Experimental Study of Effect of Minimum Quantity Lubrication (MQL) in Turning AISI 1040 Steel

A Project Thesis

By

Mohammad Wahidul Islam

Department of Industrial & Production Engineering
Bangladesh University of Engineering & Technology
Dhaka-1000

April, 2004

Experimental Study of Effect of Minimum Quantity Lubrication (MQL) in Turning AISI 1040 Steel

A Project Thesis

By

Mohammad Wahidul Islam

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 ENGINEERING** in Industrial & Production Engineering.

Department of Industrial & Production Engineering
Bangladesh University of Engineering & Technology
Dhaka-1000

April 2004

The thesis titled **Experimental Study of Effect of Minimum Quantity Lubrication (MQL) in Turning AISI 1040 Steel,** submitted by Mohammad Wahidul Islam, Roll No. 040208010F, session April 2002, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **MASTER OF ENGINEERING** in Industrial & Production Engineering on April 2004.

BOARD OF EXAMINERS

1. ______________________

Dr. Nikhil Ranjan Dhar — Chairman (Supervisor)
Associate Professor
Industrial & Production Engineering Department
BUET, Dhaka.

2. ______________________

Dr. M. Ahsan Akhtar Hasin — Member
Associate Professor
Industrial & Production Engineering Department
BUET, Dhaka.

3. ______________________

Dr. A. K. M. Masud — Member
Assistant Professor
Industrial & Production Engineering Department
BUET, Dhaka.

Department of Industrial & Production Engineering
Bangladesh University of Engineering & Technology
Dhaka-1000

April 2004

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.

Countersigned

Dr. Nikhil Ranjan Dhar
Supervisor & Associate Professor
Industrial & Production Engineering Department
BUET, Dhaka

Mohammad Wahidul Islam

Acknowledgements

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

The author also expressed his gratitude to Dr. Md. Golam Mohiuddin, Professor and Head of Industrial and Production Engineering Department, Bangladesh University of Engineering and Technology for his support and kind interest in this project work. The author is grateful to Dr. A. K. M. Masud, Assistant Professor of Industrial & Production Engineering Department, BUET, Dhaka

The author is deeply indebted to Md. Abu Hayat Mithu, graduate student, Md. Tanveer Ahmed, under-graduate student, and Sumaiya Islam, Research Assistant, IPE Department, BUET for their help at various stages of the work A special word of thanks is due to all staff members of Machine Tools Laboratory for their helps in conducting the experimental work.

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

April, 2004 Author

Abstract

Minimum quantity lubrication 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** 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.

Compared to the dry and wet machining, MQL machining performed many superiors mainly due to substantial reduction in cutting zone temperature enabling favorable chip formation and chip-tool interaction. It also provides substantial reduction in tool wear, which enhanced the tool life, dimensional accuracy. Furthermore, it provides environment friendliness (maintaining neat, clean and dry working area, avoiding inconvenience and health hazards due to heat, smoke, fumes, gases etc. and preventing pollution of the surroundings) and improves the machinability characteristics.

Contents

List of Figures

List of Tables

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 tha manufacturing shops. The performance and service life of engineering component depends on their material, dimensional and forms accuracy and surface quality. Machining and grinding is done to attain the desired accuracy and surface integrity finish the preformed blanks.

The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, 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 and grinding with high cutting velocity, feed and depth of cut is inherently associated with generetion of large amount of heat and high cutting tempereture. 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 smell in size, which leads to dimensional and form inaccuracy. On the other hend, high cutting temperature accelerates the growth of tool weer end also enhances the chances of premature failure of the tool by plastic deformation and thermal fracturing. The surface quality of the products also deteriorates with the increase in cutting temperature due to built-up-edge formation, oxidation, rapid corrosion and induction of tensile residual stress and surface micro-cracks. These problems are more predominent in grinding where cutting temperature is, as such, very high due to much higher specific energy requirement and cutting velocity. Such problem becomes more acute and serious if the work materials are very hard, strong and heat resistive and when the machined or ground part is subjected to dynamic or shock loading during their functional operations. Therefore, it is essential to reduce the cutting temperature as far as possible. In industries, the machining temperature and its detrimental effects are generally reduced by (a) proper selection of process parameters, geometry of the cutting tools and proper selection and application of cutting fluid and (b) using heet 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-basad type.

The major socio-economic problems that arise due to conventional type and method of application of cutting fluids are (a) inconvaniencas 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 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 es a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors (as shown in Fig.1 1). The minimization of cutting fluid also leads to economical benefits by way of seving lubricant costs and workpiece/tool/ machine cleaning cycle time.

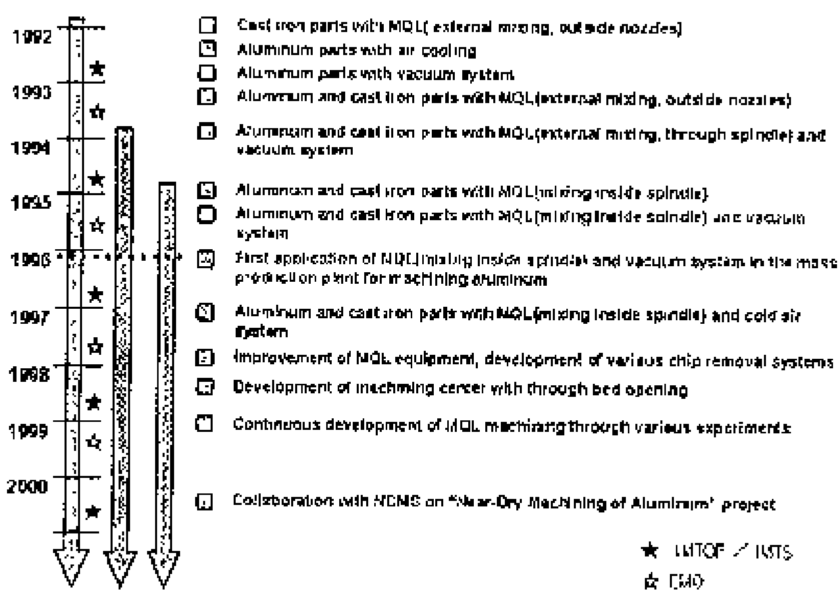


Fig. 1.1 History of dry machining development

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

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 due to cutting force fluctuations at the free surfece 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 hend, 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 stressas 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 adventing with vast and rapid developments in the modern areas like aerospace technology and nuclear science.

Past research has been focused on the temperature and its distribution in the cutting zone because it is believed that it has a direct impact on tool life [**Chao and Trigger 1955**]. The primary function of cutting fluids is to reduce this cutting temperature and increase tool life [**Shaw et al. 1951**]. The cutting fluids are believed to reduce cutting temperature either by removing heat as a coolant or reducing the heat generation as a lubricant. In eddition, the cutting fluid has a practical function as a chip-handling medium [**Beaubien 1964**]. Cutting fluids also help in machining of ductile materials by reducing or preventing formation of a built-up edge (BUE), which degrades the surface finish [**Heginbotham and Gogia 1961**].

Usually 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 machining process and harder materials and for demand for precision machining, the control of machining temperature by more effective and efficient cooling has become extremely essential.

Generally, suitable cutting fluid is employed to reduce this problem through cooling and lubrication at the cutting zone. But it has been experienced [**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 [1989] reported that a coolant applied at the cutting zone through a high pressure jet nozzle could reduce the contact length and coefficient of friction at chip-tool interface and thus could reduce cutting forces and increase tool life to some extent.

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

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

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

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

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

A recent development [**Chandrasekaran et al. 1998**] in this context is the use of Co_2 snow as the coolant in machining. This is feasible if Co_2 in liquid form under pressure (60 bars) is fed to the cutting zone and diffused through a capillary jet. This results in a change of state and the formation of Co_2 snow (endothermic reaction resulting in a temperature of -79^oC). Earlier investigations [**Thoors and Chandrasekaran 1994**] observed that Co_2 snow could function as a good cutting fluid/coolant under certain circumstances, which are very much related to the tool-work combination and the actual mode of feeding the coolant to the cutting zone.

1.1.2 Adverse effects of cutting fluid applications

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

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

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

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

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

- environmental pollution due to breakdown of the cutting fluids into harmful gases at high cutting temperature (Fig.1.2)
- biological hazards to the operators from the bacterial growth in the cutting fluids
- requirements of additional systems for pumping, local storage, filtration, temporary recycling, cooling and large space requirement
- disposal of the spent cutting fluids which also offer high risk of water pollution and soil contamination

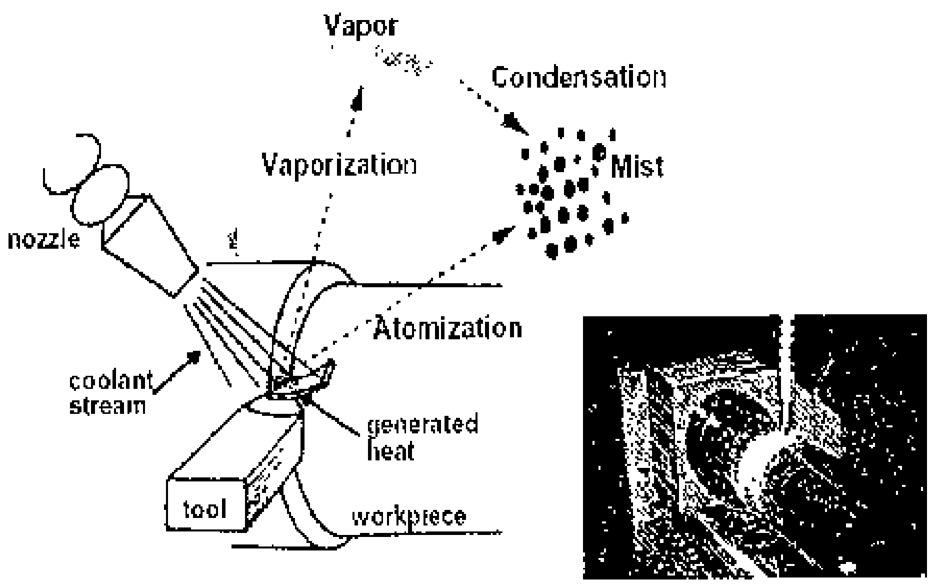


Fig. 1.2 Mist formation during machining with flood cooling

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

It has been estimated **[Bennett 1983]** that about one million workers are exposed to cutting fluids in the United States alone. Since cutting fluids are complex in composition, they may be more toxic than their constituents and may be irritant or allergenic Also, both bacteria and fungi can effectively colonize the cutting fluids and serve as source of microbial toxins Hence significant negative effects, in terms of environmental, health, and safety consequences, are associated with the use of cutting fluids. The effects of exposure to the fluids on health have been studied for over 50 years; beginning with the concern that cutting fluid (oil) is a potential etiologic factor for occupational skin cancer (Epidemiological studies indicate that long-term exposure to metalworking fluids can lead to increased incidence of several types of cancer). The international Agency for Research on Cancer has concluded that there is "sufficient evidence" that mineral oils used in the workplace is carcinogenic [**Peter et al.1996**] Basically, workers are exposed to metal cutting fluids via three routes [**Bennett et al. 1985**]; skin axposure, aerial exposure and ingestion (Fig.1.3).

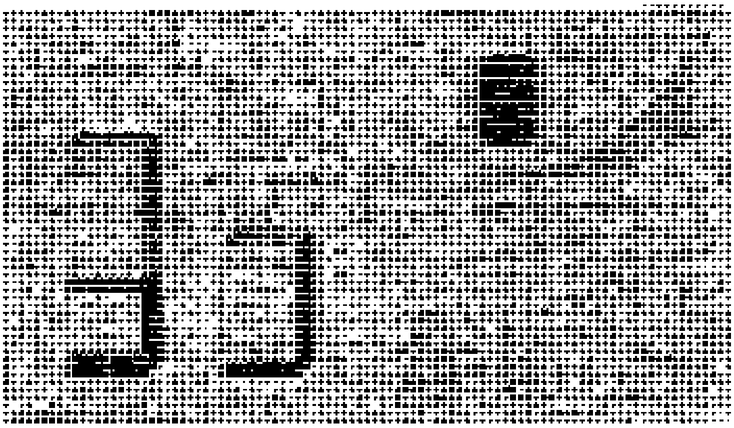


Fig. 1.3 Cost and health hazard of using cutting fluid

Skin exposure is the dominant route of exposure, and it is believed that about 80 percent of all occupational diseases are caused by skin contact with fluids [**Bennett et al.1985**]. Cutting fluids are important causes of occupational contact dermatitis, which may involve either irritant or allergic mechanisms. Water mixed fluids generally determine irritant contact dermatitis and allergic contact dermatitis when they are in touch with workers skin. Non-water-miscible fluids usually cause skin disorders such as foliculitis, oil acne, keratoses and carcinomas (Fig.1.4).

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 ganerated then may condense to form mist (Fig.1.1 and Fig 1.4). 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 air for several hours even several days in the workers breathing zones. These drifting droplets tend evaporate further Inhaled particles (with aerodynamic diameters less than 10 μm) deposit in the various regions of the respiratory system by the complex action of the different deposition mechanisms. The 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.1.4 Mist formation during turning operation under flood cooling condition

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 Particulata 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 litereture 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 many 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 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. Furfher the conventional cutting fluids ere 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 hard 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 lubrication for the turning of steel based on experimental measurement of cutting temperature, chip formation, dimensional deviation.

1.2 Objectives of the Present Work

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

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. chip shape, chip color and chip reduction coefficient
ii. cutting temperature and
iii. dimensional deviation

in machining AISI 1040 steel by the industrially used carbide tool (uncoated) at different speeds, feeds and depth of cut combinations.

The scopes of the present work are design and development of

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

and analysis of data by

i. collecting chip for categorizing with respect to their shape and color
ii. collecting chip for measuring chip reduction co-efficient and
iii. measuring dimensional deviation

Chapter-2

Design and Development 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 Delivery System

Minimum quantity lubrication 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** or **microlubrication**, 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. Compressor supplies high-pressure air (7 bar) and the pump supplies the cutting fluid (60 ml/hr) from the cutting fluid reservoir tank. The eir and the cutting fluid are mixed in a mixing chamber so that the mixture contains Minimum Quantity of Lubricants (MQL). The mixture of cutting fluid and air (MQL) is impinged at a high speed through the nozzle at the chip-tool interface. The schematic view of the minimum quantity lubrication applicator is shown in Fig 2.1.

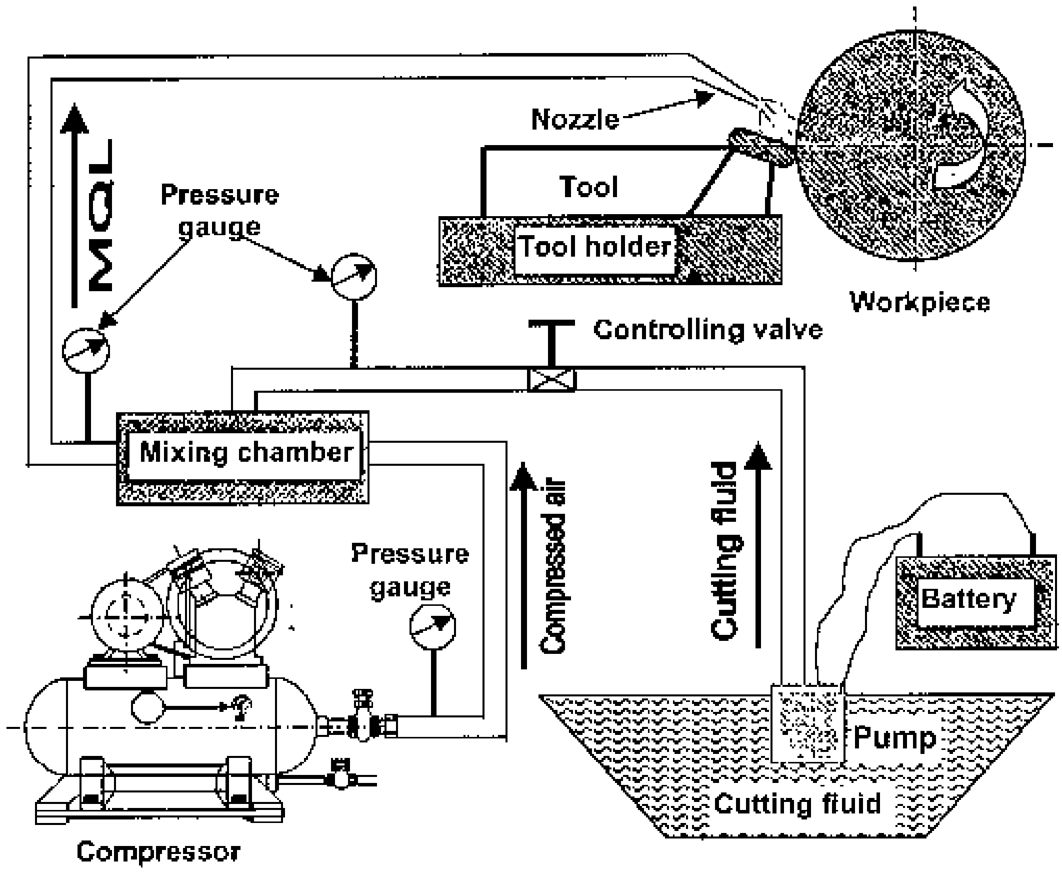
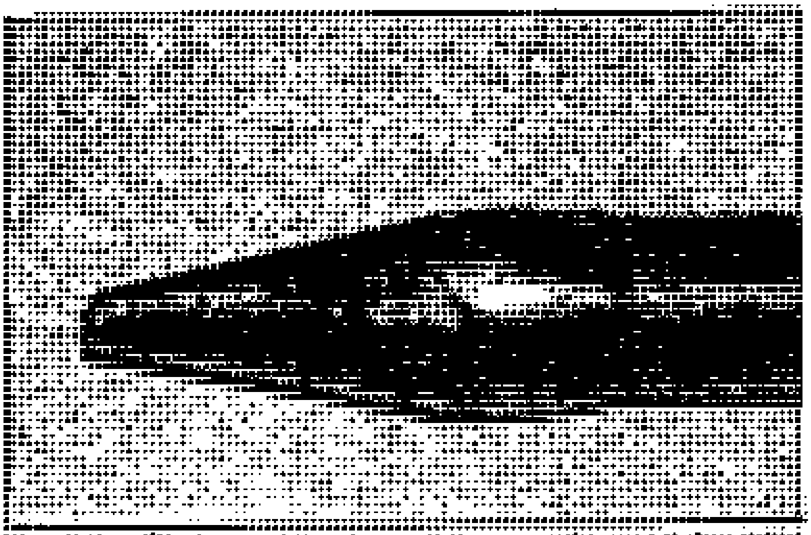


Fig. 2.1 Schematic view of MQL unit

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 1.5.0 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.



[illegible] 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 end evaluate the role of such MQL on machinability characteristics of some commonly used tool-work combinations 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. The compositions, strength, hardness and industrial use of this steel are given in Table 3.1.

Table-3.1 Characteristics of the used steel [**Rothman 1988 & Bagchi 1979**]

Work material	BHN	UTS (Kgf/mm^2)	Chemical composition (wt %)	Applications
AISI 1040 steel	180	63	C - 0.410, Mn - 0.700, P - 0.040, S - 0.050	• Shafts & crank shafts • Automobile axles • Spindles • Lightly stressed gears

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

Considering common interest and time constraint only uncoated carbide inserts of grade P30 have been used for the present work. Wide scope will remain for further study on MQL effect in machining steels by coated carbides and exotic materials by high performance ceramics, CBN and diamond.

Effectiveness of cooling and the related benefits depend on how closely the 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 undertaken 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.

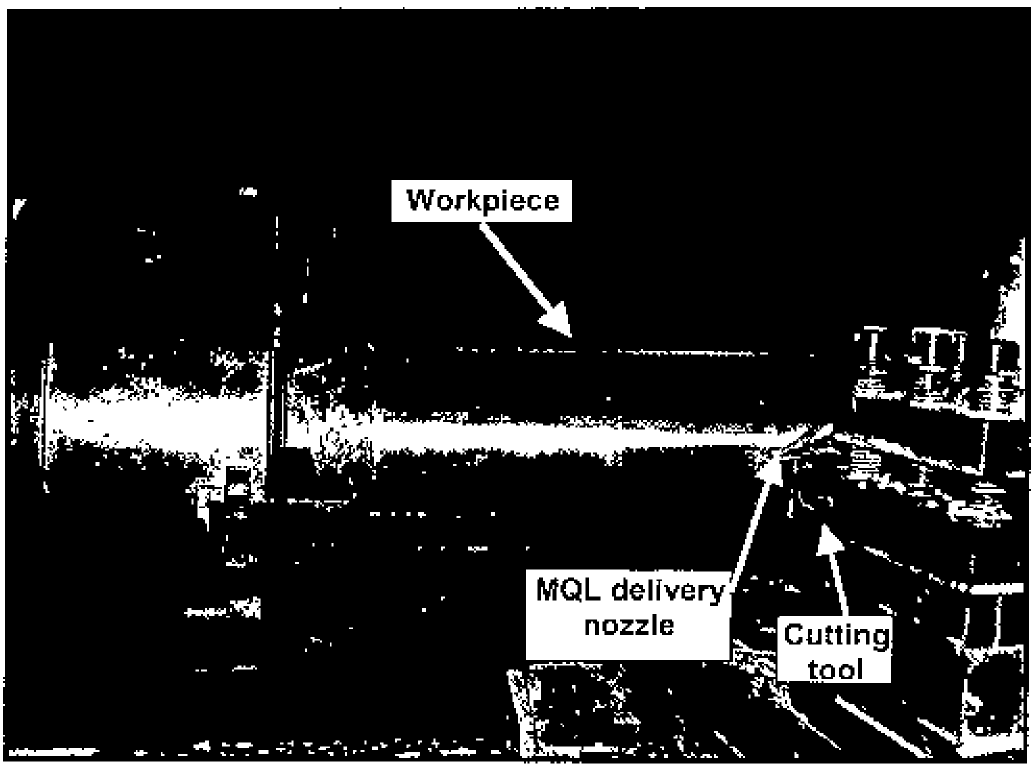


Fig. 3.1 Photographic view of MQL delivery nozzle injecting MQL during machining

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 3.2. It has already been reported [**Dhar et al 2002, 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 3.3.

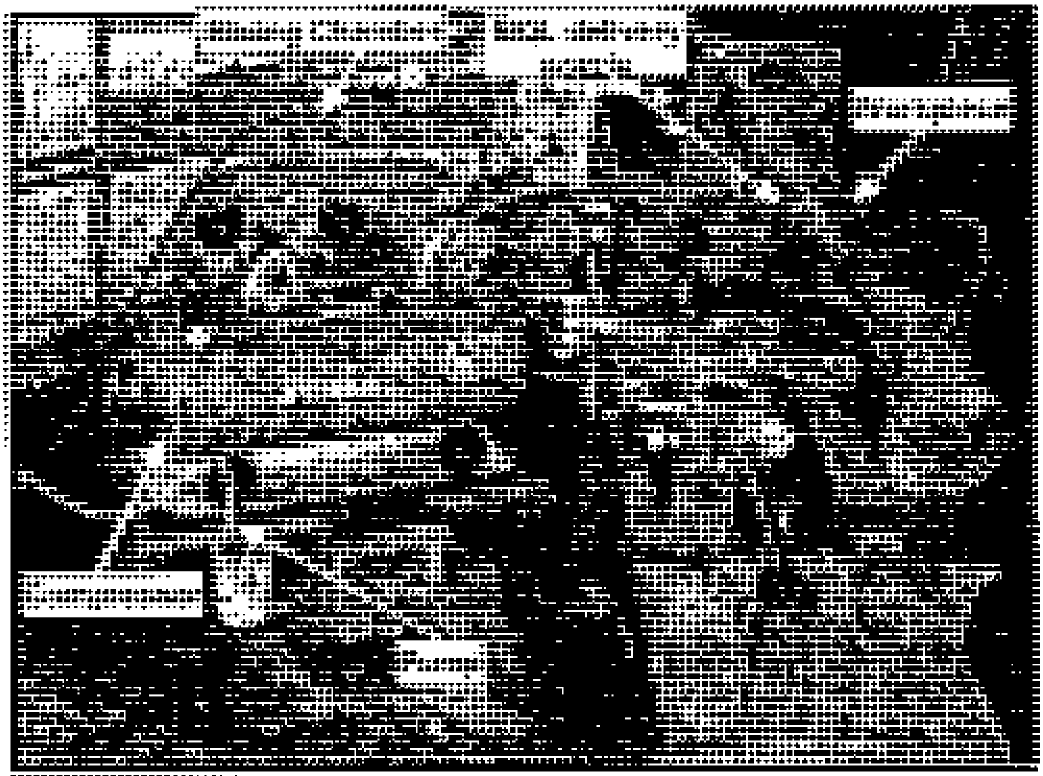
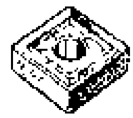


Fig. 3.2 Photographic view of the experimental set-up for turning steel with MQL

Table-3.2 Machining responses investigated

Investigation on	Environment		
	Dry	Wet	MQL
Temperature calibration	☑		
Cutting temperature	☑	☑	☑
Chip morphology	☑	☑	☑
Dimensional deviation	☑	☑	☑

Table-3.3 Experimental conditions

Machine tool	BMTF Lathe, Bangladesh, 4 hp
Work material	AISI 1040 steel (size: φ110 X 620 mm)
Cutting tool	Carbide, TTS (P-30 ISO specification), Drillco  **SNMM 120408**
Tool holder	PSBNR 2525 M12 (ISO specification), Drillco
Geometry	-6°, -6°, 6°, 6°, 15°, 75°, 0.8 (mm)
Process parameters	
Cutting velocity, V_c	64, 80, 90 and 130 m/min
Feed rate, S_o	0.10, 0.13, 0.16 and 0.20 mm/rev
Depth of cut, t	1.0 mm
MQL supply	Air: 7 bar, Lubricant: 60ml/h through external nozzle
Environment	dry, wet (flood cooling) and minimum quantity lubrication (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_o 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 1.0 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]** and
- 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 (a) parasitic emf generation by secondary junction (b) proper calibration and (c) electrical insuletion 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.3.3 taking care of the aforesaid factors.

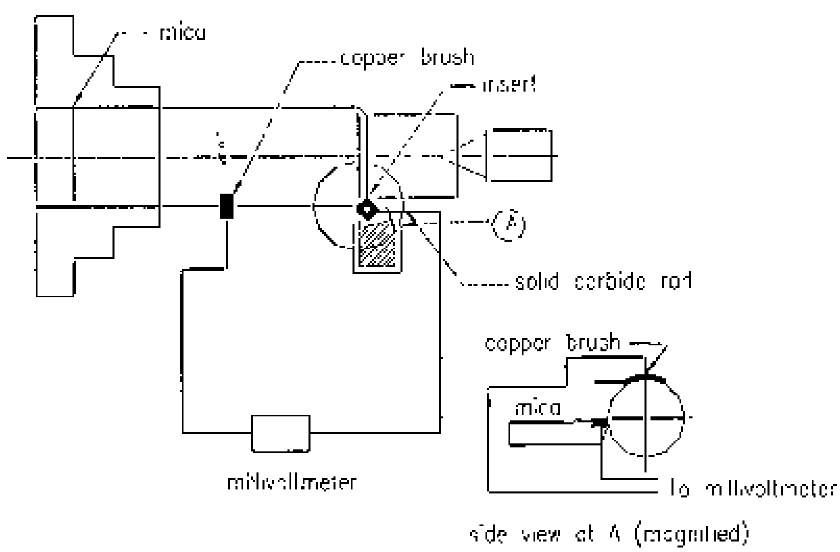


Fig. 3.3 Schematic view of the tool-work thermocouple loop

Tool-work thermocouple can be calibrated in several ways, which include (a) furnace calibration [**Bus et al. 1971 and Byrne 196]** (b) resistance heating [**Alvedid 1970**] (c) embedded silver bit technique [**Barrow 193**] (d) induction healing [**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.3.4 schematically shows the set-up. The work-tool thermocouple junction was constructed using a long continuous chip of the concerned work-material and a tungsten carbide insert to be used in actual cutting. To avoid generation of parasitic emf, a long carbide rod was used to extend the insert. A standard chromel-alumel thermocouple is mounted at the site of tool-work (junction of chip and insert) junction. The oxy-acetylene torch simulated the heat ganeration phenomena in machining and raised the temperature at the chip-tool interface. Standard thermocouple directly monitored the junction temperature (measured by a Eurotherm Temperature Controller and Programmer, model 818P, made in UK) when the emf generated by the hot junction of the chip-tool was monitored by a digital multimeter (model: DH 334, Philips). Fig.3.5 shows the photographic view tool-work thermocouple set up.

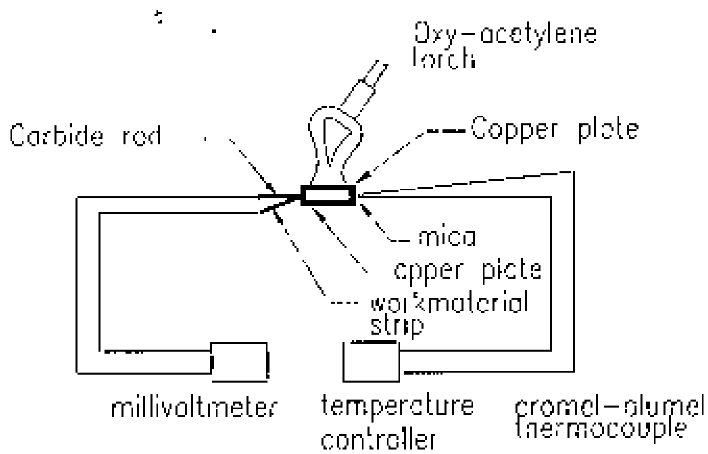


Fig 3.4 Scheme of calibration of present tool work thermocouple

Fig.3.5 Photographic view of the present tool-work thermocouple set up

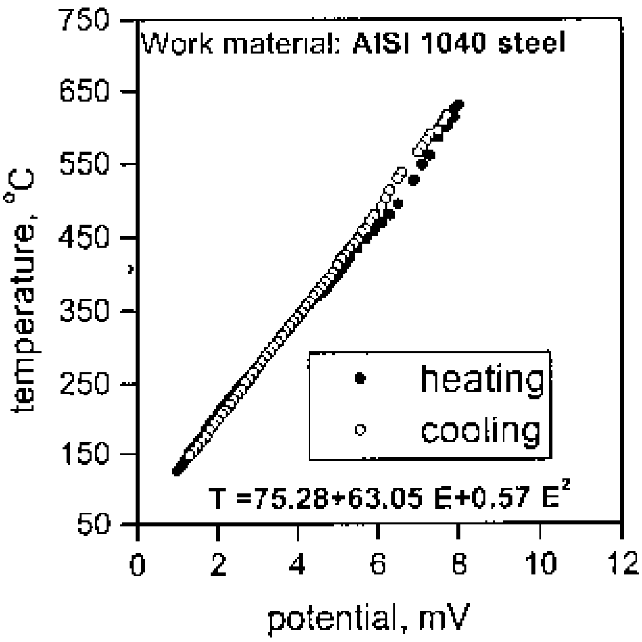


Fig. 3.6 Temperature calibration curve for carbide and AISI-1040 steel

Fig.3.6 shows the calibration curve obtained for the tool-work pair with tungsten carbide (P30 Grade, Drillco) 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 thicknesses of the chips were 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.

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. Therefora, 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. 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 uncoated insert at different V_c and S_o under dry, wet and MQL conditions have been shown in Fig.3.7.

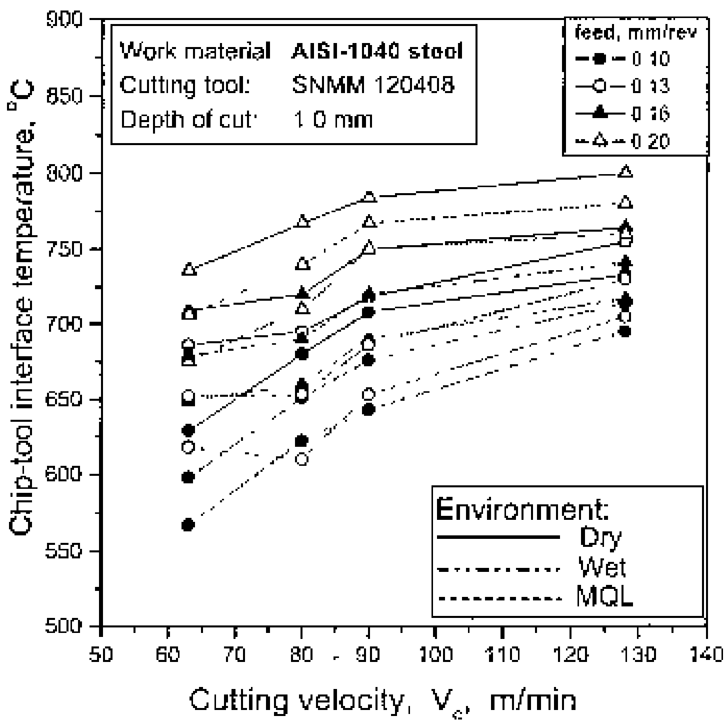


Fig.3.7 Variations in chip-tool interface temperature that of V_c and S_o in turning AISI-1040 steel by SNMM insert under dry, wet and MQL conditions.

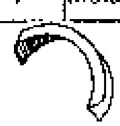
3.2.2 Machining chips

The chip samples collected while turning the AISI 1040 steel by the insert of configuration SNMM at different V_c-S_o combinations under both dry, wet and MQL conditions have been visually examined and categorized with respect to their shape and color.

The results of such categorization of the chips produced at different conditions and environments by the AISI-1040 steel at different feeds have been shown in Table-3.4.

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.3.8, Fig 3.9, Fig 3.10 and Fig.3.11.

Table-3.4 Shape and color of chips **of AISI-1040 steel** at different feeds

Cutting velocity, V_c m/min	Environment	Feed rate, S_o, mm/rev							
		0.10		0.13		0.16		0.20	
		Shape	Color	Shape	Color	Shape	Color	Shape	Color
64	Dry	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	Wet	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	MQL	♣	Metallic	♣	Metallic	♣	Metallic	♣	Metallic
80	Dry	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	Wet	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	MQL	♣	Metallic	♣	Metallic	♣	Metallic	♣	Metallic
90	Dry	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	Wet	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	MQL	♣	Metallic	♣	Metallic	♣	Metallic	♣	Metallic
130	Dry	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	Wet	☆	Blue	☆	Blue	☆	Blue	☆	Blue
	MQL	♣	Metallic	♣	Metallic	♣	Metallic	♣	Metallic
Chip shape									
Chip group		♣ Half turn		●Tubular		☆ Spiral		★ Ribbon	

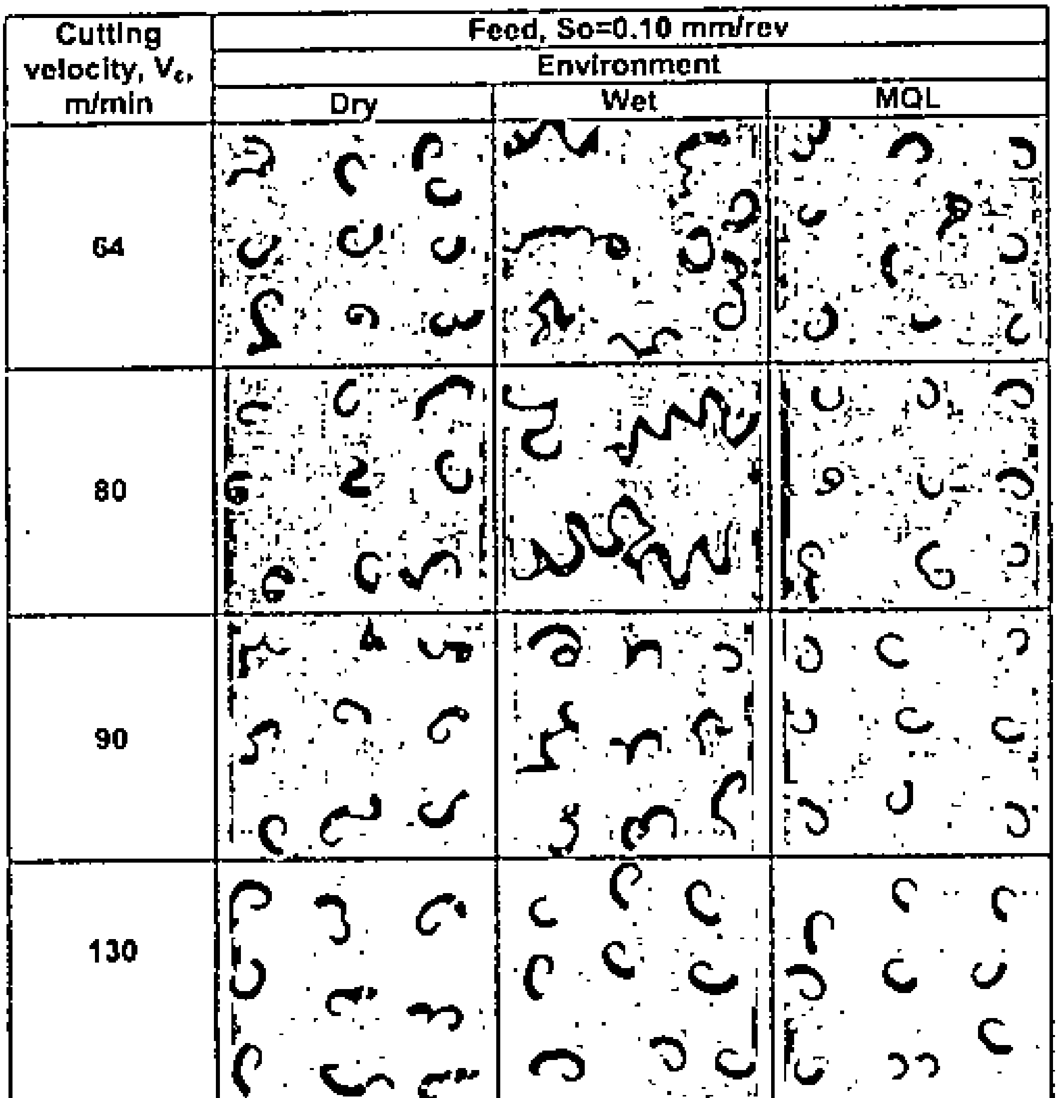


Fig.3.8 Actual forms of chips produced during turning at different cutting velocity and 0.10 mm/rev feed rate under dry, wet and MQL conditions.

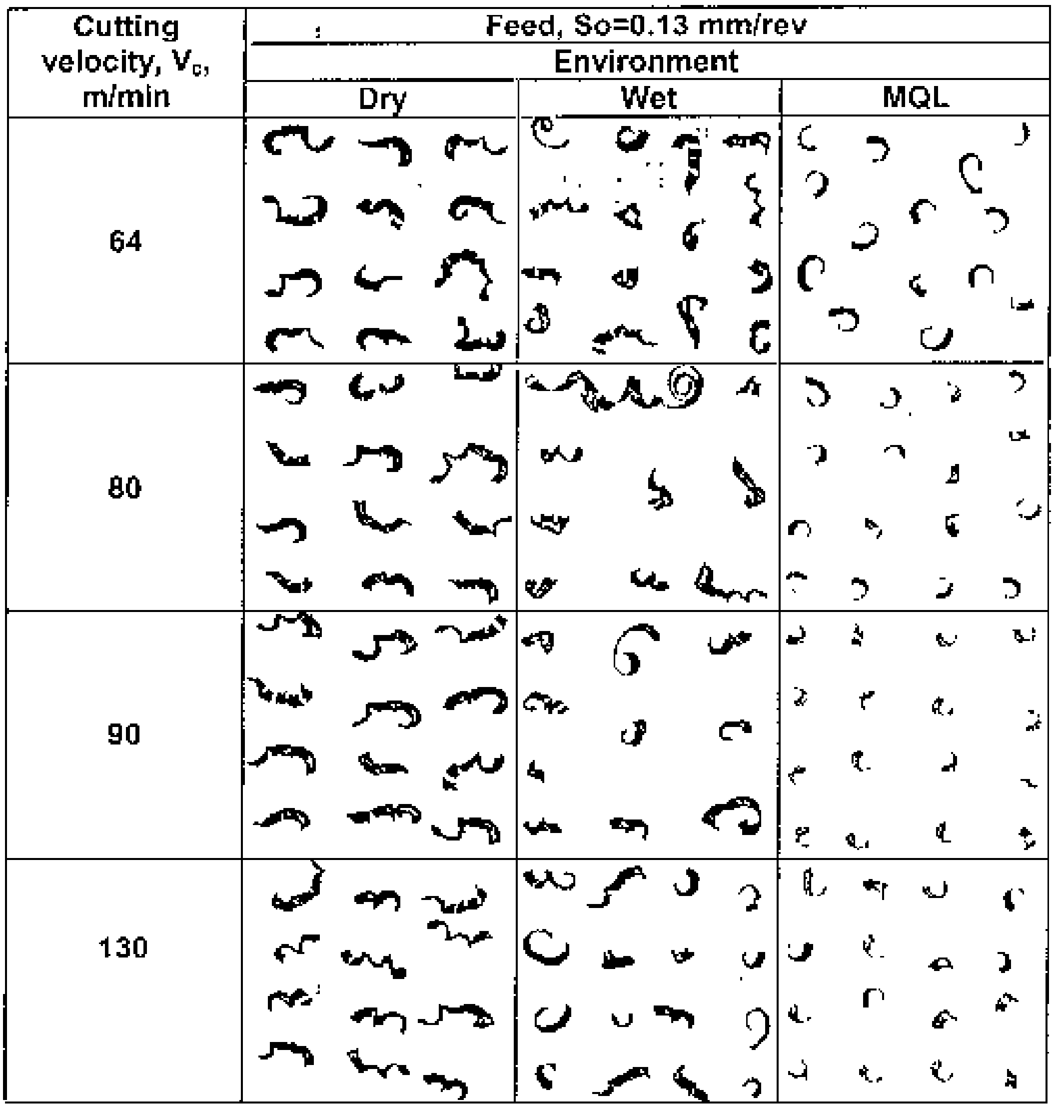


Fig.3.9 Actual forms of chips produced during turning at different cutting velocity and 0.13 mm/rev feed rate under dry, wet and MQL conditions.

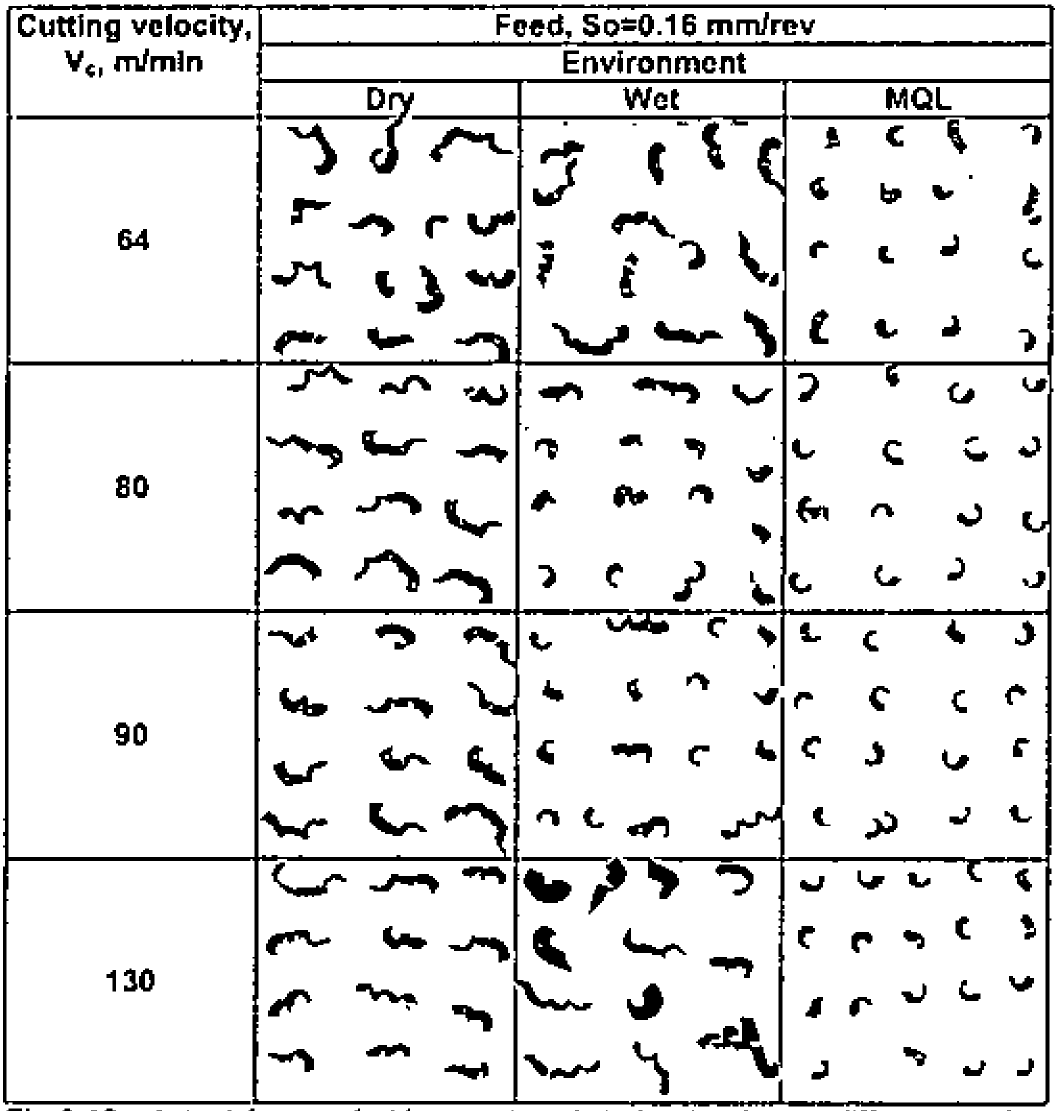


Fig.3.10 Actual forms of chips produced during turning at different cutting velocity and 0.16 mm/rev feed rate under dry, wet and MQL conditions.

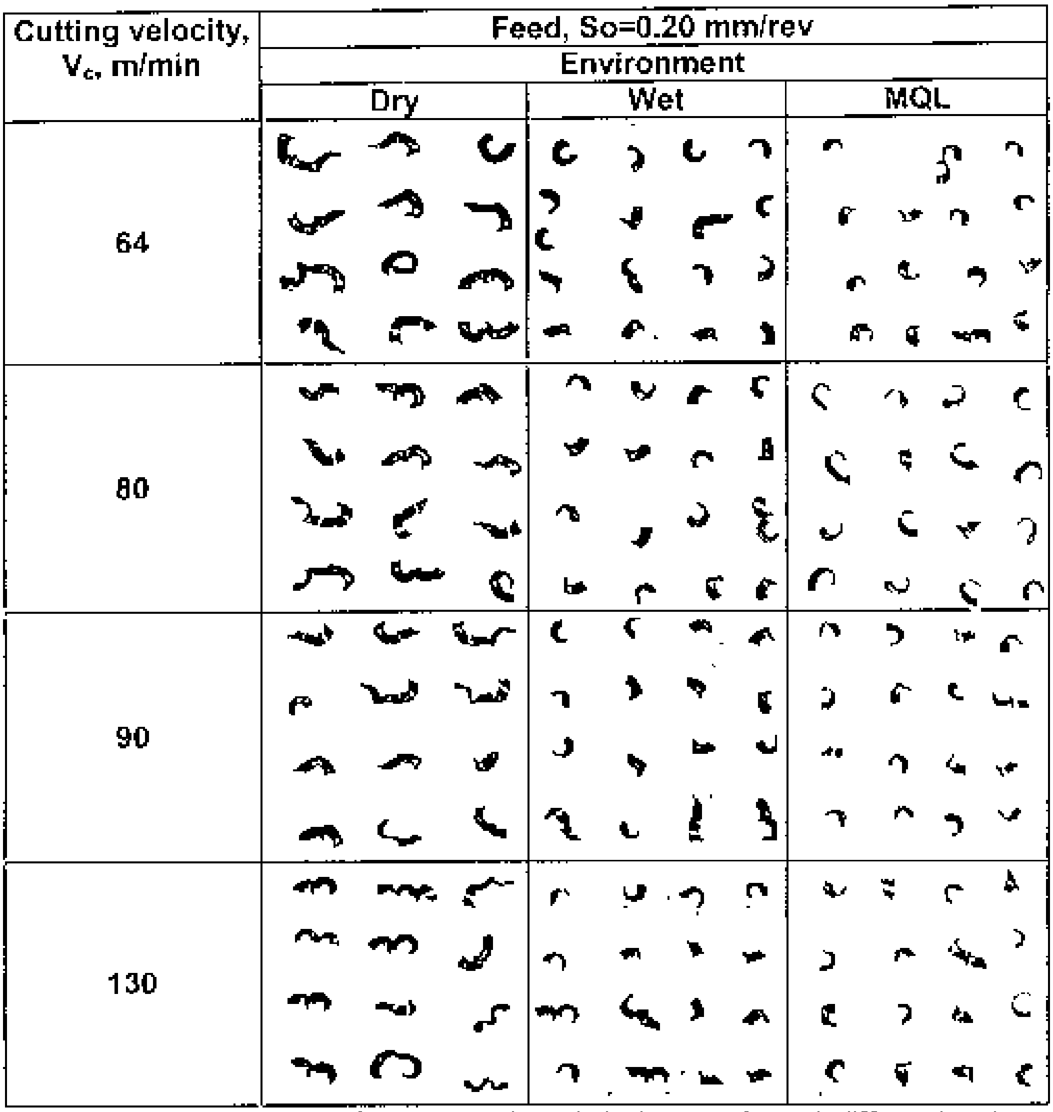


Fig.3.11 Actual forms of chips produced during turning at different cutting velocity and 0.20 mm/rev feed rate under dry, wet and MQL conditions

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.3.12.

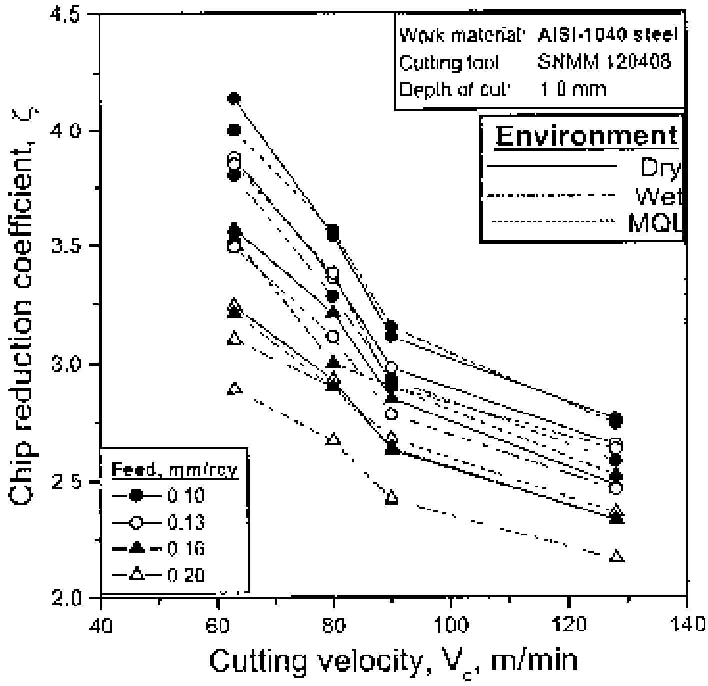


Fig.3.12 Variation in ζ with cutting velocity and feed rate during turning under dry, wet and MQL conditions

3.2.3 Dimensional deviation

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 micro cracks.

In the present work, only dimensional deviation on diameter have been investigated to evaluate the relative role of MQL on this major aspects.

During straight turning in a center lathe, the diameter of the machined part is generally found to

i. increase along length of cut due to gradual wear of the tool tip
ii. decrease due to thermal expansion and subsequent cooling of the job if the job temperature rises significantly during machining
iii increase due to system compliance of the machine-fixture-tool-work (M-F-T-W) system under the action of the cutting forces

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

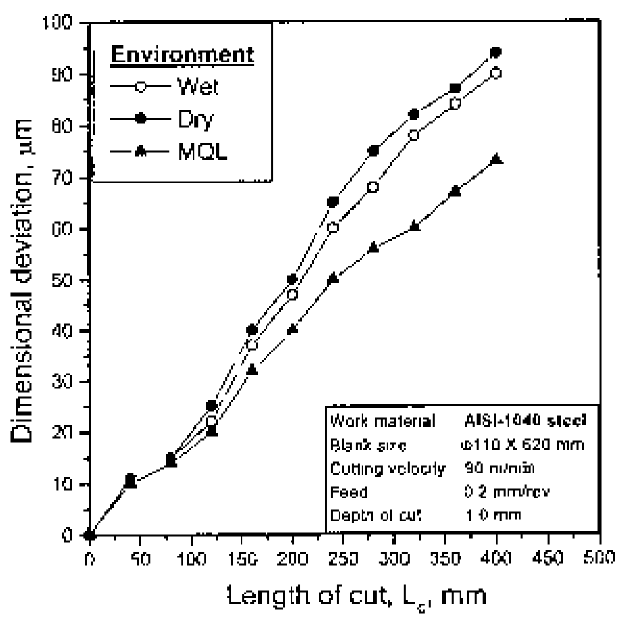


Fig.3.13 Dimensional deviations observed after one full pass under dry, wet MQL conditions

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.

The gradual increase in dimensional deviations on diameter observed along the length of cut on the AISI-1040 steel rod after one full pass of machining at cutting velocity of 90 m/min, 1.0 mm depth of cut and 0.2 mm/rev feed under dry, wet and MQL conditions have been shown in Fig.3.13.

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 experimental setup consisted of an electrically insulated carbide tool insert clamped into a tool holder. A K-type thermocouple is spot welded onto the insert at the tool-chip interface and is secured further by a coating of ceramic cement Embedding it in several layers of mica electrically insulates the alumel lead wire, which measures the e.m.f generated at the interface. A small aperture is cut on the top layer of mica to allow the wire to contact the insert as shown both in Fig.3.4 and Fig.3.5 respectively. During calibration, the emf is measured and the temperature is measured by a K-type thermocouple at the point where the tool and chip would contact during cutting. An oxygen-acetylene torch or a propane torch applies the necessary heat for approximating the heat generated during metal cutting. Measurements are taken after a few minutes of heating to insure a quasi-steady state. Also, only the cooling of the insert is used to maintain a consistent calibration.

A plot of the measured potential for a given temperature during calibration is shown in Fig.3.6 for carbide tool and AISI-1040 steel workpiece. In this case, linear correlation between the temperature and emf is observed Although result from the calibration varied slightly for this test, good correlation was attained when regression was performed (R^2 = .92-.97).

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 figure Fig.3.7 is 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 AISI 1040 steel when machined by the pattern type SNMM insert under dry condition produced more or less half turn et different higher feeds. The geometry of the SNMM insert is such that the chips of this steel (AISI-1040 steel) 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 appaared 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 color of the chips have also become much lighter i.e. metallic or golden from blue or grey depending upon V_c and S_o due to reduction in cutting temperature by minimum quantity lubrication.

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 value of ζ depends [**Kronenberg 1943**] mainly on apparent coefficient of friction, μ_a at the chip-tool interface and effective rake as,

$$\zeta = e^{\mu_a\left(\frac{\pi}{2}-\gamma_e\right)} \tag{4.1}$$

In machining ductile metals, particularly steels, the actual value of τ_s is affected [**Abuladze 1962**] by the values of tool rake angle and as,

$$\tau_s = 0.74\sigma_u \varepsilon^{0.6\Delta} \tag{4.2}$$

where,

- σ_u Ultimate tensile strength of the work material at normal condition
- Δ Percentage elongation of the work material
- ε Average cutting strain (= cot β + tan (β - γ_e)
- β Shear angle (cot β= ζ - tan γ_e)
- τ_s Dynamic yield shear strength of the work material

The figure Fig.3.12 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 and 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 and 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.

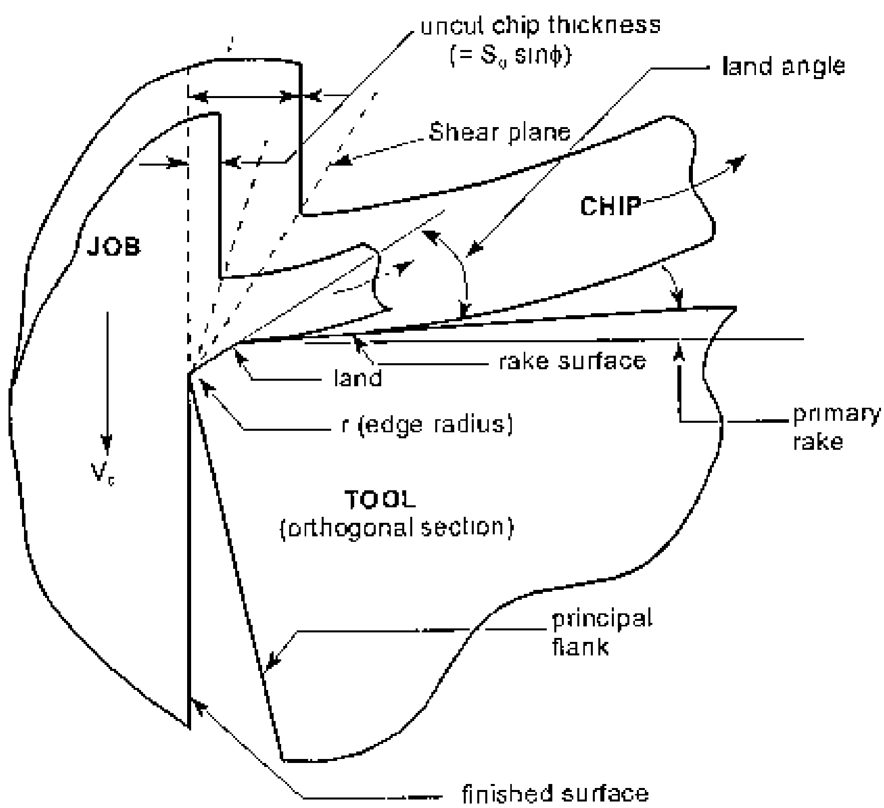


Fig.4.1 Schematic view of machining with varying uncut chip thickness.

It is also noted in this figure that ζ decreased all along also with the increase in S_0 expectedly due to increase in average rake angle with increase in uncut chip thickness as has been schematically indicated in Fig.4.1.

Fig.3.12 shows that MQL has reduced the value of ζ particularly at lower values of V_C and S_0 when the SNMM insert machined the steel rod 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 Dimensional Deviation

The quality of any machined product of given material is generally assessed by dimensional accuracy, which govern the performance and service life of that product. For the present study, only dimensional accuracy has been considered for assessment of quality of product under dry, wet and MQL machining. Fig.3.12 clearly shows that dimensional inaccuracy can be remarkably reduced by the present method of MQL in machining AISI 1040 steel rod 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 substantial reduction in dimensional deviation observed in the present investigation can be reasonably attributed mainly to reduction in the auxiliary flank wear of the inserts by MQL. The order of dimensional deviation possible due to other two reasons for the present job specimen of so large diameter and L/D ratio less than 4 0 and the cutting conditions undertaken has been roughly estimated and found to be around 1.0 μm.

Fig 3 13 shows that the nature of increase of dimensional deviation with the progress of machining AISI 1040 steel rod. Dimensional inaccuracy has been respectively enhanced under dry and wet conditions and reduced under MQL condition, expectedly. The machining tests conducted for studying the role of MQL on dimensional inaccuracy was separately carried by fresh insert after completion of tool wear test. Dimensional deviation, for each tool-work-environment combination, was measured along the job axis after one complete pass.

Chapter-5

Conclusions

Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. Typically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Minimum quantity lubrication (MQL) presents itself as a viable alternative for machining with respect to heat dissertation, chip formation, and dimensional deviation. This study compares the mechanical performance of minimum quantity lubrication to completely dry and wet lubrication for the turning of AISI-1040 steel based on experimental measurement of chip shape, chip color, chip reduction coefficient, cutting temperature and dimensional deviation. The results indicate that the use of minimum quantity lubrication leads to reduced chip reduction coefficient, lower cutting temperature and lower dimensional deviation.

The present MQL systems enabled reduction in average chip-tool interface temperature upto 12% depending upon the work materials, tool geometry and 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 color 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

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

Chapter-6

References

Abrao, A. M., Aspinwall, D. K. and Ng, E.G., "Temperature Evaluation when Machining Hardened Hot Work Die Steel using PCBN Tooling", *Ind. Diamond Rev.* 56, pp.40-44 (1996).

Abuladze, N. G., "Thesis for Kand. Sc.", *Georgia Polytechnic Institute, Tbilisi,* (1962)

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

Alvedid, B., "Cutting Temperature Thermo-electrical Measurements", *Annals of CIRP*, Vol.18, pp.547-554 (1970).

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

Bagchi, S. N. and Prakash, K., "Industrial Steel: Reference Book" *Wiley Eastern Ltd., New Delhi 110002, India* (1979)

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

Barron, R. F., "Monographs on Cryogenic 3: Cryogenics System", 2nd. Ed. *Oxford University Press, New York*, USA, (1985).

Barrow, G., "A Review of Experimental and Theoretical Techniques for Assessing Cutting Temperatures", *Annals of CIRP*, Vol.22, pp 203-211, (1973) Barrow, G., Graham, W., Kurimoto, T. and Leong, Y. F., "Determination of Rake Face Stress Distribution in Orthogonal Machining", *Int. J. Mach. Tool Des. Res.* Vol. 22, pp.75 (1982).

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

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

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

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

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

Bhattacharyya, A., "On the Friction Process in Metal Cutting", *Proc. 6th Int. Conference on MTDR, Manchester, UK*, pp 491-505 (1965).

Bhattacharyya, A., "Metal Cutting-Theory and Practice", *Central Book Publishers, India*, pp.324-329 (1984).

Braiden, P.M., "The Calibration of Tool-Work Thermocouples", *Proc. 8th Int Conference on MTDR*, pp.653-666 (1967).

Bus, C., Touwen, A.L., Veenstra, P.C. and Van Der Wolf, A.C.H., "Thermoelectric Characteristics of Carbides", *Proc. 12th Int. Conference on MTDR*, pp.397-400 (1971).

Byrne, Gerry, "Thermoelectric Signal Characteristics and Average Interfacial temperatures in the Machining of Metals under Geometrically Defined Conditions", *Int. J. of Machine Tool and Manufacture*, Vol.27/2, pp.215-224 (1987).

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

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

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

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

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

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

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

Chen, N. N. S. and Pun, W. K., "Stresses at the Cutting Tool Wear Land", Int. *J. of Mach. Tools Manuf.*, Vol.28(2), pp.79 (1988).

Childs, T. H. C., Mahdi, M I and Barrow, G., "On the Stresses Between the Chip and Tool during Metal Turning" *Annals of CIRP*, Vol.38 (1), pp 55 (1989).

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

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

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

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

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

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

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

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

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

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

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

Hahn, R. S., "On the Temperature Developed at the Shear Plane in the Metal Cutting Processes", *Proc. U S. Nat. Congross of Applied Mechanics, Trans. of the ASME*, pp 661 (1951)

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

Herbert, E G., "The Measurement of Cutting Temperature", *Proc. of the Institute of Mechanical Engineering*, Vol.1, pp.289-329 (1926)

Hinterman, H. E. and Chattopadhyay, A. K., "Low Pressure Synthesis of Diamond Coating", *Annals of CIRP*, Vol.42/2 (1993)

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

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

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

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

Kagiwada, T. and Kananuchi, T., "Numerical Analysis of Cutting Temperature and Flowing Ratios of Generated Heat", *ASME Int. Thermal, Series III*, Vol. 31(3), pp.624 (1988)

Kato, S., Yamaguchi, K. and Yamada, M., "Stress Distribution at the Interface between Tool and Chip in Machining", ASME, *Tech. Eng. Ind.*, pp. 683 (1972).

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

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

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

Konenberge, M., "Cutting Angle Relationship on Metal Cutting Tools", *Mechanical Engineering, December*, pp.901 (1943)

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

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

Leith, D., Raynor, P.C., Boundy, M. G and Cooper, S. J., "Performance of Industrial Equipment to Collect Coolant Mist", AIHA *J. No.*57, (1996).

Leshock, C.E. and Shin, Y.C., "Investigation on Cutting Temperature in Turning by a Tool-Work Thermocouple Technique", *Trans. of the ASME*, Vol.119, pp.502-508 (1997).

Li, X.S. and Low, I.M., "Ceramic Cutting Tools-An Introduction", *Key Eng Meter.* Vol.96, pp.1-18 (1994).

Lo Casto, S., Lo Valvo, E and Micari, F., "Measurement of Temperature Distribution within Tool in Metal Cutting Experimental Tests and Numerical Results", *J. of Mech. Working Tech.*, Vol.20, pp.35 (1989)

Loewen, E. G. and Shaw M. C., "On the Analysis of Cutting Tool Temperature", *Trans. of the ASME*, Vol.76, pp.217-231 (1954)

Matsumoto, Y and Hsu, D.C., "Workpiece Temperature Rise during the Cutting of AISI 4320 Steel", *Wear*, Vol. 116, pp.309-317 (1987).

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

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

Mondal, B., Chattopadhyay, A.B., Virkar, A and Paul, A., "Development and Performance of Zirconia-toughened Alumina Ceramic Tools", *Wear*, Vol. 156, pp. 365-383 (1992).

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

Nashchokin, V. V., "Engineering Thermodynamics and Heat Transfer", *MIR Publisher, Moscow, the USSR*, (1979).

"National Industrial Competitiveness through Energy, Environment and Economics (NICE3)", *Air Products and Chemicals, Inc., Allentown, PA.* (1997).

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

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

Ostafiev, V. A and Noschenko, A. N., "Numerical Analysis of Three Dimensional Heat Exchange in Oblique Cutting", *Annals of CIRP*, Vol 134 (1985)

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

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

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

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

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

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

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

Prins, O D , "The Influence of Wear on the Temperature Distribution at the Rake Face", *Annals of CIRP*, Vol.19, pp 579-584 (1971).

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

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

Rothman, M. F., "High Temperature Property Data: Ferrous Alloy", Metal *Park, OH 44073, USA* (1988)

Satoshi, I., Teiji, Y., Shinichi, M. and Kazuo, M., "Machinability of Ni_3Al Based Intermetallic Compounds", *J. of Material Processing Technology*, Vol.63, pp.181-186 (1997).

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

Shaw, M. C., "Metal Cutting Principles", *Clarendon Press, Oxford University Press*, pp.284-287 (1984).

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

Sheng, P. and Munoz, A., "Environmental Issues in Product Design-for-Manufacture", *7th Int . Conf. on Design for Manufacturing* (1993).

Singamneni, S. B., "Role of Controlled Contact Cutting on the Mechanism and Mechanics of Chip Formation and the Induced Stresses in Turning Carbide Inserts", *Doctoral Dissertation, Dept. of Mech. Engg., IIT Kharagpur* (1993).

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

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

Stephenson, D. A., "Tool-work Thermocouple Temperature Measurement: Theory and Implementation Issue", Trans. *of the ASME*, Vol.115, pp.432-437 (1993).

Stephenson, D. A. and Agapiou, J. S., "Metal Cutting Theory and Practice", *New York*, pp 425 (1997).

Stevenson, M. G., Wright, P. K. and Chow, J. G., "Further Developments in Applying the Finite Element Method to the Calculation of Temperature

Distributions in Machining and Comparisons with Experiment", *Trans. of the ASME,* Vol.105, pp.149-154 (1983).

Strenskovski, J. S. and Kyung-jin, M., "Finite Element Prediction of Chip Geometry and Tool and Workpiece Temperature Distributions in Orthogonal Cutting", *Trans. of the ASME,* Vol.112, pp.313-318 (1990)

Tay, A. O., Stevenson, M. G. and Davis, G. V., "Using the Finite Element Method to Determine Temperature Distributions in Orthogonal Machining", *Proc. IMechE,* Vol.188, pp.627-638 (1974).

Tay, A. O., Stevenson, M. G., Davis, G. V. and Oxley, P. L. B., "A Numerical Method for Calculating Temperature Distribution in Machining, from Force and Shear Angle Measurements", *Int. J. Mach. Tool. Des. Res.* Vol.16, pp.335-349 (1976)

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

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

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

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

Tuan, W. H. and Brook, R. J., "The Toughening of Alumina with Nickel Inclusions", *J. of Eru. Ceramic Soc.*, Vol. 6, pp.31-37 (1990)

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

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

Venkatesh, V. C., "Experimental Techniques in Metal Cutting", *Prentice* Hall, India (1987).

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

Wang. J., Ponton, C. B., and Marquis, P. M., "Silver Toughened Alumina Ceramics", *Br Cerma. Trans.*, Vol. 92, pp. 67-74, (1993)

Wang, Z. Y., Rajurkar, K. P. and Murugappan, M., "Cryogenic PCBN Turning of Ceramic (Si_3N_4)", *Wear*, Vol 95, pp.1-6 (1996).

Weiner, J. H., "Shear-Plane Temperature Distribution in Orthogonal Cutting", *Trans. of ASME*, Vol.77, pp.1331 (1955).

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

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

Wright, P. K and Trent, E. M., "Metallographic Methods of Determining Temperature Gradients in Cutting Tools", *J. Iron Steel Inst.* pp.364-368 (1973).

Yamaya, S. and Shibuki, K., "Study of Alumina Ceramic Tools", *Tungolay*, Vol.19 (26), pp.34-37 (1974)