the primary shear zone is less significant for its lesser intensity and distance from the rake surface. But the heat generated at the chip-tool interface is of much greater significance, particularly under high cutting speed conditions where the heat source is a thin flow-zone seized to the tool [**Trent 1984**]. The coolant cannot act directly on this thin zone but only externally cools the chip, workpiece and the tool, which are accessible to the coolant. Removal of heat by conduction through the chip and the workpiece is likely to have relatively little effect on the temperature at the chip-tool and work-tool interface.

A cutting fluid may impart two more actions, namely the mechanical strength reducing action and the electro-chemical action. The mechanical strength reducing action (known as the Rehbinder effect) seemed to be negligible when steel jobs are machined at moderate cutting speeds with carbide tools **[Kurimoto and Barroe 1982]**. The influence of the electric current flowing through the cutting zone on the rate of tool wear is also well known [**Ellis and Barrow 1969**]. However, most commercial cutting fluids are non electro-conductive, and as such the situation with respect to current flow will not vary significantly from the dry cutting case. The electrochemical action is treated as a corrosion phenomenon in respect of tool wear.

The machining temperature could be reduced to some extent by improving the machinability characteristics of the work material metallurgically, optimizing the tool geometry and by proper selection of the process parameters [**Muraka 1979, Dieter 1981 and Jawahir 1988**]. Some recent techniques have enabled partial control of the machining temperature by using heat resistance tools like coated carbides, CBN etc. But CBN tools are very expensive.

A tribological experiment was attempted [**Farook et al. 1998**] to modify the contact surface of turning inserts by deposition of a soft bearing material by EDM. It was observed that although the modified inserts offer reduced cutting force, their beneficial effect on surface finish is marginal. At higher cutting velocities the brought on layers are fast depleted with cutting time and makes no contribution to wear resistance of the tool, especially at the flanks. It was reported [**Alaxender et al. 1998**] that coolant injection offers better cutting performance in terms of surface finish, tool force and tool wear when compared to flood cooling.

1.1.2 Adverse Effects of Cutting Fluid Applications

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

The application of cutting fluid may not always reduce the cutting tool wear as is commonly believed. Rather some conditions like machining steels by carbide tools, the use of coolant may increase tool wear. It has been experienced [**Shaw et al. 1951**] that there was more tool wear when cutting with coolant than cutting dry in case of machining AISI 1020 and AISI 4340 steels by M-2 high speed steel tool cutting. Seah et al. [**1995**] also reported that at the first stage of machining (first 40 seconds or so), tool wear was faster in wet cutting than in dry cutting. Later on, the wear rate stabilized and was somewhat the same for both dry and wet machining.

During machining, the cutting tool generally undergoes **[Trent 1983]** both flank wear and crater wear. Flank wear generally causes an increase in the cutting forces, dimensional inaccuracy and vibration. Crater wear takes place on the rake face of the tool where the chip slides over the tool surface. Another experimental investigation was conducted **[Cozzens et al. 1995]** on single point boring. This was aimed to study the role of cutting fluid, tool and workpiece material, tool geometry and cutting conditions on machinability. The results indicated that the cutting fluid conditions had no significant effect on surface texture, forces and built-up edge. Since boring is a high-speed operation and lubrication is ineffective, no effect was seen on the forces. However, the cutting fluid was found to have a significant effect on surface integrity.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained **[Satoshi et al. 1997]** by such cutting fluid. But surface finish did not improve significantly. Wearing of cutting tools not only causes loss of the cutting edges or tips of the inserts but loss of the entire insert after wear of all the corners. From an environmental perspective, therefore, the significant waste is not the portion of the tool worn away by the tool-work contact, but the remaining portion of the tool that is disposed after its useful life [**Sheng and Munoz 1993**].

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

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

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

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

Several other epidemiological studies have also suggested that exposure to fluid mist may be associated with increased risk of airway irritation, chronic bronchitis, asthma and even laryngeal cancer [**Bennett et al. 1985 and Eisen et al. 1994**]. The Occupational Safety and Health Administrations

(OSHA) standard for airborne particulate (largely due to fluid mist) is 5 mg/m^3, and the United Autoworkers (UAW) has proposed a reduction in the standard to 0.5 mg/m^3. The oil mist level in a plant ranged from 4.2 to 15.6 mg/m^3 but fell to between 0.47 to 1.68 mg/m^3 when a different cutting fluid was substituted in the system [**Welter 1978**].

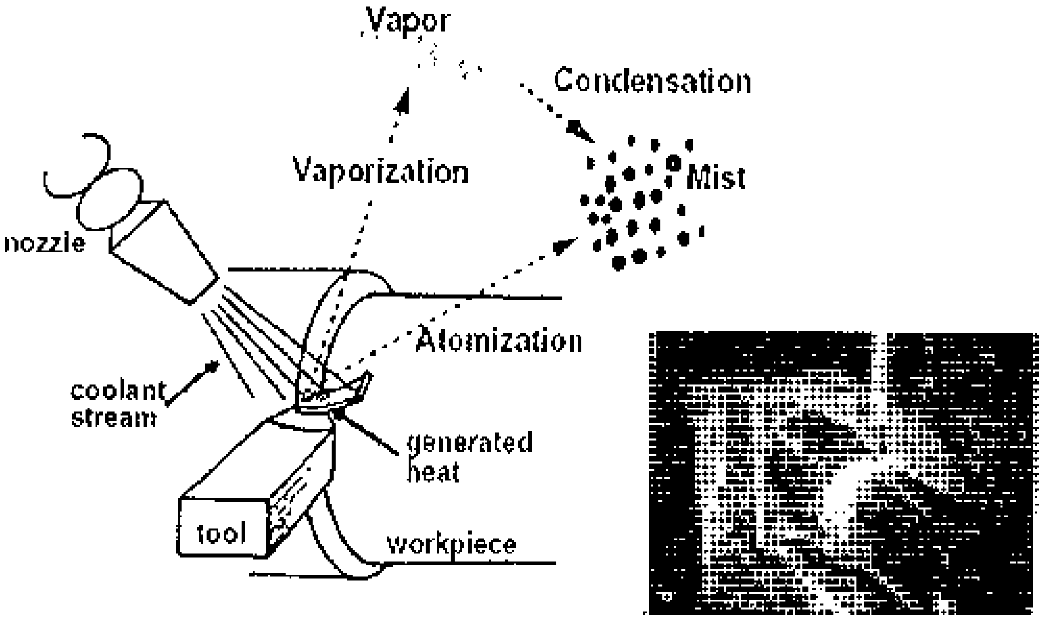


Fig. 1.1 Mist formation during machining with flood cooling

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

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

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

1.1.3 Summary of the Review

A review of the literature on machinability of different commercial steel highlights the immense potential of the control of machining temperature, tool life, machined surface and its detrimental effects. It is realized that the machining temperature has a critical influence on chip reduction coefficient, cutting forces, tool wear and tool life. All these responses are very important in deciding the overall performance of the tool. At the elevated temperature the cutting tools may undergo plastic deformation and attain rapid tool wear because by adhesive, abrasive, chemical and diffusion wear at the flanks and the crater. The dimensional accuracy and surface integrity of the workpiece also deteriorate due to high temperature. The conventional cutting fluids are not that effective in high speed machining 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.

Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling and chip flushing functions. Typically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Minimum quantity lubrication (MQL) presents itself as a viable alternative for machining with respect to tool wear, heat dissertation and machined surface quality.

This research compares the mechanical performance of minimum quantity lubrication to completely dry and wet lubrication for the turning of steel based on experimental measurement of cutting temperature, chip formation, tool life and surface finish.

1.2 Objectives of the Present Work

The main objective of the present work is to make a thorough and systematic experimental investigation on the role of MQL on the major machinability characteristics and overall benefits in respects of

i. mechanism of machining
ii. cutting temperature
iii. tool wear and tool life
iv. quality of the finished surface (surface roughness and dimensional deviation)

In machining AISI 1040 steel by the industrially used uncoated carbide insert at different speeds, feeds and depth of cut combinations. These results are expected to enable optimization of the MQL process and machining conditions for deriving maximum benefits.

The scopes of the present work are design and fabrication of

i. a minimum quantity lubrication (MQL) applicator
ii. a MQL machining set up
iii. a temperature measuring technique

iv. a tool wear measuring and
v. surface roughness measuring

1.3 Methodology

The sanctioned work is entirely experimental in nature. Proper design of experiment would be done for reasonably quantitative assessment of the role of the machining and the MQL cooling parameters on the technological responses. The general methodology would be as follows:

- Design and fabrication of appropriate MQL delivery system
- Design and fabrication of micro nozzle for application of the MQL jet
- Assessment of chip morphology under dry, wet and MQL environments
- Metallurgical study of the chips to explore the nature of chip-tool interaction
- Monitoring of cutting zone temperature by tool-work thermocouple principle
- Study of the effects of MQL on surface integrity along the surface finish
- Study of growth of flank wear, notch wear and crater wear under optical microscope
- SEM analysis of the rake and flank surface to study the mechanism of wear

Chapter-2

Design and Fabrication of MQL Applicator

2.1 Introduction

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

- ineffectiveness in desired cooling and lubrication
- health hazards due to generation of obnoxious gases and bacterial growth
- inconvenience due to uncleanliness of the working zone

- corrosion and contamination of the lubricating system of the machine tools
- need of storage, additional floor space, pumping system, recycling and disposal
- environmental pollution and contamination of soil and water.

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

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

- effective cooling by enabling MQL jet reach as close to the actual hot zones as possible
- avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes
- minimum consumption of cutting fluid by pin-pointed impingement and only during chip formation

2.2 Design and Fabrication of the MQL System

The MQL needs to be supply at high pressure and impinged at high speed through the nozzle at the cutting zone. Considering the conditions required for the present research work and uninterrupted supply of MQL at constant pressure around 3.5 bar over a reasonably long cut, a MQL delivery system has been designed, fabricated and used. The schematic view of the MQL set up is shown in Fig 2.1. In this system, a compressor is used to supply high-pressure air (3.5 bar) and the fluid pump supplies the cutting fluid from the fluid reservoir. This high pressure-air from the compressor enters into two chambers. One is fluid chamber and another is mixing chamber. The fluid chamber is connected at the bottom with the mixing chamber by a nipple. A needle is inserted in the nipple 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.

The mixing chamber has two-inlet port and 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 compressed air and cutting fluid is impinged at a high speed through the nozzle at the chip-tool interface.

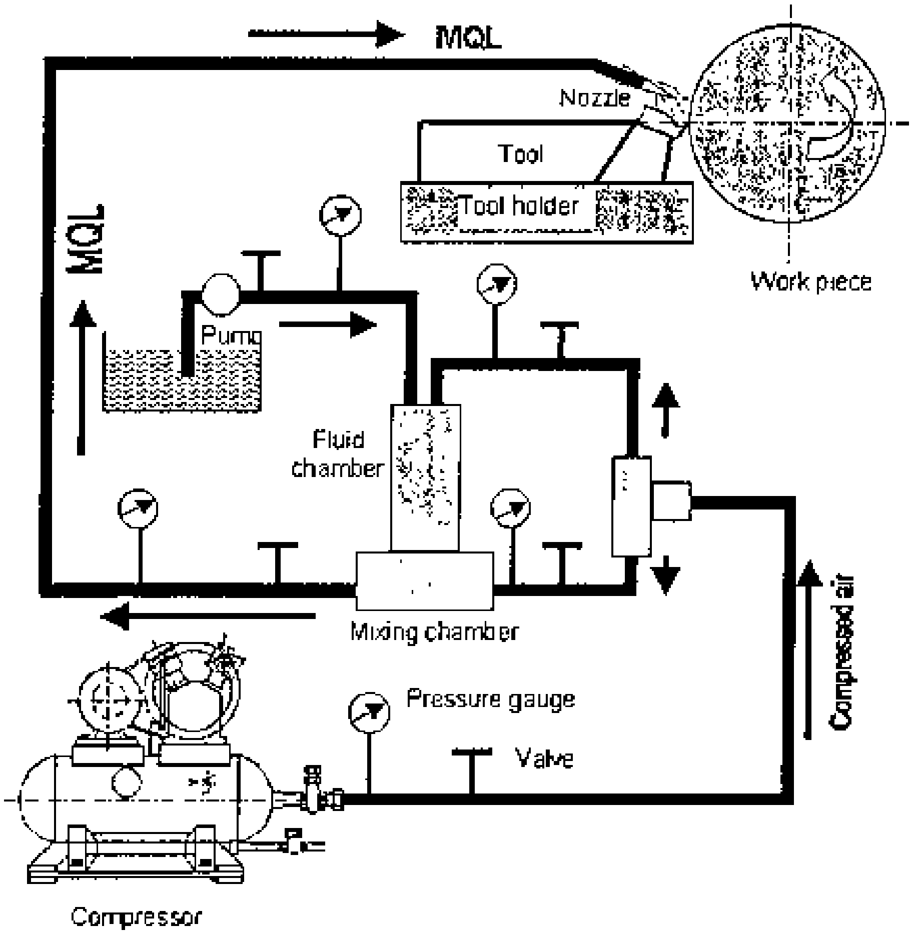


Fig. 2.1 Schematic view of MQL unit

2.3 Design and Fabrication of the Nozzle

The nozzle has been designed so that the nozzle spray pattern, covering area and MQL rate can be controlled. The nozzle developed and used and its setting along the tool holder are shown in Fig.2.2. The nozzle with two tips of 1.50 mm bore diameter was fixed to the tool post and is connected with flexible pipe connecting end to supply MQL in the form of jets to the cutting zone. The expected result of this arrangement is effective cooling with economical MQL dispensing. The construction and setting of the nozzle tips have been made primarily aiming:

- less interference with the flowing chips
- high speed MQL jet reaching quite close to the chip-tool contact zone
- simple and low cost.

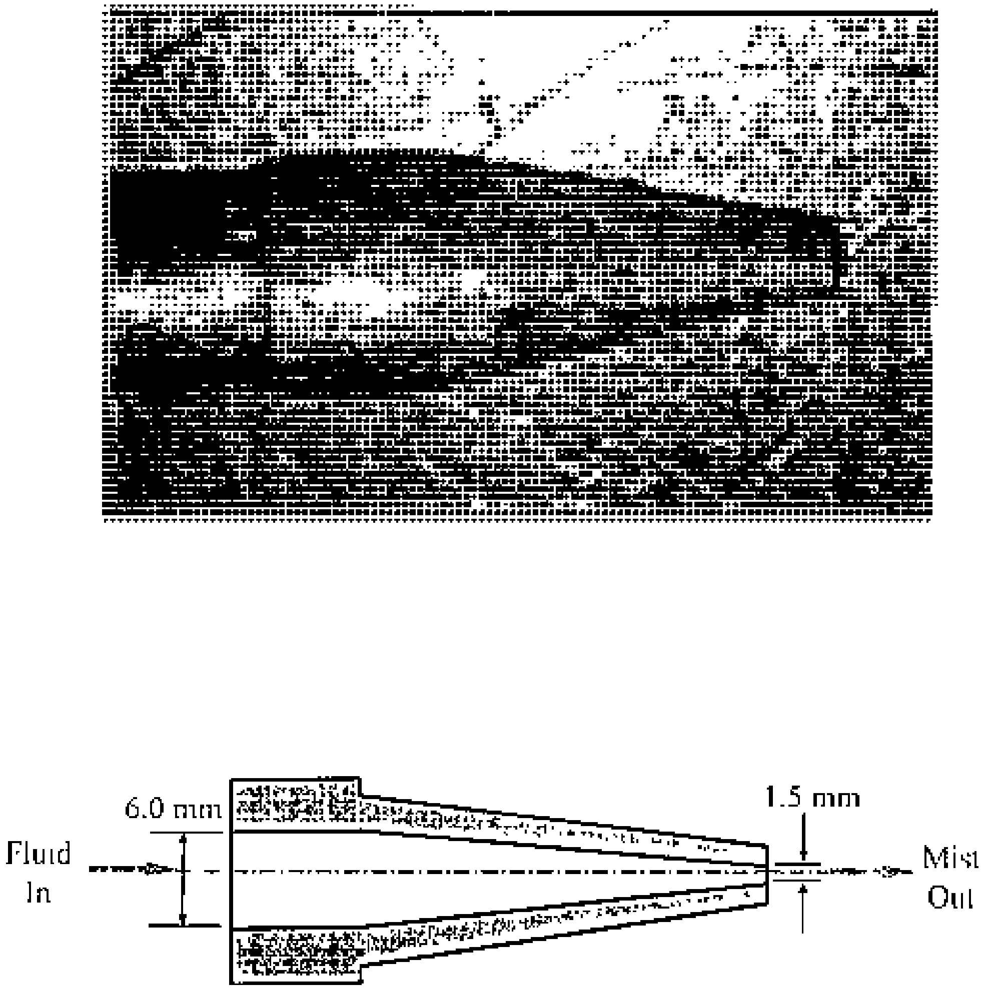


Fig. 2.2 Photographic and schematic view of the nozzle used for MQL delivery at the cutting zone

Chapter-3

Experimental Investigations

3.1 Experimental Procedure and Conditions

The beneficial role of MQL on environment friendliness has already been established. The aim of the present work is primarily to explore and evaluate the role of such MQL on machinability characteristics of commonly used tool-work combination mainly in terms of cutting temperature and chip-forms, which govern productivity, product quality and overall economy.

The machining tests have been carried out by straight turning of AISI-1040 steel on a lathe (4 hp: BMTF, Bangladesh) by standard uncoated carbide insert at different cutting velocities (V_c) and feeds (S_o) under dry, wet and MQL conditions.

Machining ferrous metals by carbides is a major activity in the machining industries. Machining of steels involves more heat generation for their ductility and production of continuous chips having more intimate and wide chip-tool contact. Again, the cutting temperature increases further with the increase in strength and hardness of the steels for more specific energy requirement. Keeping these facts in view the commonly used steel like AISI-1040 steel has been undertaken for the present investigations.

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

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

Effectiveness of cooling and the related benefits depend on how closely the MQL jet can reach the chip-tool and the work-tool interfaces where, apart from the primary shear zone, heat is generated. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view tool configuration (Drillco) namely SNMM-120408 has been underlaken for the present investigation. The inserts were clamped in a PSBNR-2525 M12 (Drillco) type tool holder.

The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The final arrangement made and used has been shown in Fig 3.1. The MQL jet is directed along the main cutting edge to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges. The photographic view of the experimental set-up is shown in Fig.3.2.

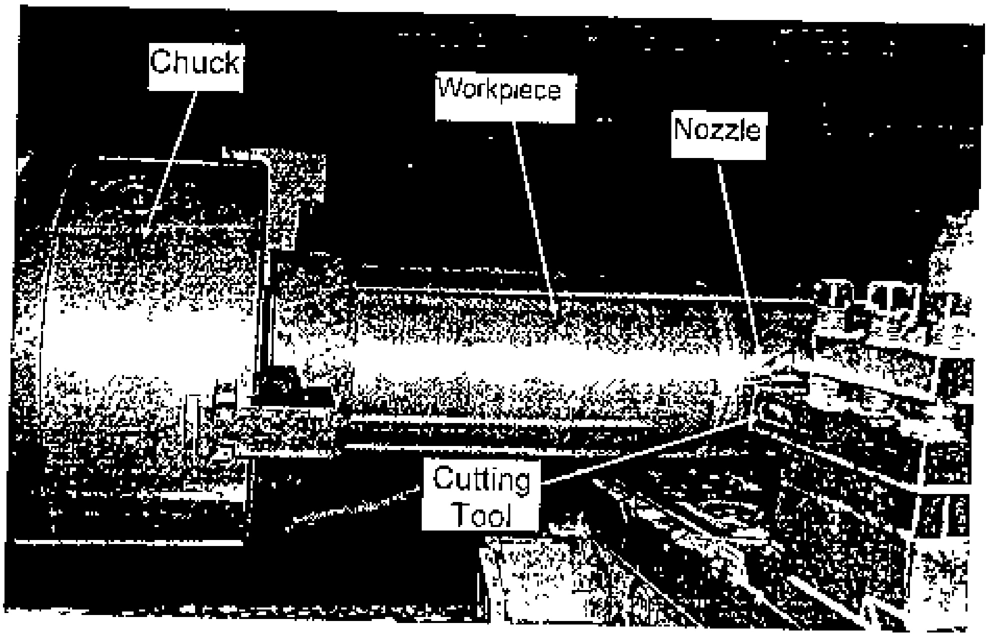


Fig. 3.1 Photographic view of MQL delivery nozzle injecting MQL during machining

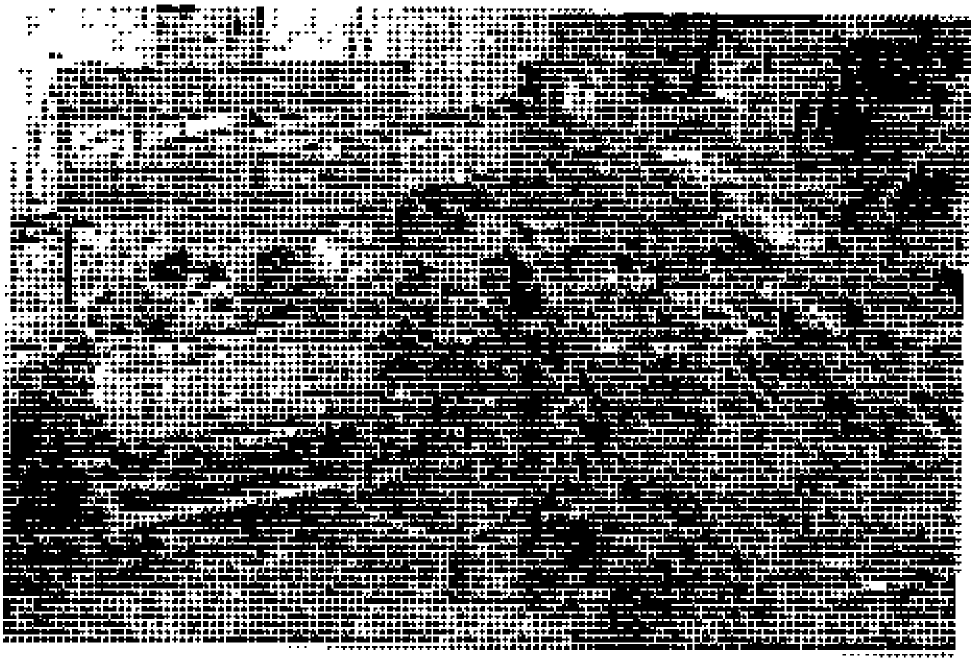
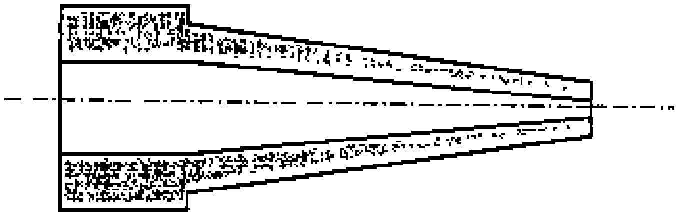


Fig.3.2 Photographic view of the experimental set-up for turning steel with MQL

Mixing chamber



Nozzle tip

Fig.3.3 Photographic view of the mixing chamber and nozzle

The machining responses that have been studied and evaluated for assessing the machinability characteristics of the steel specimen under both dry, wet (flood cooling) and minimum quantity lubrication (MQL) conditions are indicated in Table 3.1. It has already been reported **[Paul et al. 2000 and Seah et al. 1995]** that use of conventional cutting fluids (wet machining) does not serve the desired purpose in machining steels by carbides, rather reduces tool life and often may cause premature failure of the insert by brittle fracture. The conditions under which the machining tests have been carried out are briefly given in Table 3.2.

Table-3.1 Machining responses investigation

Investigation on	Environment		
	Dry	Wet	MQL
Temperature calibration	√	√	√
Chip morphology	√	√	√
Cutting zone temperature	√	√	√
Surface roughness	√	√	√
Deviation in job dimension	√	√	√
Tool wear	√	√	√

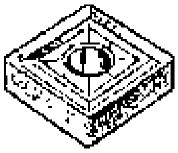
Table-3.2 Experimental conditions

Machine tool : BMTF Lathe, Bangladesh, 4 hp

Work Material : AISI 1040 steel (size: φ110 X 620 mm)

Size : Φ110 X 620 mm

Cutting Tool : Uncoated Carbide (SNMM 120408-PM), Drillco



SNMM 120408

Tool holder : PSBNR 2525 M12 (ISO specification), Drillco

Working tool geometry : -6, -6, 6, 6, 15, 75, 0.8 (mm)

Process parameters

Cutting velocity, V_C : 72, 94, 139 and 164 m/min

Feed rate, S_O : 0.10, 0.13, 0.16 and 0.20 mm/rev

Depth of cut, t : 1.5 mm

MQL supply : Air: 3.5 bar, Lubricant: 200ml/h through external nozzle

Environment : Dry, wet (flood cooling) and MQL

A number of cutting velocity and feed have been taken over relatively wider ranges keeping in view the industrial recommendations for the tool-work materials undertaken and evaluation of role of variation in V_c and S_0 on effectiveness of MQL.

Keeping in view less significant role of depth of cut (t) on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.5 mm, which would adequately serve the present purpose. The machining responses have been monitored and studied using sophisticated and reliable equipment and techniques as far as possible.

Cutting temperature can be measured using direct and indirect techniques [**Venkatesh 1987**]. Direct methods include the use of -

- temperature sensitive powders [**Narutaki and Yamane 1979**]
- infrared measurement [**Prins 1971 and Abrao et al. 1996**]
- the tool-work thermocouple techniques [**Stephenson 1993, Gottwein 1925**]
- embedded thermocouple techniques [**Matsumoto and Hsu 1987 and Kitagawa et al. 1997**]

whereas indirect methods mainly include micro structural changes [**Wright and Trent 1973**] and micro hardness changes [**Wright and Trent 1973**] in the tool materials due to high cutting temperature.

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

- parasitic emf generation by secondary junction
- proper calibration and
- electrical insulation of the tool and the job.

In the present work the average cutting temperature has been measured by tool-work thermocouple technique as indicated in Fig.3.4 taking care of the aforesaid factors.

Tool-work thermocouple can be calibrated in several ways, which include (a) furnace calibration [**Bus et al. 1971 and Byrne 1987**] (b) resistance heating **[Alvedid 1970]** (c) embedded silver bit technique [**Barrow 1973**] (d) induction heating **[Braiden 1967]** (e) lead bath technique [**Shaw 1984**] and (f) flame heating [**Leshock and Shin 1997**].

For the present investigation, the calibration of the work-tool thermocouple has been carried out by external flame heating. Fig.3.5 schematically shows the set-up. The work-tool thermocouple junction was constructed using a long continuous chip of the concerned work-material end a tungsten carbide insert to be used in actual cutting. To avoid generation of parasitic emf, a long carbide rod wes used to extend the insert. A standard chromel-alumel thermocouple is mounted at the site of tool-work (junction of chip and insert) junction. The oxy-acetylene torch simulated the heat generation phenomena in machining and raised the temperature at the chip-tool interface. Standard thermocouple directly monitored the junction temperature (measured by a Eurotherm Temperature Controller and Programmer, model: 818P, made in UK) when the emf generated by the hot junction of the chip-tool was monitored by e digital multimeter (RISH Multi 15S, India). Fig.3.6 shows the photographic view tool-work thermocouple set up.

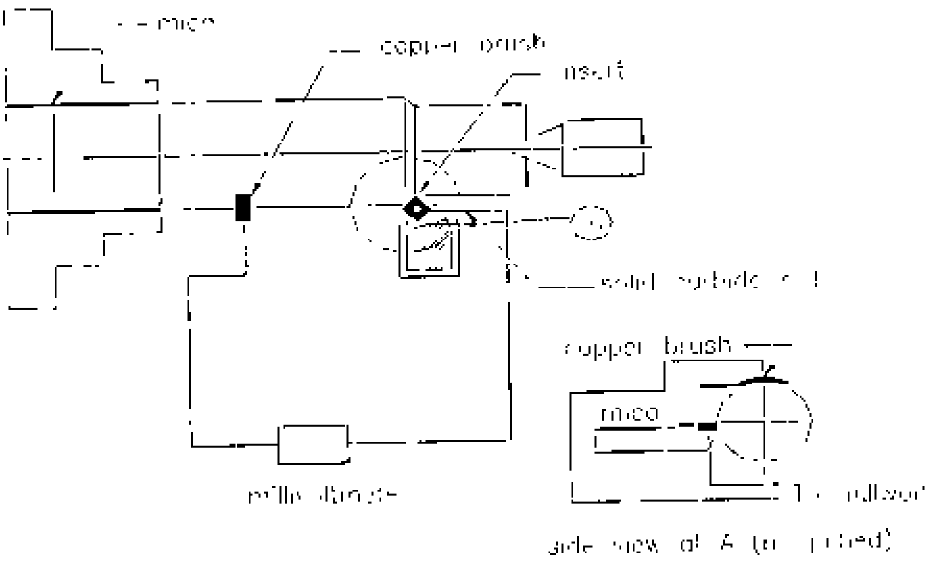


Fig. 3.4 Schematic view of the tool-work thermocouple

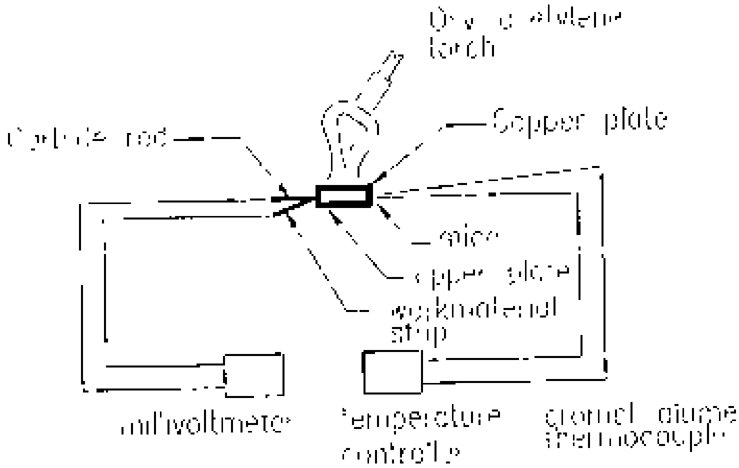


Fig 3.5 Scheme of calibration of tool work thermocouple

Fig.3.6 Photographic view of the tool-work thermocouple set up

Fig.3.7 shows the calibration curve obtained for the tool-work pair with carbide (SNMM 120408-PM) as the tool material and the steel undertaken as the work material. In the present case, almost linear relationships between the temperature and emf have been obtained with multiple correlation coefficients around 0.994.

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

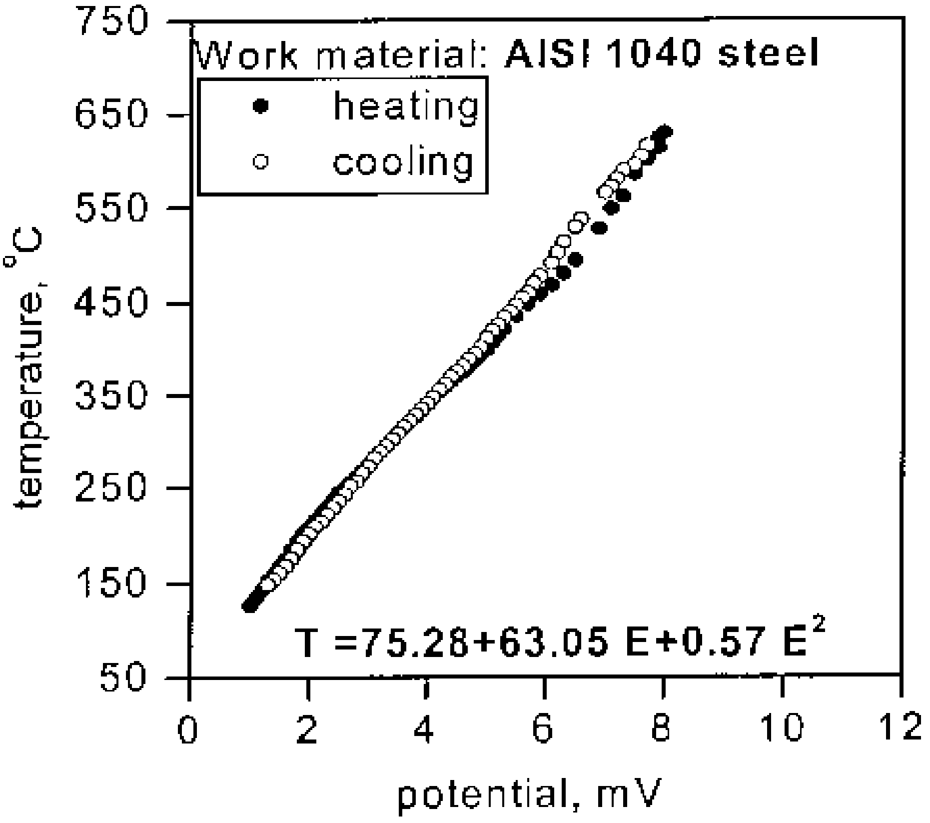


Fig. 3.7 Temperature calibration curve for carbide and steel

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

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

After machining the steel rod by the insert, at different V_c-S_o combinations under both dry, wet and MQL, the dimensional deviation on diameter in axial direction of the machined jobs was measured by a sensitive dial gauge which was firmly fitted on the saddle and travelled slowly parallel to the job axis.

3.2 Experimental Results

3.2.1 Cutting Temperature

During machining any ductile materials, heat is generated at the (a) primary deformation zone due to shear and plastic deformation (b) chip-tool interface due to secondary deformation and sliding (c) work-tool interfaces due to rubbing. All such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. Therefore, attempts are made to reduce this detrimental cutting temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface where the temperature is high. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V_c when the chip-tool contact becomes almost fully plastic or bulk.

However, it was observed that the MQL jet in its present way of application enabled reduction of the average cutting temperature by about 5 to 10% depending upon the levels of the process parameters, V_c and S_o and the types of the cutting inserts. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

The cutting temperature generally increases with the increase in V_c and S_o, though in different degree, due to increased energy input and it could be expected that MQL would be more effective at higher values of V_c and S_o.

In the present work, the average chip-tool interface temperature could be effectively measured under dry, wet and MQL condition very reliably throughout the experimental domain. The photographic view of the tool work thermocouple technique for measuring cutting zone temperature is shown in Fig. 3.8. However, the distribution of temperature within the tool, work and chip cannot be determined effectively using experimental techniques. The evaluated role of MQL on average chip-tool interface temperature in turning the steel by the carbide insert at different V_c and S_o under dry, wet and MQL conditions have been shown in Fig.3.9 and Fig.3.10 respectively.

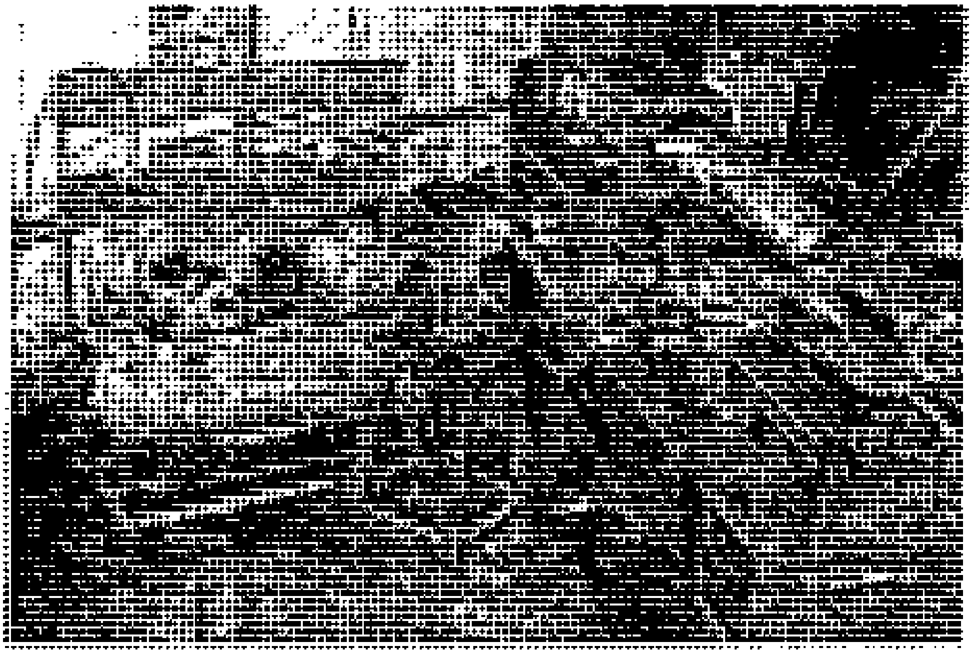


Fig.3.8 Photographic view of the tool-work thermocouple

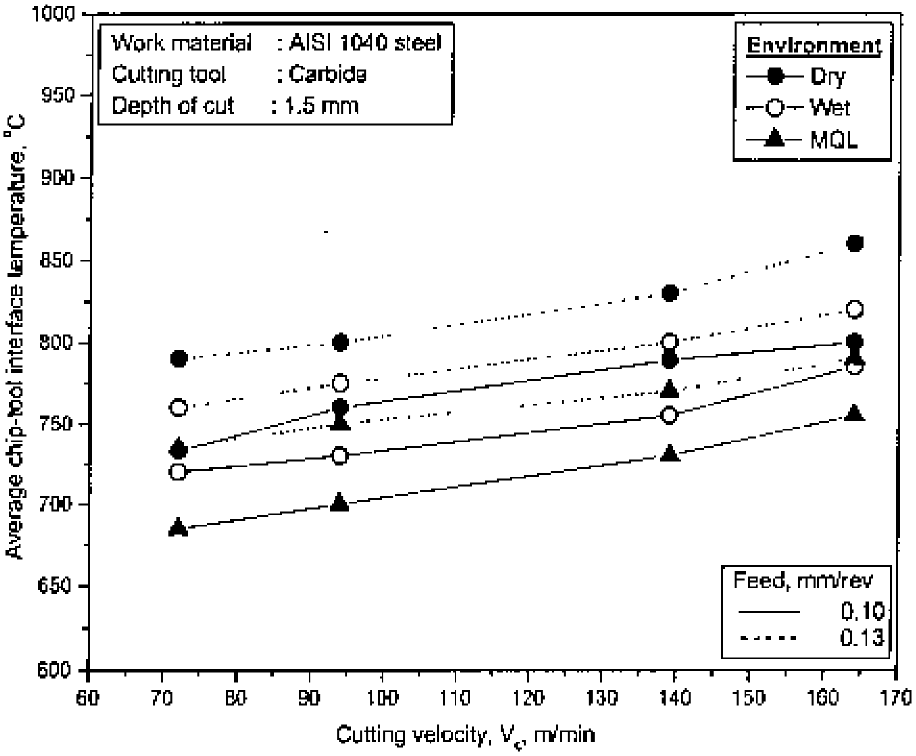


Fig.3.9 Variation in chip tool interface temperature with cutting velocity at feed rate 0.10 and 0.13 mm/rev under dry, wet and MQL conditions

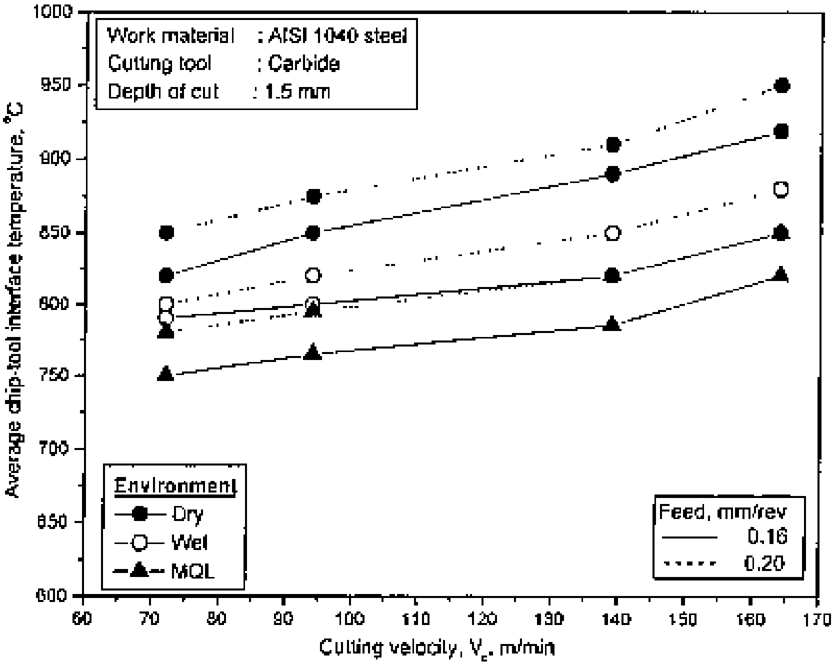
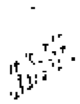


Fig.3.10 Variation in chip tool interface temperature with cutting velocity at feed rate 0.16 and 0.20 mm/rev under dry, wet and MQL conditions

3.2.2 Machining Chips

The chip samples collected while turning the steel by the insert of configuration SNMM at different V_c-S_0 combinations under both dry, wet and MQL conditions have been visually examined and categorized with respect to their shape and colour. The results of such categorization of the chips produced at different conditions and environments by the AISI-1040 steel at different feeds have been shown in Table-3.3.

Table-3.3 Shape and colour of chips at different cutting velocities and feeds

Feed rate, S_o (mm/rev)	Cutting velocity, V_c (m/min)	Environment					
		Dry		Wet		MQL	
		Shape	Colour	Shape	Colour	Shape	Colour
0.10	72	Half turn	Burnt blue	Half turn	Metallic	Half turn	Metallic
	94	Spiral	Blue	Half turn	Metallic	Half turn	Metallic
	139	Spiral	Golden	Spiral	Metallic	Spiral	Metallic
	164	Spiral	Golden	Spiral	Metallic	Spiral	Metallic
0.13	72	Spiral	Burnt blue	Half turn	Metallic	Spiral	Metallic
	94	Half turn	Burnt blue	Half turn	Metallic	Spiral	Metallic
	139	Spiral	Burnt blue	Spiral	Metallic	Half turn	Metallic
	164	Half turn	Burnt blue	Spiral	Metallic	Half turn	Metallic
0.16	72	Half turn	Burnt blue	Half turn	Golden	Half turn	Metallic
	94	Half turn	Burnt blue	Spiral	Golden	Half turn	Metallic
	139	Half turn	Burnt blue	Spiral	Golden	Half turn	Metallic
	164	Half turn	Burnt blue	Spiral	Golden	Half turn	Metallic
0.20	72	Spiral	Burnt blue	Spiral	Golden	Half turn	Metallic
	94	Spiral	Burnt blue	Spiral	Golden	Half turn	Metallic
	139	Spiral	Burnt blue	Spiral	Metallic	Half turn	Metallic
	164	Spiral	Burnt blue	Spiral	Metallic	Half turn	Metallic
							
Half turn		Tubular		Spiral		Ribbon	

The actual forms of the chips produced by the AISI-1040 steel during machining by the SNMM type insert with a different feeds at different cutting velocities under dry, wet and MQL conditions are shown in Fig.3.11, Fig.3.12, Fig.3.13 and Fig.3.14 respectively.

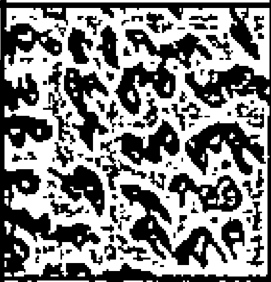
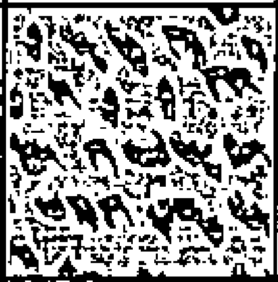
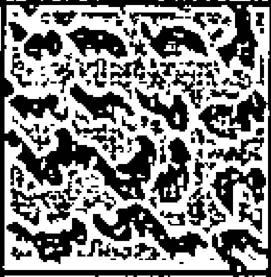
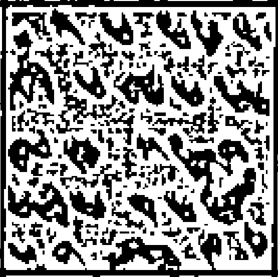
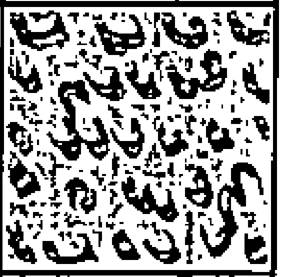
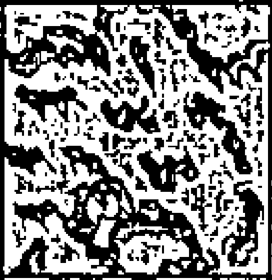
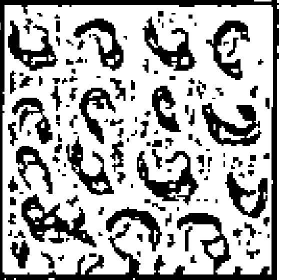
Cutting velocity (m/min)	Feed rate, S_o=0.10 mm/rev		
	Environment		
	Dry	Wet	MQL
72			
94			
139			
164			

Fig.3.11 Chips produced during turning steel at different V_c and S_o= 0.10 mm/rev under dry, wet and MQL conditions.

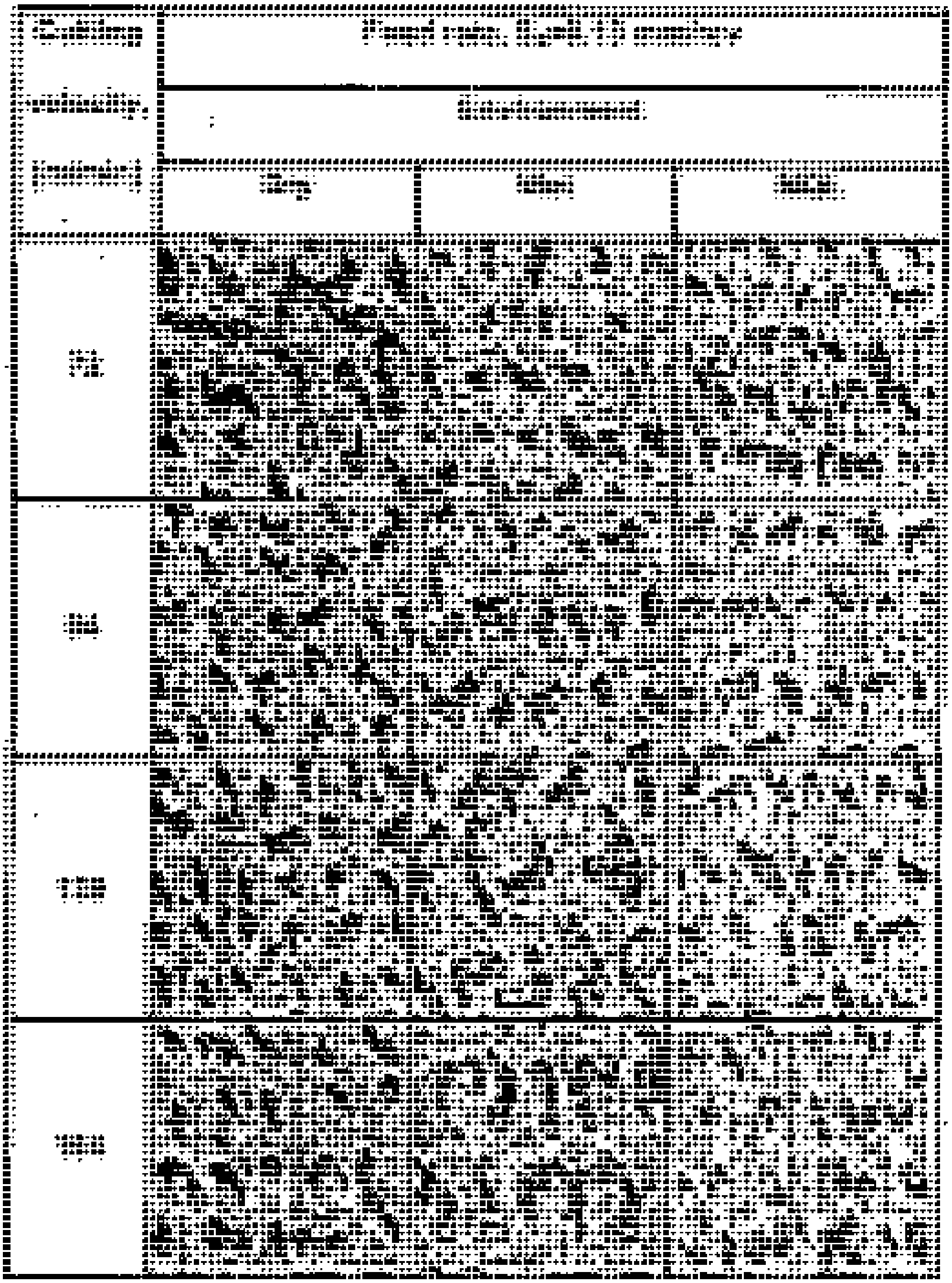


Fig.3.12 Chips produced during turning steel at different V_c and S_o=0.13 mm/rev under dry, wet and MQL conditions.

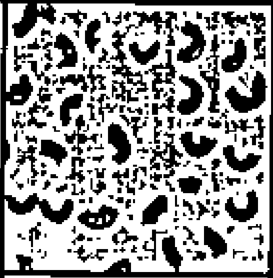
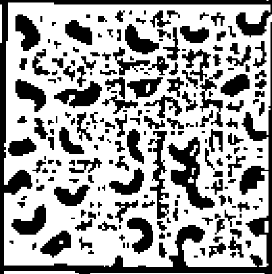
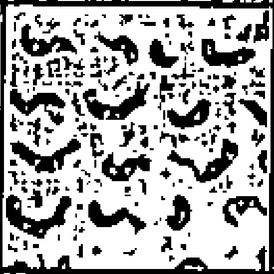
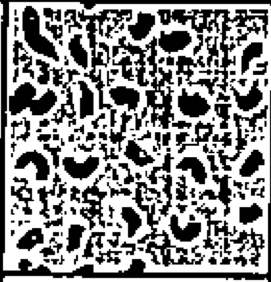
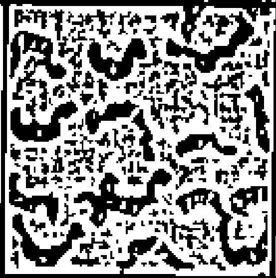
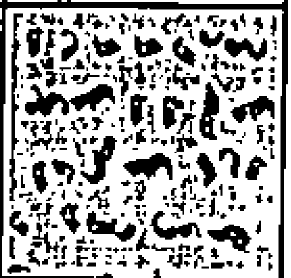
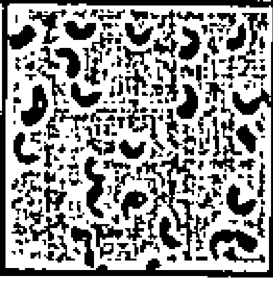
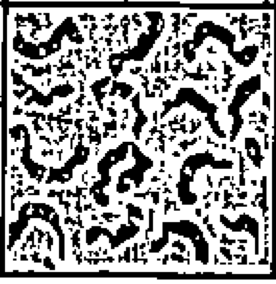
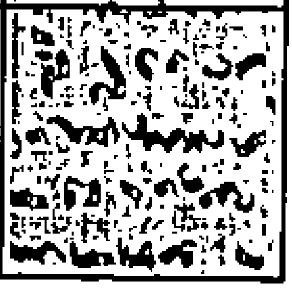
Cutting velocity, (m/min)	Feed rate, S_o=0.16 mm/rev		
	Environment		
	Dry	Wet	MQL
72			
94			
139			
164			

Fig.3.13 Chips produced during turning steel at different V_c and S_o=0.16 mm/rev under dry, wet and MQL conditions.

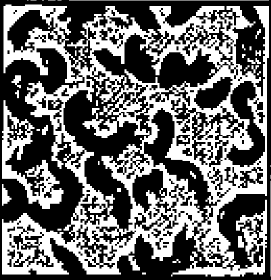
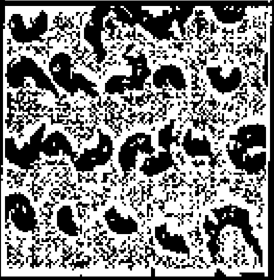
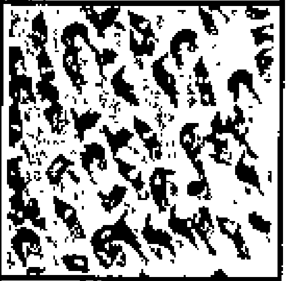
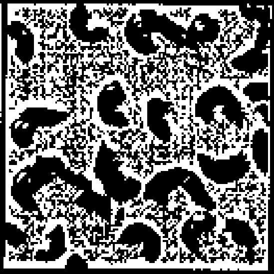
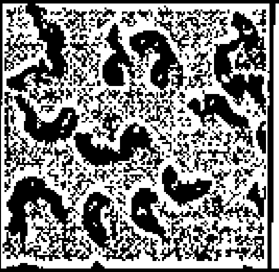
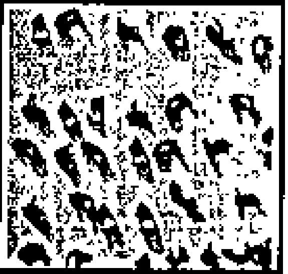
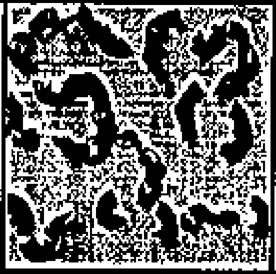
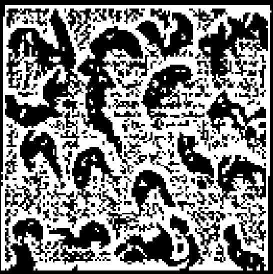
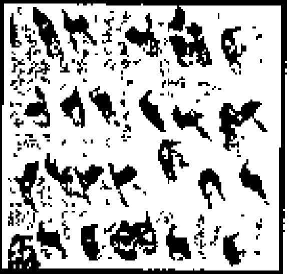
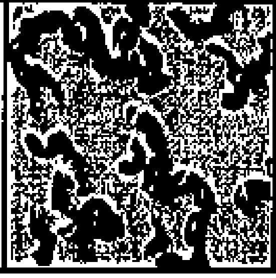
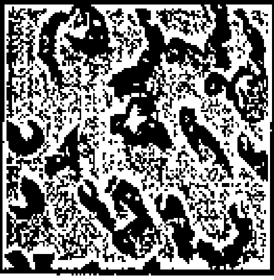
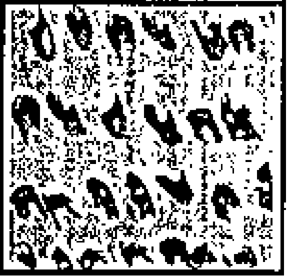
Cutting velocity, (m/min)	Feed rate, S_o=0.20 mm/rev		
	Environment		
	Dry	Wet	MQL
72			
94			
139			
164			

Fig.3.14 Chips produced during turning steel at different V_c and S_o=0.20 mm/rev under dry, wet and MQL conditions.

Another important machinability index is chip reduction coefficient, ζ (ratio of chip thickness after and before cut). For given tool geometry and cutting conditions, the value of ζ depends upon the nature of chip-tool interaction, chip contact length and chip form all of which are expected to be influenced by MQL in addition to the levels of V_c and S_o. The variation in value of ζ with change in V_c and S_o as well as machining environment evaluated for AISI-1040 steel have been plotted and shown in Fig.3.15 and Fig.3.16.

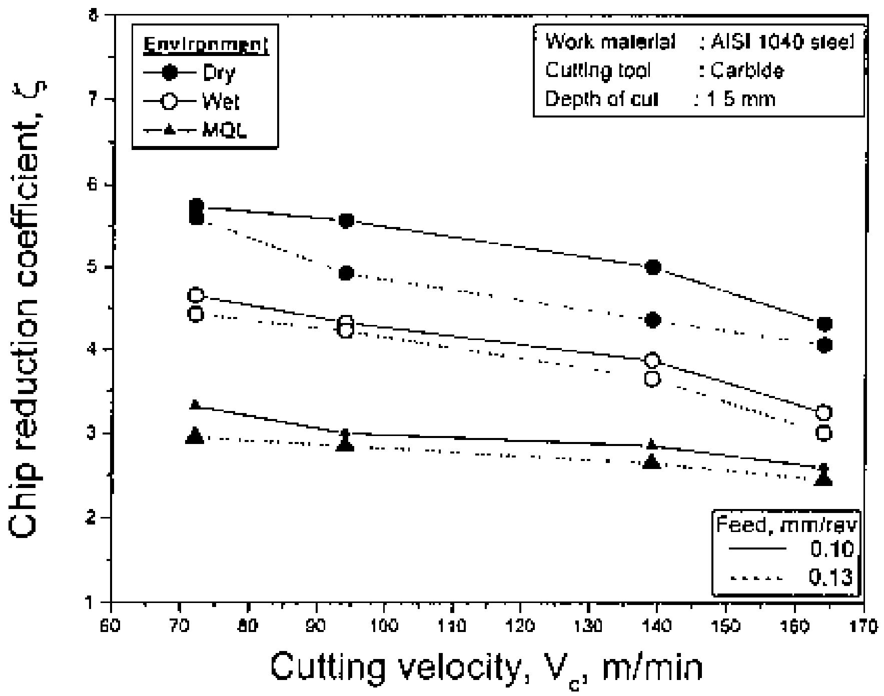


Fig.3.15 Variation in ζ with cutting velocity at feed rate 0.10 and 0.13 mm/rev under dry, wet and MQL conditions.

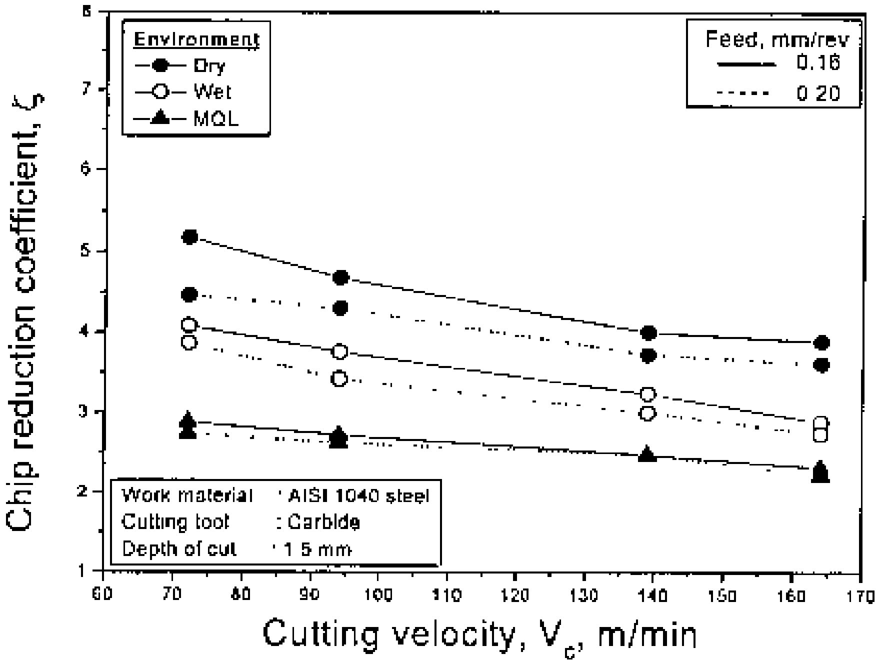


Fig. 3.16 Variation in ζ with cutting velocity at feed rate 0.16 and 0.20 mm/rev under dry, wet and MQL conditions.

3.2.3 Cutting Tool Wear and Condition

Productivity and economy of manufacturing by machining are significantly influenced by life of the cutting tools. Cutting tools may fail by brittle fracturing, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears. With the progress of machining time the tools attain crater wear at the rake surface and flank wear at the clearance surfaces. The usual pattern and the parameters of wear that develop in cutting tools are schematically shown in Fig.3.17. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems. The life of carbide tools, which mostly fail by wearing, is assessed by the actual machining time after which the average value (V_B) of its principal flank wear reaches a limiting value, like 0.3 mm. Therefore, attempts should be made to reduce the rate of growth of flank wear (V_B) in all possible ways without sacrifice in MRR. It is already mentioned that wear of cutting tools are generally quantitatively assessed by the magnitudes of V_B, V_M, V_N, V_S, K_T, etc. shown in Fig.3.17, out of which V_B is considered to be the most significant parameter at least in R&D work.

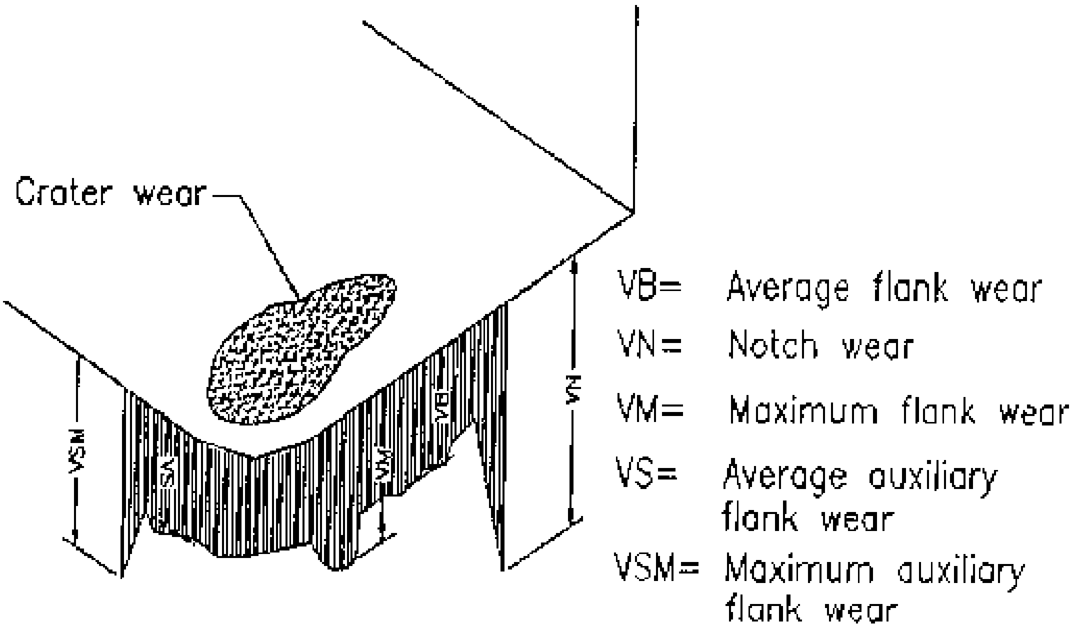


Fig.3.17 Geometry of wear of turning tool

The growth of principal flank wear, V_B with progress of machining recorded while turning the steel, undertaken, by the SNMM type insert at the same feed and depth of cut but moderately high cutting velocities under dry, wet and MQL conditions have been shown in Fig.3.18 and Fig.3.19 respectively.

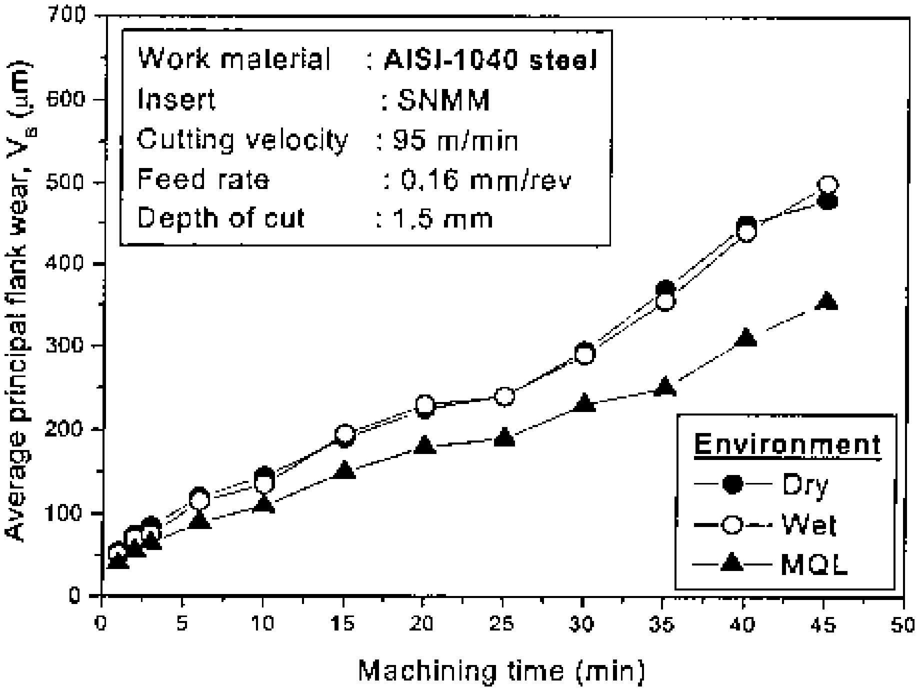


Fig.3.18 Growth of average principal flank wear, V_B with machining time under dry, wet and MQL conditions

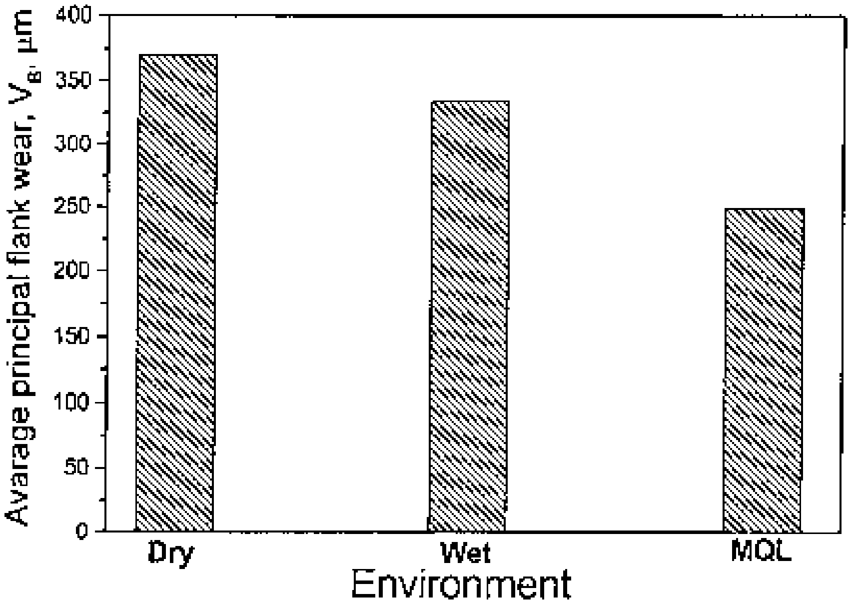


Fig.3.19 Average principal flank wear, V_B developed in the insert after machining steel for 35 minutes under dry, wet and MQL conditions.

The auxiliary flank wears 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 wears, V_S with machining time under dry, wet and MQL conditions have been shown in Fig.3.20 and Fig.3.21 respectively.

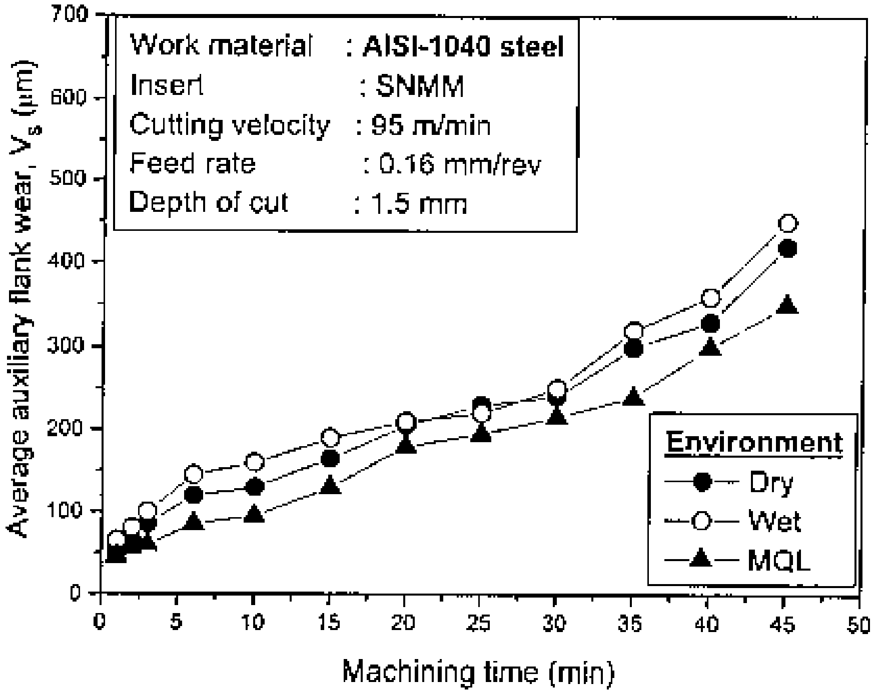


Fig.3.20 Growth of average auxiliary flank wear, V_S with time under dry, wet and MQL conditions.

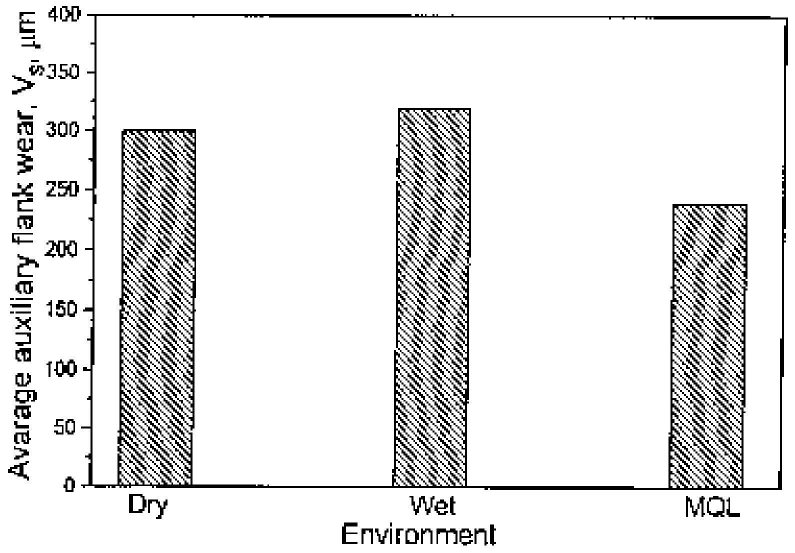
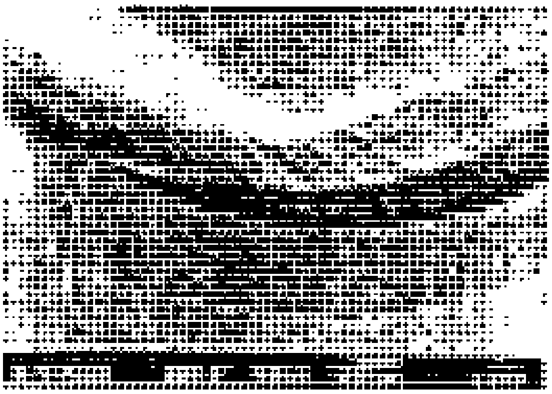


Fig.3.21 Average auxiliary flank wear, V_S developed in insert for 35 minutes under dry, wet and MQL conditions.

The pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining the different steels over reasonably long period have been observed under SEM to see the actual effects of different environments on wear of the carbide inserts of present two configurations. The SEM views of the worn out insert after about 45 minutes of machining of the steel under dry, wet and MQL conditions have been shown in Fig.3.22.

(a) Dry machining (b) Wet machining



(c) MQL machining

Fig.3.22 SEM views of the worn out insert after machining 45 minutes under (a) dry, (b) wet and (c) MQL conditions

3.2.4 Product Quality

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

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

During straight turning in a center lathe, the diameter of the machined part 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
- increase due to system compliance of the machine-fixture-tool-work (M-F-T-W) system under the action of the cutting forces.

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

The variation in diameter of the job was precisely measured along its axis after one full pass of the machining over 400 mm length with full depth, at reasonably high feed and cutting velocity suitable for the tool-work combination. This has been done for all the tool-work-environment combinations undertaken keeping the initial diameter and length of the steel rods same and uniform as far as possible.

Fig.3.23 shows the effect of MQL on the dimensional accuracy of the turned job. MQL provided better dimensional accuracy in respect of controlling the increase in diameter of the finished job with machining time. The finished job diameter generally deviates from its desired value with the progress of machining, i.e. along the job-length mainly for change in the effective depth of cut due to 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 were 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 decrease in dimensional deviation desirably.

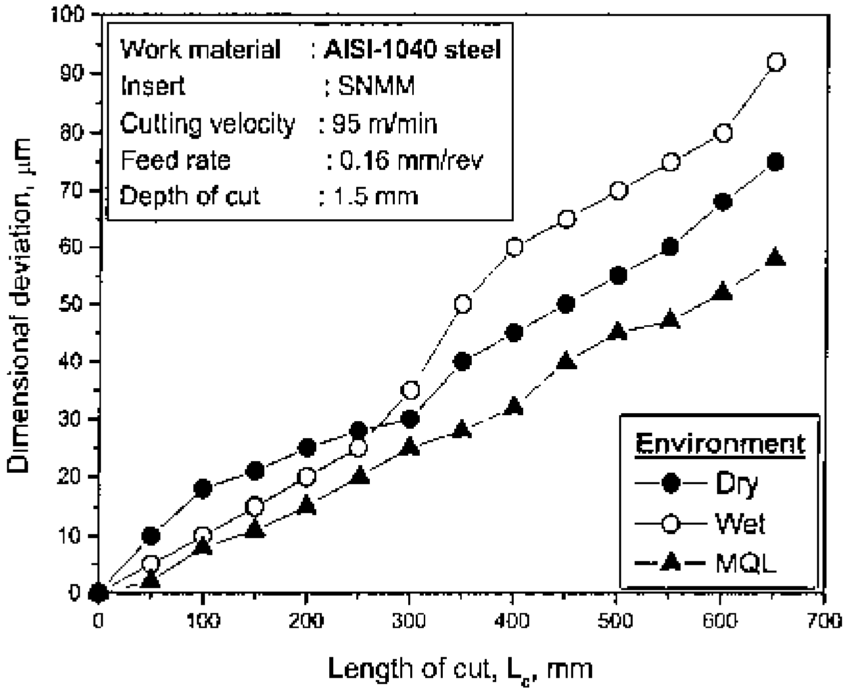


Fig.3.23 Dimensional deviation observed after one full pass turning of the rod under dry, wet and MQL conditions.

Surface roughness is another important index of machinability, which is substantially influenced by the machining environment for given tool-work pair and speed-feed combinations. Surface roughness has been measured after a few seconds of machining with sharp tool while recording the chip-tool interface temperature. The photographic view of the surface roughness technique for measuring surface roughness is shown in Fig.3.24. The surface roughness attained after 45 seconds of machining of steel by the sharp carbide insert (SNMM 120408-PM, Drillco) at various V_c-S_0 combinations under dry, wet and MQL conditions are shown in Fig.3.25 and Fig.3.26 respectively. The variation in surface roughness observed with progress of machining of the steel by the insert at a particular set of V_c, S_0 and t under dry, wet and MQL conditions have been in shown in Fig.3.27.

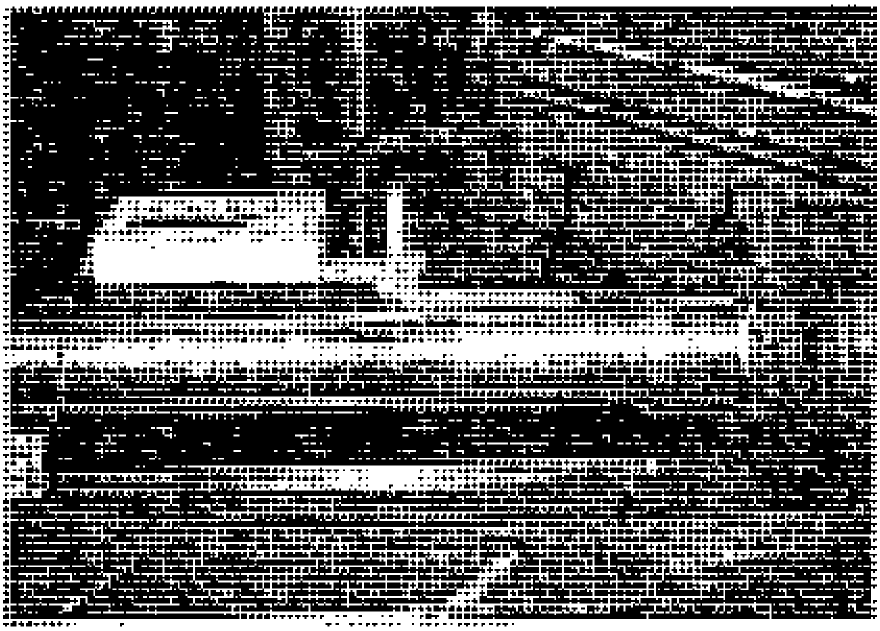


Fig. 3.24 Photographic view of the surface roughness measuring technique

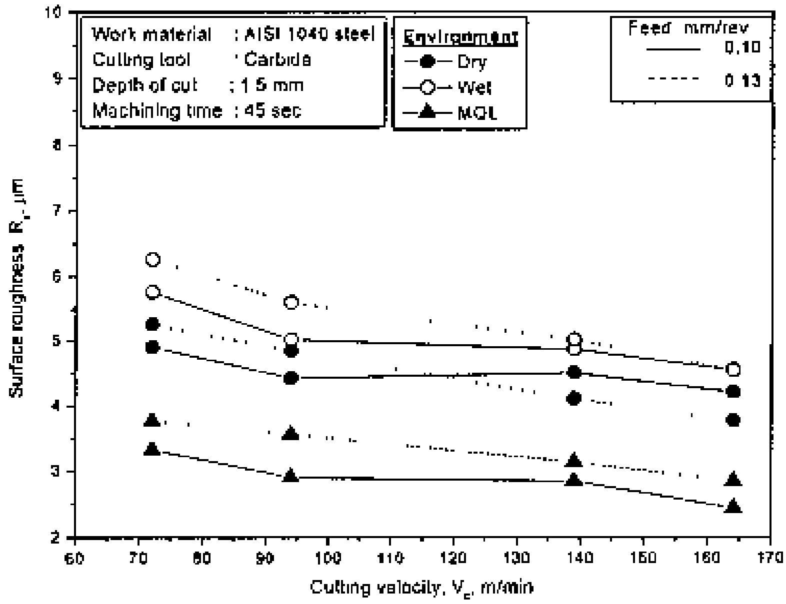


Fig. 3.25 Variation in roughness with cutting velocity at feed rate 0.10 and 0.13 mm/rev under dry, wet and MQL conditions.

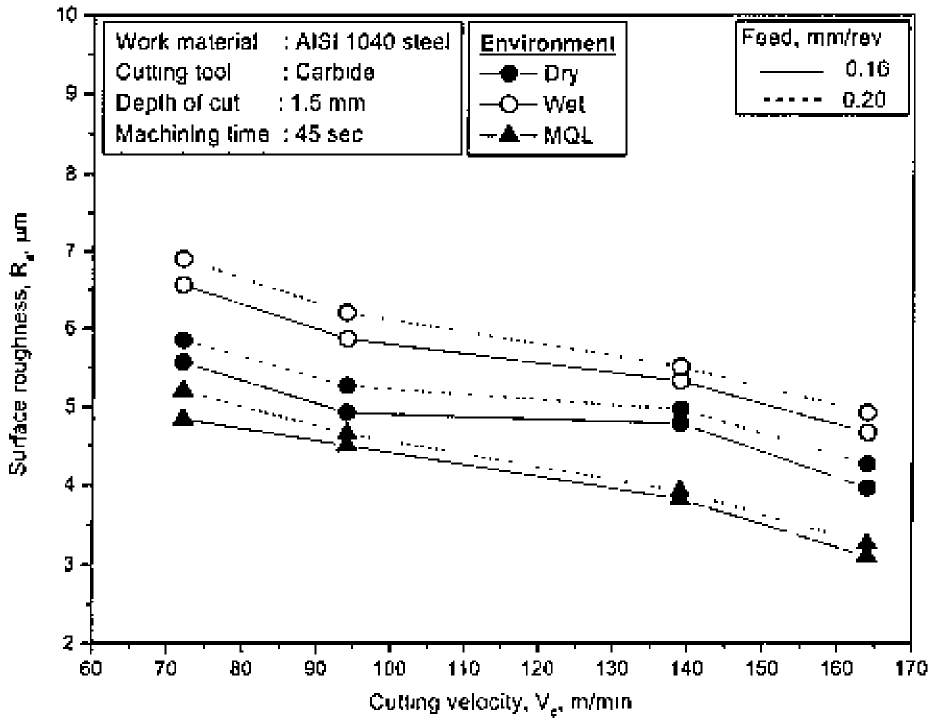


Fig. 3.26 Variation in roughness with cutting velocity at feed rate 0.16 and 0.20 mm/rev under dry, wet and MQL conditions.

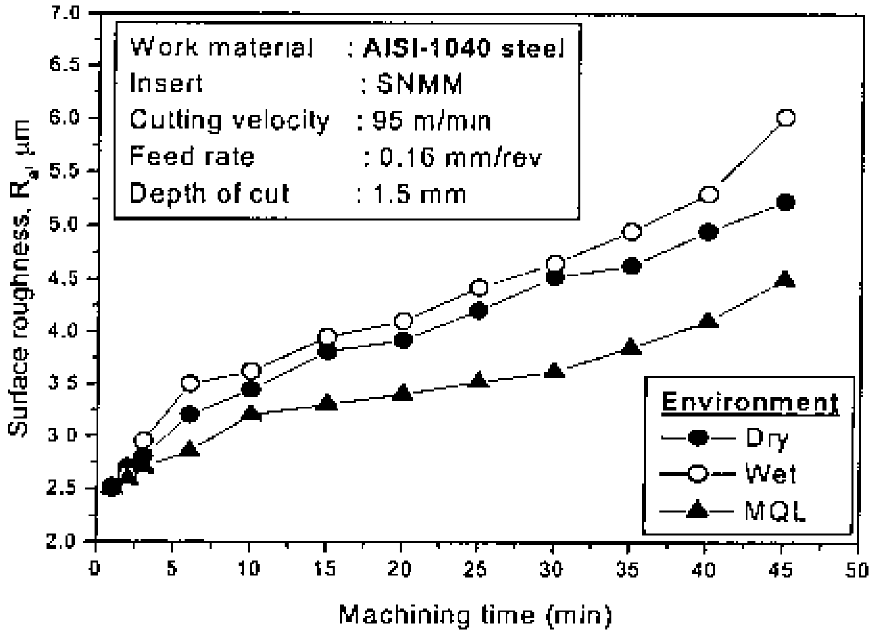


Fig.3.27 Surface roughness with progress of machining under dry, wet and MQL conditions

Chapter-4

Discussion on Experimental Results

4.1 Cutting Temperature

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

Tool-work thermocouple technique is as such simple and reliable to measurement of average cutting temperature. The literature shows a wide range of the calibration methods and procedures. Most of these methods calibrate the tool and the workpiece in an isolated environment, without consideration to the machining experimental setup. This presents problems, because the experimental setup is different than the calibration setup. The calibration setup used in this study is close to the experimental setup and thus many factors such as parasitic emf's are included into the calibration.

The average chip-tool interface temperature, θ_{avg} have been determined from the tool work thermocouple technique and plotted against cutting velocity for different feeds and environments undertaken. The figures Fig.3.9 and Fig.3.10 are showing how and to what extent θ_{avg} has decreased due to minimum quantity lubrication (MQL) under the different experimental conditions. With the increase in V_c and S_o, θ_{avg} increased as usual, even under MQL, due to increase in energy input.

Apparently more drastic reductions in θ_{avg} are expected by employing MQL jets. But practically it has not been so because the MQL jet has been employed in the form of thin jet along the cutting edge and towards only the chip-tool interface instead of bulk cooling. Also the jets, like any cutting fluid, could not reach deeply in the chip-tool interface for plastic or bulk contact, particularly when V_c and S_o are large.

The roles of variation of process parameters on percentage reduction of average interface temperature due to MQL have not been uniform. This may be attributed to variation in the chip forms particularly chip-tool contact length, C_N which for a given tool widely vary with the mechanical properties and behaviour of the work material under the cutting conditions. The value of C_N affects not only the cutting forces but also the cutting temperature. In the present thermal modelling also the value of C_N had to be incorporated as the span of heat input at the chip-tool interface. Post cooling of the chips by MQL jet is also likely to influence θ_{avg} to some extent depending upon the chip form and thermal conductivity of the work materials.

4.2 Machining Chips

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

Table-3.4 shows that the carbide insert produced spiral and half turn chips at different higher feeds under both dry and wet conditions. The geometry of the SNMM insert is such that the chips first came out continuously got curled along normal plane and then hitting at the principal flank of this insert broke into pieces with regular size and shape. When machined with MQL the form of these ductile chips did not change appreciably but their back surface appeared much brighter and smoother. This indicates that the amount of reduction of temperature and presence of MQL application enabled favourable chip-tool interaction and elimination of even trace of built-up edge formation. The colour of the chips has also become much lighter i.e. metallic from blue or burnt blue depending upon V_c and S_o due to reduction in cutting temperature by minimum quantity lubrication. Fig.3.11 to Fig.3.14 shows the actual forms and colour of chips produced during turning under different environments. The shape and colour of the chips significantly changed with the application of MQL.

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

The figure Fig.3.15 and Fig.3.16 clearly shows that throughout the present experimental domain the value of ζ gradually decreased with the increase in V_C though in different degree for the different tool-work combinations, under both dry, wet end MQL conditions.

The value of ζ usually decreases with the increase in V_C particularly at its lower range due to plasticization and shrinkage of the shear zone for reduction in friction and built-up edge formation at the chip-tool interface due to increase in temperature end sliding velocity. In machining steel by carbide tool, usually the possibility of built-up edge formation and size and strength of the built-up edge, if formed gradually increase with the increase in temperature due to increase in V_C and also S_O and then decrease with the further increase in V_C due to too much softening of the chip material and its removal by high sliding speed.

It is also noted in this figure that ζ decreased all along also with the increase in S_O expectedly due to increase in average rake angle with increase in uncut chip thickness as has been schematically indicated in Fig.4.1.

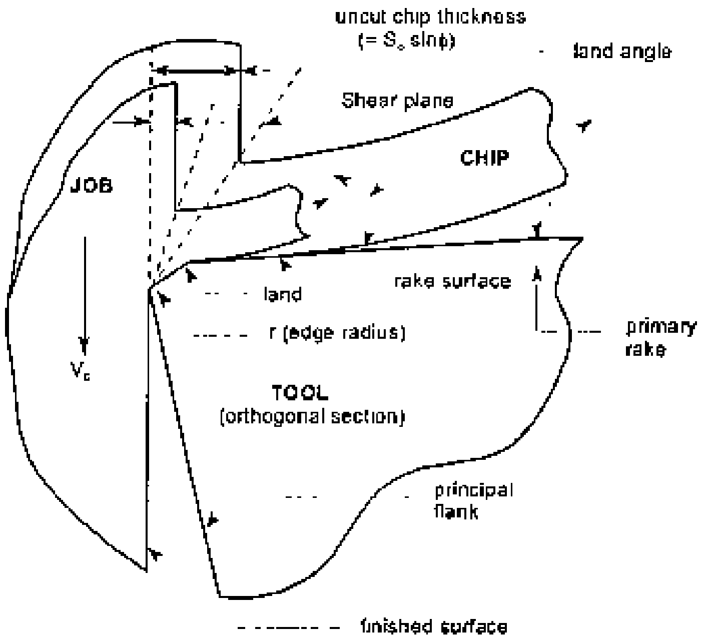


Fig.4.1 Schematic view of machining with varying uncut chip thickness

Fig.3.15 and Fig.3.16 show that MQL has reduced the value of ζ particularly at lower values of V_c and S_o. By MQL applications, ζ is reasonably expected to decrease for reduction in friction at the chip-tool interface and reduction in deterioration of effective rake angle by built-up edge formation and wear at the cutting edges mainly due to reduction in cutting temperature.

4.3 Cutting Tool Wear and Condition

The insert selected and used attained flank wear and crater wear progressively in varying pattern and magnitude while machining steel under dry, wet and MQL conditions undertaken for the present investigations. Premature and catastrophic type of tool failure by plastic deformation or micro fracture was not found to occur expectedly within the present experimental domain.

It is already mentioned that wear of cutting tools are generally quantitatively assessed by the magnitudes of V_B, V_S, K_T etc. shown in Fig.3.17, out of which V_B is considered to be the most significant parameter at least in R&D work.

It was reported [**Dhar et al. 2000 and Seah et al. 1995**] earlier that application of conventional cutting fluid does not help in reducing tool wear in machining steels by carbides rather may aggravate wear.

Fig.3.18 shows the growth in average flank wear, V_B, on the main cutting edge under dry, wet (conventional cooling with 1:20 soluble oil) and MQL conditions. The gradual growth of V_B, the predominant parameter to ascertain expiry of tool life, observed under all the environments indicates steady machining without any premature tool failure by chipping, fracturing etc. establishing proper choice of domain of process parameters.

It has already been reported **[Dhar et al 2004]** that the application of MQL jet along the auxiliary cutting edge substantially changes chip formation and controls the cutting temperature. These enabled reduced rate of tool wear and improved tool life as revealed by Fig.3.18. It is also evident from this figure that usual flood cooling by soluble oil could not reduce flank wear (V_B) in the carbide insert while machining the steel. Such wet cutting causes faster oxidation and corrosion of tha tool surfacas and rapid microfracturing of the cutting edges by thermo-mechanical shocks due to fluctuation in temperature and stresses, which compensates or often surpasses the reduction of adhesion and diffusion wear of the carbide inserts expected due to cooling and lubrication by the cutting fluid in continuous machining like turning of steels. But application of MQL jet has substantially reduced growth of V_B as can be seen in Fig.3.18. 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. The favorable effect of MQL on flank wear of the insert has been briefly shown in Fig.3.19. After 35 minutes of machining the insert attained around 370 μm average flank wear under dry and 335μm under wet machining whereas MQL reduced flank wear to 250 μm only.

Another important tool wear criteria are average auxiliary flank wear, V_S, 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 [**Klocke and Eisenblatter 1997**]. The growth of, V_S has been depicted in Fig.3.20 for all the trials undertaken. The nature of growth of V_S matches with that of V_B expectadly. The application of MQL has reduced V_S. Fig.3.21 clearly shows the amount of auxiliary flank wear after machining for 35 minutes and depicts beneficial role of MQL, which is expected to provide better surface finish and dimensional accuracy.

The SEM views of the worn out insert after being used for about 45 minutes of machining under dry, wet and MQL conditions are shown in Fig.3.22. Under all the environments, abrasive scratch marks appeared in the flanks. The examination of the craters revealed deep scratches left by the backside of the chip on the rake surface of the tool. There have also been some indications of adhesive wear in the insert. Some plastic deformation and micro chipping were found to occur under dry and wet machining. Severe groove wear and notch wear at the flank surfaces were found in insert under both dry and wet conditions. The notch wear on main cutting edge develops mainly because of oxidation and chemical wear where the thermo-mechanical stress gradient is also very high. The notch wear on the auxiliary cutting edge develops mainly because of its interaction with the uncut ridges of the work surface and mechanism of this wear is abrasive. Effective temperature control by MQL almost reduced the growth of notch and groove wear on the main cutting edge. It has also enabled the reduction in the auxiliary notch wear. Further the figure clearly shows reduced average flank wear, average auxiliary flank wear and crater wear under MQL condition.

4.4 Product Quality

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. For the present study, only dimensional accuracy and surface finish have been considered for assessment of quality of product under dry and MQL machining.

Fig.3.25 clearly shows that the present method of MQL jet in machining steel rod can reduce dimensional inaccuracy by carbide insert. It has been mentioned earlier that the diameter in straight turning of long rod may deviate from the theoretically expected value due to progressive wear of the tool-tip, variation of compliance of the M-F-T-W system along the axis of lathe and thermal expansion or distortion of the job, if much heated. The reduction in dimensional deviation observed in the present investigation can be reasonably attributed mainly to reduction in the auxiliary flank wear of the insert by minimum quantity lubrication. The order of dimensional deviation possible due to other two reasons for the present job specimen of so large diameter and L/D ratio less than 4.0 and the cutting conditions undertaken has been roughly estimated and found to be around 1.0μm.

Careful observation of the figure presenting dimensional deviation under various machining conditions and those presenting average auxiliary flank wear visualises that dimensional deviations observed have close relation with corresponding auxiliary flank wear, particularly V_S for which actual depth of cut is reduced from the apparent depth of cut by the depth of maximum flank wear.

Surface finish is also an important index of machinability or grindability because performance and service life of the machined/ground component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface microcracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part(s). Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining. Even if it is to be finally finished by grinding, machining prior to that needs to be done with surface roughness as low as possible to facilitate and economize the grinding operation and reduce initial surface defects as far as possible.

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

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.

Fig. 3.26 and Fig. 3.27 clearly show that surface roughness as such increased with the increase in feed and decreased with the increase in V_c. Reduction in roughness with the increase in V_c may be attributed to smoother chip-tool interface with lesser chance of built-up edge formation in addition to possible truncation of the feed marks and slight flattening of the tool-tip. Increase in V_c may also cause slight smoothing of the abraded auxiliary cutting edge by adhesion and diffusion type wear and thus reduced surface roughness. It is evident in Fig.3.26 and Fig.3.27 that MQL could provide marginal improvement in surface finish at the beginning of machining with the fresh cutting edge. 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.

Fig.3.27 shows the variation in surface roughness with machining time under all the three environments. As MQL reduced average auxiliary flank wear and notch wear on auxiliary cutting edge, surface roughness also grew very slowly under MQL conditions. Conventionally applied cutting fluid did not reduce tool wear compared to dry machining. But the surface roughness deteriorated drastically under wet machining compared to dry, which may possible be attributed electrochemical interaction between insert and work piece **[MaClure et al 2003]**. It appears from Fig.3.27 that surface roughness grows quite fast under dry machining due to more intensive temperature and stresses at the tool-tips, MQL 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.

Chapter-5

Conclusions

MQL provided significant improvements expectedly, though in varying degree, in respect of chip formation modes, surface finish throughout the V_c-S_o range undertaken mainly due to reduction in the average chip tool interface temperature. Flood cooling by soluble oil could not control the cutting temperature appreciably and its effectiveness decreased further with the increase in cutting velocity and feed rate.

The present MQL systems enabled reduction in average chip-tool interface temperature upto 10% depending upon the cutting conditions and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices. Due to MQL application, the form and colour of the steel chips became favourable for more effective cooling and improvement in nature of interaction at the chip-tool interface.

MQL reduced the cutting temperature, such reduction has been more effective for those tool-work combinations and cutting conditions, which provided higher value of chip reduction coefficient, ζ for adverse chip-tool interaction causing large friction and built-up edge formation at the chip-tool interface. Favourable change in the chip-tool interaction and retention of cutting edge sharpness due to reduction of cutting zone temperature seemed to be the main reason behind reduction of cutting forces by the MQL.

The significant contribution of MQL jet in machining the steel by the carbide insert undertaken has been the reduction in flank wear, which would enable either remarkable improvement in tool life or enhancement of productivity (MRR) allowing higher cutting velocity and feed. Such reduction in tool wear might have been possible for retardation of abrasion and notching, decrease or prevention of adhesion and diffusion type thermal sensitivity wear at the flanks and reduction of built-up edge formation which accelerates wear at the cutting edges by chipping and flaking. Minimum cooling lubrication (MQL) reduces deep notching and grooving, which are very detrimental and may cause premature and catastrophic failure of the cutting tools.

Dimensional accuracy and surface finish also improved mainly due to reduction of wear and damage at the tool tip by the application of MQL.

MQL, if properly employed, can enable significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of MQL system.

Chapter-6

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