# Effects of Minimum Quantity Lubrication by Vegetable Oil-based Cutting Fluid on Machinability of Steel

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By

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# Declaration

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

Mohammad Muhshin Aziz Khan

**This work is dedicated to my loving**

**Father**

**Late M. Abdul Qaiyum Khan**

**&**

**Mother**

**Farida Akhter Khanam**

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# List of Symbols

| | |
|---|---|
| $V_c$ | Cutting velocity |
| $S_o$ | Feed rate |
| t | Depth of cut |
| $\zeta$ | Chip reduction coefficient |
| $\sigma_u$ | Ultimate tensile strength of the work material |
| $\Delta$ | Percentage elongation of the work material |
| $\varepsilon$ | Average cutting strain |
| $\beta$ | Shear angle |
| $\tau_s$ | Dynamic yield shear strength of the work material |

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# 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.

Significant progress has been made in dry and semidry machining recently, and minimum quantity lubrication (MQL) machining in particular has been accepted as a successful semidry application because of its environmentally friendly characteristics. A number of studies have shown that MQL machining can show satisfactory performance in practical machining operations. However, there has been little investigation of the cutting fluids to be used in MQL machining. In this regard the proposed research work has been carried out with a view to study the effects of minimum quantity lubrication (MQL) by vegetable oil-based cutting fluid on the cutting performance of AISI

9310 steel, as compared to completely dry and wet machining in terms of chip-tool interface temperature and tool wear reduction, tool life increment and machined surface protection. An approach based on the process parameters (speeds, feeds and depth of cut) has also been performed to identify the suitable MQL nozzle position for better cooling action. In the study, the minimum quantity lubrication will be provided with a spray of air and vegetable oil.

Compared to the dry or wet machining, MQL machining performed much superior 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, and surface finish. 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.

# Chapter-1

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## *Introduction*

Turning is a type of machining process, which is shown in Fig.1.1 on a manual lathe and from a side view. In this process, material is removed by sliding a hard cutting tool through a softer material and forming a chip. The main process variables in this case are the cutting speed, the feed rate, and the depth of cut. Cutting speed is either given as the rotation velocity of the workpiece or as the linear tangential velocity of the workpiece at the tip of the cutting tool, feed rate is defined as the linear distance that tool traverses during one rotation of the workpiece, and cutting depth is the radial engagement between the cutting tool and the workpiece.

### 1.1 High Production Machining

Any manufacturing process for its fruitful implementation essentially needs to be technologically acceptable, technically feasible and economically viable. The fourth dimension that has been a great concern of the modern industries and society is environment-friendliness in and around the manufacturing shops.

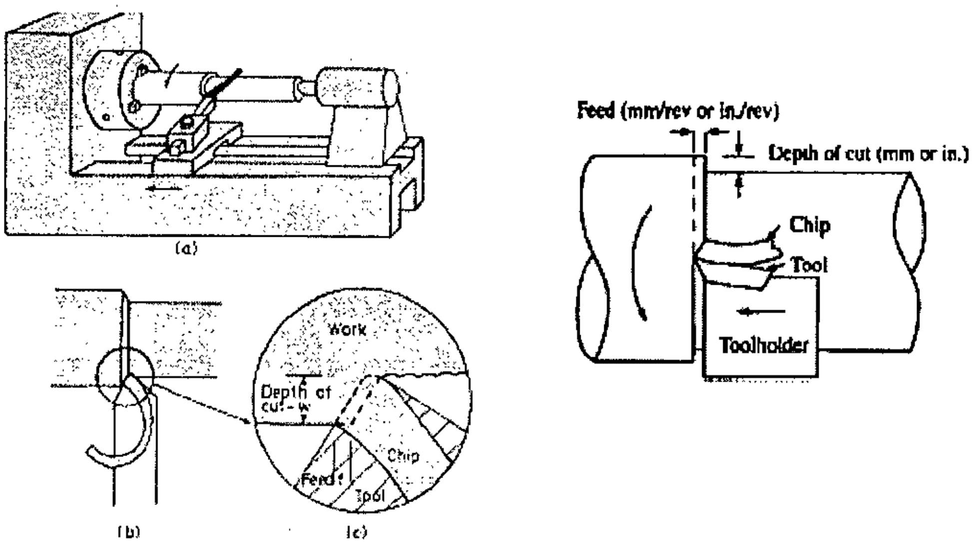



**Fig.1.1** Traditional turning process **[Trent 1977; Kalpakjian 1997]**

The performance and service life of engineering component depends on their material, dimensional and form accuracy and surface quality. Machining and grinding 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 liberalisation and global cost competitiveness, insists high material removal rate and high stability and long life of the cutting tools.

But high production machining and grinding with high cutting velocity, feed and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product.

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

In industries, the machining temperature and its detrimental effects are generally reduced by:

i. proper selection of process parameters and geometry of the cutting tools
ii. proper selection and application of cutting fluid

iii. using heat and wear resistant cutting tool materials like carbides, coated carbides and high performance ceramics (CBN and diamond are extremely heat and wear resistive but those are too expensive and are justified for very special work materials and requirements where other tools are not effective).

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

The major socio-economic problems that arise due to conventional type and method of application of cutting fluids are:

i. inconveniences due to wetting and dirtiness of the working zone
ii. possible damage of the machine tool by corrosion and mixing of the cutting fluid with the lubricants
iii. environmental pollution due to break down of the cutting fluid into harmful gases
iv. biological hazards to the operators from bacterial growth in the cutting fluids
v. 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, clean, neat and pollution free machining and grinding. Ample researches have been carried out and are still going on in this direction. Minimum Quantity Lubrication (MQL) by agents like soluble and vegetable oils appears to be a promising technique for effective cooling without the problems associated with conventional cutting fluid applications. But it is also essential to be assured that productivity and overall economy are not affected while deriving the environmental benefits of Minimum Quantity Lubrication (MQL). Rather it is necessary to explore the possible technological benefits of such Minimum Quantity Lubrication (MQL) and optimise it for maximum overall socio-economic benefits.

## 1.2 Selection and Application of Cutting Fluids

Functions of cutting fluids used in machine shops are to control temperature (Primarily) through cooling and lubrication and to remove chips and metal fines (Secondarily) from tool-workpiece interface [**Aronson 1994**]. Thus the application of cutting fluids helps in improving the life and function of cutting tools and achieving the desired size, finish and shape of the workpiece [**Sluhan 1994**]. However, the use of cutting fluid generally causes economy of tools and it becomes easier to keep tight tolerances and to maintain workpiece surface properties without damages [**Sales, Diniz** and **Machado 2001**]. These are, therefore, the key factor in machine shop productivity and production of quality machined parts [**Aronson 1994; Sluhan 1994** and **Tuholski 1993**].

Choosing the right cutting fluid, for a particular operation, can be confusing and time consuming. To select a fluid for an application, advantages and disadvantages of cutting fluid products should be compared through review of product literature and usage history. However, the following factors should be considered when selecting the fluid [**Aronson 1994; Sluhan 1994; Bienkowski 1993** and **Lukas 1994**]:

i. Cost and life expectancy

ii. Fluid compatibility with work material and machine components

iii. Speed, feed and depth of cutting operation

iv. Type, hardness and microstructure of the metal being machined

v. Ease of fluid maintenance and quality control

vi. Ability to separate fluid from the work and cuttings

vii. The product's applicable temperature operating range

viii. Optimal concentration and $P^H$ ranges

ix. Storage practices

x. Ease of fluid recycling or disposal

Above all, during cutting fluid selection, benefits of a fluid's versatility should be weighed against its performance in each metal working application [**Aronson 1994;** and **State of Ohio EPA 1993**].

The most common cutting fluids used today belong to one of two categories based on their oil content [**Sluhan 1994** and **Bienkowski 1993**]:

i. **Oil-Based Cutting Fluids**- including straight oil and soluble oils

ii. **Chemical Cutting Fluids**- including synthetics and semisynthetics

Cutting fluids vary in suitability for metalworking operations. Petroleum-based cutting fluids are frequently used for drilling and tapping operations due to their excellent lubricity while water-miscible fluids provide the cooling properties required for most turning and grinding operations.

Straight oils, so called because they do not contain water, are basically petroleum or mineral oils. These oils may have additives designed to improve specific properties [**Aronson 1994** and **Tuholski 1993**]. Generally no additives are required for such easiest task as light-duty machining of ferrous and nonferrous metals [**Bienkowski 1993** and **Foltz**], whereas, for more severe applications i.e. heavy-duty operations, some wetting agents (typically up to 20% fatty oils) need to be added to coat the cutting tool, workpiece and metal fines [**Koelsch 1994**] and thus, improve ability of the oil to handle large amounts of metal fines and help guarding against microscopic welding in heavy-duty machining [**Foltz**]. However, straight oils offer good rust protection, extended sump life, easy maintenance and resistance to rancidity [**Bienkowski 1993**]. But the problems associated with application of these oils are of their poor heat dissipating properties and increased fire risk [**Bienkowski 1993** and **Foltz**] and consequently, their restriction to low-speed machining [**Aronson 1994**].

Soluble oils, also known water-soluble oils, are generally comprised of 60-90% petroleum or mineral oil, emulsifiers, and other additives [**Aronson 1994; Bienkowski 1993** and **IWRC 1990**]. These offer improved cooling capabilities and good lubrication due to blending of oil and water [**Koelsch 1994**] and suitable for light and medium duty operations involving the variety of ferrous and nonferrous application [**IWRC 1996**]. But the presence of water makes soluble oils more susceptible to rust control problems, bacterial growth and rancidity, tramp oil contamination and evaporation losses. Moreover, misting of soluble oils may produce a dirty and unsafe work environment, through slippery surfaces and inhalation hazards [**IWRC 1996**].

Chemical cutting fluids, called synthetic or semi-synthetic fluids, are stable, performed emulsions which contain very little oil and mix easily with water. Such type of cutting fluids relies on chemical agents for lubrication and friction reduction [**Bienkowski 1993**].

Synthetic fluids contain no petroleum and mineral oil [**Sluhan 1994** and **Foltz**] and generally consist of chemical lubricants and rust inhibitors dissolved in water. These fluids are designed for high cooling capacity, lubricity, corrosion prevention and easy maintenance [**IWRC 1996**] and make them able to handle heavy-duty grinding and cutting operations on tough, difficult-to-machine and high temperature alloys [**Sluhan 1994**]. Despite of the benefits offered, a number of health and safety concerns, such as misting and dermatitis, remain with the use of synthetics in the shop [**Bienkowski 1993**]. Synthetic fluids are also easily contaminated by other machine fluids such as lubricating oils and need to be monitored and maintained to be used effectively [**Aronson 1994** and **Koelsch 1994**].

Semi-synthetic fluids are essentially a hybrid of soluble oil and synthetics. These oils contain small dispersions of mineral oil, typically 2-30%, in a water-dilutable concentrate [**Aronson 1994; Bienkowski 1993** and **Oberg et al. 1992**]. Semi-synthetic fluids provide better control over rancidity and bacterial growth, generate less smoke and oil mist and have good corrosion protection [**IWRC 1996**]. However, the water hardness affects stability of semi-synthetics. These fluids may also cause misting, foaming and dermatitis.

Enormous efforts to reduce or eliminate the use of lubricant in metal cutting are, therefore, being made from the viewpoint of cost, ecological and human health issues [**Aronson 1995**; **Heisel et al. 1994**, **Honma et al. 1996** and **Klocke** and **Eisenblätter 1997**]. But with the need for high production machining, the control of cutting zone temperature is an important aspect of modern machining and grinding operations. Dry machining technologies and minimum quantity lubrication (MQL) which uses a fine spray of cooling medium are, therefore, being pursued as alternatives for conventional coolants. However, dry machining and MQL will only be acceptable on condition that the main tasks of coolants in machining processes can be successfully replaced. From viewpoints of Performance, cost, health, safety and environment, vegetable oils are, therefore, a viable alternative to petroleum-based metalworking cutting fluids [**Skerlos** and **Hayes 2003**; **Krahenbuhl 2005**], because

i. Vegetable oil, used in this experiment, has a viscosity at $40^0$C of 84 cP and flash point of $340^0$C (open cup), which are much higher than the reference values established in DIN 51562 & DIN EN ISO 2592 respectively.
ii. Molecules, being long, heavy, and dipolar in nature, create a dense homogeneous and strong lubricating film that gives the vegetable oil a greater capacity to absorb pressure.

iii. The lubricating film layer provided by vegetable oils, being intrinsically strong and lubricious, improves workpiece quality and overall process productivity reducing friction and heat generation.

iv. A higher flash point yields opportunities for increased rates of metal removal as a result of reduced smoke formation and fire hazard.

v. The higher boiling point and greater molecular weight of vegetable oil result in considerably less loss from vaporization and misting.

vi. Vegetable oils are nontoxic to the environment and biologically inert and do not produce significant organic disease and toxic effect.

vii. No sign and symptom of acute and chronic exposure to vegetable oil mist have been reported in human **[ACGIH 1991]**.

## 1.3 Selection of Cutting Tool

All cutting operations require tool materials that can withstand the difficult conditions produced during machining. There are primarily three problems all cutting tools face: wear at the cutting edge, heat generated during the cutting process and thermo-mechanical shock. Characteristics that allow tool materials to stand up to the cutting process include hardness, toughness, wear resistance, and chemical stability. In general, increased hardness improves wear resistance but is associated with decreased toughness. Depending on machining conditions and workpiece properties, different degrees of hardness or toughness are required.

High-speed steels (HSS) are important to discuss due to their extensive use in metal cutting and to demonstrate the need for ceramic tools. High-speed steels have the lowest hardness and highest fracture toughness of general use tools. The primary reason high-speed steel tools are not used more extensively is that they soften significantly at temperatures above 500°C, as shown in Fig.1.2. This softening behavior limits high-speed steels to relatively low cutting speeds on softer materials, and has caused the need for carbide and ceramic cutting tools that maintain hardness at elevated cutting temperatures.

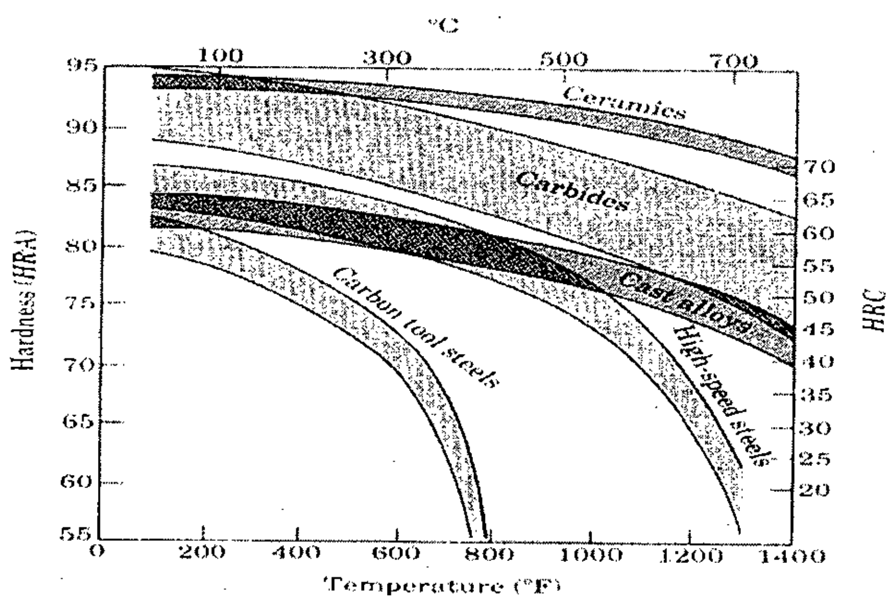



**Fig. 1.2** Hot Hardness of several cutting tool materials (**Kalpakjian 1997**)

Aluminum oxide ($Al_2O_3$) tools make up one of the most important classes of ceramic cutting materials. They have very high hardness and wear resistance, while also providing better chemical stability than carbides [**Kalpakjian 1997**]. $Al_2O_3$ based tools can be divided into two groups: white ceramics that consist of pure alumina mixed with 2% to 5% zirconia ($ZrO_2$), and black ceramics that add 30% to 40% TiC or TiN to alumina [**Edwards**

**1993**]. The zirconia in white ceramics is added to improve fracture toughness compared to pure alumina, without significantly compromising hardness and wear resistance. The TiC or TiN additions in black ceramics improve hot hardness of these tools compared to white ceramics, but at the expense of decreased fracture toughness. Thus, white ceramics can be used for more aggressive cutting conditions where impact loading or thermal shock may occur, while black ceramics are reserved for finishing conditions on hard work pieces where consistent mechanical and thermal loads are experienced. Despite their good chemical stability, high hot hardness and high wear resistance, pure oxide ($Al_2O_3$+$ZrO_2$) ceramic tools have not been effective in machining nickel-based alloys **[Ezugwu et al. 1999]** The poor performance of pure oxide ceramic tools can be attributed to their poor thermal shock resistance, low fracture toughness or low resistance to mechanical shock at elevated temperature. Moreover, tool life was severely limited by excessive notching at the depth of cut region via welding and pull-out, which may be caused by the relatively low mechanical toughness of ceramic tools [**Suh 1980**].

Sialons are materials based on silicon nitride ($Si_3N_4$), and are formed by sintering a mixture of $SiO_2$, $Al_2O_3$, $Si_3N_4$, $Y_2O_3$, and MgO powders. Sintering causes the $SiO_2$ to react with $Al_2O_3$ and $Y_2O_3$ to form a liquid that reacts with the $Si_3N_4$ to form silicon aluminum oxy-nitride. Due to chemical affinity, sialons diffuse rapidly into steels and are not suitable for cutting these alloys. However, they maintain hardness at very high temperatures, which makes them ideal for machining heat-resisting super alloys at high cutting speeds. They are capable of material removal rates 4 times higher than ceramic-coated carbide tools when used to machine super alloys [**Mehrotra 1998**].

Silicon nitride ($Si_3N_4$) can be used as a cutting tool, but does not sinter easily to full density. Additions are often made to assist sintering, but hot pressing is typically required to achieve good strength. Similar to sialon tools, diffusion into iron makes $Si_3N_4$ tools unsuitable for machining steels. They are generally restricted to grey cast iron and some nickel-based alloys [**Jack 1986**].

It has been possible to synthetically produce diamonds since 1958. Diamond particles are produced by heating carbon to approximately $1500^0$C and applying pressures of 6 GPa, much like the process to convert boron nitride from hexagonal to cubic form [**Edwards 1993**]. To form a cutting tool, 1-30 μm diamond particles are sintered at high temperature and pressure onto a cemented carbide base [**DeGarmo et al. 1988**]. The carbide base provides a ductile support for the hard and brittle diamond layer. This technique is also used often in the production of PCBN cutting tools. However, diamond tools exhibit excellent wear resistance in applications like machining high silicon content aluminum, but their performance on steel is poor. This is because the carbon that comprises diamond tools is a major alloy element in steels, so at the high interface temperatures that occur during machining, the very expensive diamond tools diffuse rapidly into the work piece.

Polycrystalline cubic boron nitride cutting tools have been developed to machine hard materials in applications where carbide tools do not maintain hardness at high cutting speeds and alumina based tools do not offer adequate toughness. The main advantages of CBN tools are that they maintain hardness even at very high temperatures [~1800 HV at 1000°C from **Tabuchi et al. 1978**], have low solubility in iron, and good fracture toughness for a ceramic [**Bossom 1990**]. That's why, ceramic materials with high hardness, in particular, cubic boron nitride (CBN), have been employed in machining hardened steel [**Tonshoff and Kaestner 1991** and **Naikai et al. 1991**]. Even though there have been reports of successful examples of using CBN tools for hard turning, the practices in the industry are still not widespread [**Chou 2003**]. Moreover, CBN tools are very expensive and justified for very special work materials and requirements where other tools are not effective.

Carbide tools were, therefore, developed in the 1930's to allow machining at higher cutting speeds (and increased production rates), [**Kalpakjian 1997**]. These tools now consume an estimated 70% of the machining market. Because the tools are typically pressed and sintered from ceramic powders (often with a cobalt binder material), they are sometimes called sintered carbides or cemented carbides. There are two basic subsets of carbide tools: tungsten carbide (WC) and titanium carbide (TiC), WC tools being the most prevalent.

Pure WC is very hard, but also brittle. To improve toughness, WC powder is mixed with 5-15% cobalt (weight percentage). Hardness and wear resistance can be improved by reducing the grain size of the WC particles, which are typically in the range of 0.5-5 μm [**Edwards 1993**]. However, an optimal grain size and cobalt percentage must be determined to allow the hardness and toughness required for a particular cutting operation.

# Chapter-2

## Literature Review

Until now, ample research and investigations have been done in different parts of the world on machinability of different materials mainly in respect of chip morphology, cutting forces, cutting temperature, chip tool interaction, dimensional accuracy, surface integrity and wear and life of cutting tool with and without (dry machining) using cutting fluid. Environmental pollution arising out of conventional cutting fluid applications has been a serious concern of the modern machining industries. Research has also been initiated on control of such pollution by MQL machining 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.

### 2.1 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 maximum 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 i) development of a work-hardened/abrasive oxide layer on the cut surface ii) formation of thermal cracks due to steep temperature gradient iii) presence of side-spread material at the edges of a newly cut surface and iv) fatigue of tool material due to cutting force fluctuations at the free surface caused by lateral motions of the edges of the chip.

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

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

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

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

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

The high specific energy required in machining under high cutting velocity and unfavorable condition of machining results in very high temperature which reduces the dimensional accuracy and tool life by plastic deformation and rapid wear of the cutting points **[Chattopadhyay and Bhattacharya 1968; Chattopadhyay** and **Chattopadhyay 1982** and **Singh et al. 1997]**. On the other hand such high temperature, if not controlled, impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, micro cracks and subsurface cracks. This problem is further intensified while machining for faster material removal in bulk and finishing very hard, strong and difficult-to-machine materials, which 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 addition, 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 the high cutting temperature is controlled by profuse cooling [**Alaxender et al. 1998; Kurimoto** and **Barroe 1982** and **Wrethin et** al. **1992**]. 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 **[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 Rebinder effect) seemed to be negligible when steel jobs are machined at moderate cutting speeds with carbide tools [**Kurimoto** and **Barroe 1982**]. The influence of the electric current flowing through the cutting zone on the rate of tool wear is also well known [**Ellis** and **Barrow 1969**]. However, most commercial cutting fluids are non electro-conductive, and as such the situation with respect to current flow will not vary significantly from the dry cutting case. The electrochemical action is treated as a corrosion phenomenon in respect of tool wear.

The machining temperature could be reduced to some extent by improving the machinability characteristics of the work material metallurgically, optimizing the tool geometry and by proper selection of the process parameters [**Muraka 1979; Dieter 1981** and **Jawahir 1988**]. Some recent techniques have enabled partial control of the machining temperature by using heat resistance tools like coated carbides, CBN etc. The thermal deterioration of the cutting tools can be reduced [**Narutaki** and **Yamane 1979**] by using CBN tools. 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 makes no contribution to wear resistance of the tool, especially at the flanks. It was reported [**Alaxender et al. 1998**] that coolant injection offers better cutting performance in terms of surface finish, tool force and tool wear when compared to flood cooling.

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 bar) 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$^{O}$C). 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.

## 2.2 Adverse Effects of Conventional Cutting Fluid

### 2.2.1 Technological Problems

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**].

### 2.2.2 Environmental Problems

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**]:

i. environmental pollution due to breakdown of the cutting fluids into harmful gases at high cutting temperature (Fig 2.1),

ii. biological hazards to the operators from the bacterial growth in the cutting fluids

iii. requirements of additional systems for pumping, local storage, filtration, temporary recycling, cooling and large space requirement

iv. disposal of the spent cutting fluids, which also offer high risk of water pollution and soil contamination.

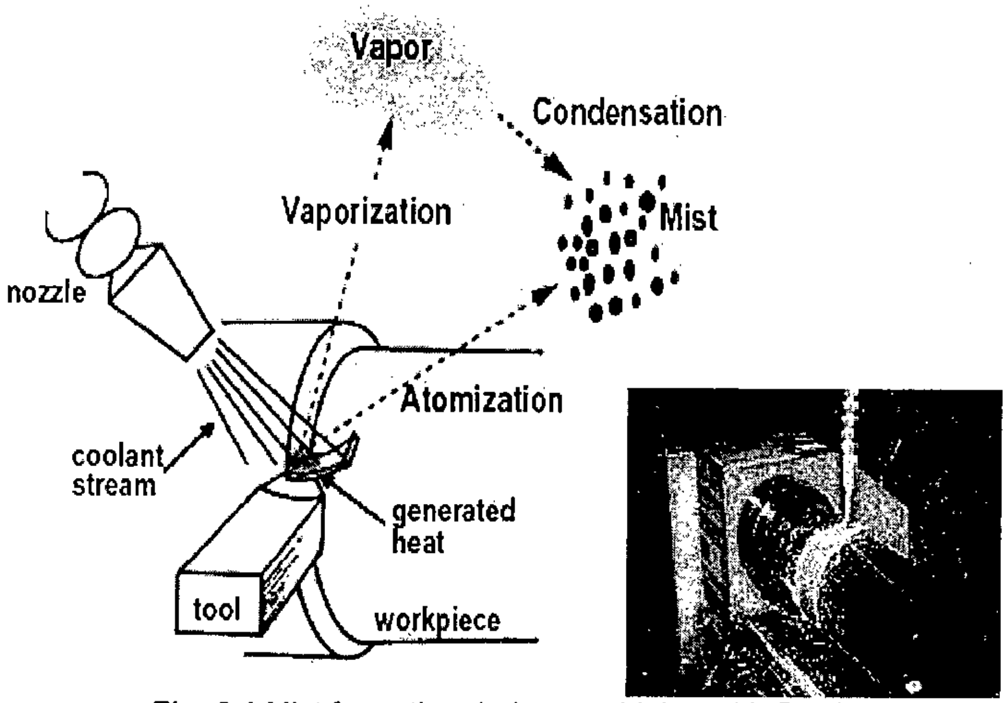



**Fig. 2.1** Mist formation during machining with flood cooling

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 cutting 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 are carcinogenic [**Peter et al.1996**]. Basically, workers are exposed to metal cutting fluids via three routes [**Bennett et al. 1985**]; skin exposure, aerial exposure and ingestion.

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

Iowa Waste Reduction Centre (**1996**) reported that besides potential skin and eye contact, inhalation is also a way to occupational exposure. Mists are aerosols comprised of liquid particles (less than 20 µm). During machining process, a considerable amount of heat is generated for which the cutting fluid may attain a temperature sufficiently higher than the saturation temperature. The vapor is produced at the solid-liquid interface as a result of boiling. Vapour may be generated also at the liquid-air interface when the fluid vapour pressure is less than the saturation pressure, namely as evaporation phenomena. Vapour generated then may condense to form mist. The non-aqueous components of the cutting fluid, such as the biocide additives, appear as fine aerosol that can enter the workroom air. Additionally, the cutting fluids impact with both stationary and rotating elements within the machine tool system, which leads to mechanical energy being transmitted to the fluid. Thus, the cutting fluid has higher surface energy and becomes less stable and disintegrates into drops (atomization). The spray from the fluid application also may generate mist. A total fluid loss of 5 to 20 percent may occur due to evaporation, atomization, splashing and 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 particulates below 2.5 µm aerodynamic diameter deposit primarily in the alveolar regions, which is the most sensitive region of lung. The particulates in size ranging from 2.5 μm to 10.0 μm deposit primarily in the air-ways. The potential health effects of exposure to cutting fluid mists have been the subjects of epidemiological studies in the automotive industry. The mist droplets can cause throat, pancreas, rectum, and prostate cancers, as well as breathing problems and respiratory illnesses. One acute effect observed is mild and reversible narrowing of airways during exposure to cutting fluid mist [**Kennedy 1989**].

Several other epidemiological studies have also suggested that exposure to fluid mist may be associated with increased risk of airway irritation, chronic bronchitis, asthma and even laryngeal cancer [**Bennett et al. 1985** and **Eisen et al. 1994**]. The Occupational Safety and Health Administrations (OSHA) standard for airborne particulate (largely due to fluid mist) is 5 $mg/m^3$, and the United Auto Workers (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**].

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

### 2.2.3 Economical Aspects

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

## 2.3 Mechanisms of Tool Wear

Metal cutting causes several types of wear mechanisms depending on cutting parameters (primarily cutting speed), workpiece material, and cutting tool material. Like most wear applications, tool wear has proved difficult to understand and predict. However, most tool wear can be described by a few mechanisms, which include: abrasion, adhesion, chemical reaction, plastic deformation, and fracture.

These mechanisms produce wear scars that are referred to as flank wear, crater wear, notch wear, and edge chipping, as illustrated in Fig.2.2. Abrasive wear results from sliding of hard abrasive inclusions in the workpiece material across the face of a cutting tool. This mechanism can dominate when machining metals with carbide or oxide inclusions, metal matrix composites, carbides, and ceramics. Adhesion results from friction welding of the workpiece and tool material, which can cause portions of the cutting tool to be plucked out. Anisotropic properties of ceramics can cause cracking along grain boundaries that assists grain pluck out **[Sibold 1991]**. Some amount of abrasive and adhesive wear is desired to allow gradual tool wear and prevent premature tool fracture or chipping of the cutting edge **[Mehrotra 1998]**. Chemical reactions between the cutting tool and workpiece (or environment) can also lead to accelerated tool wear or premature tool fracture. A good example is cutting steel with polycrystalline diamond tools, where diffusion of carbon into the steel dramatically decreases tool life. Plastic deformation can also shorten tool life, but this is rarely a problem for ceramics. Finally, aggressive cutting conditions can yield excessive mechanical and thermal loads and cause chipping or fracture.

In comparison to steel cutting tools, ceramics offer the advantages of increased resistance to abrasion due to increased hardness, improved chemical stability, better hardness retention at the elevated temperatures typical in metal cutting, and superior heat dispersal during cutting **[Adams 1991** and **Amin 1991]**. The biggest limitation of ceramic cutting tools is low fracture toughness. To compensate for the brittle nature of ceramic tools, strong cutting geometries are required. Large nose radii and wedge angles are used to improve the strength of cutting edges, as are honed or chamfered cutting edges (Fig.2.3). Even with strong tool geometries, ceramic tools can fracture prematurely if aggressive or interrupted cuts are made, machine vibration is excessive, or thermal shock occurs. By eliminating or reducing these problems, ceramic tools can achieve adequate tool life and yield improved material removal rates.

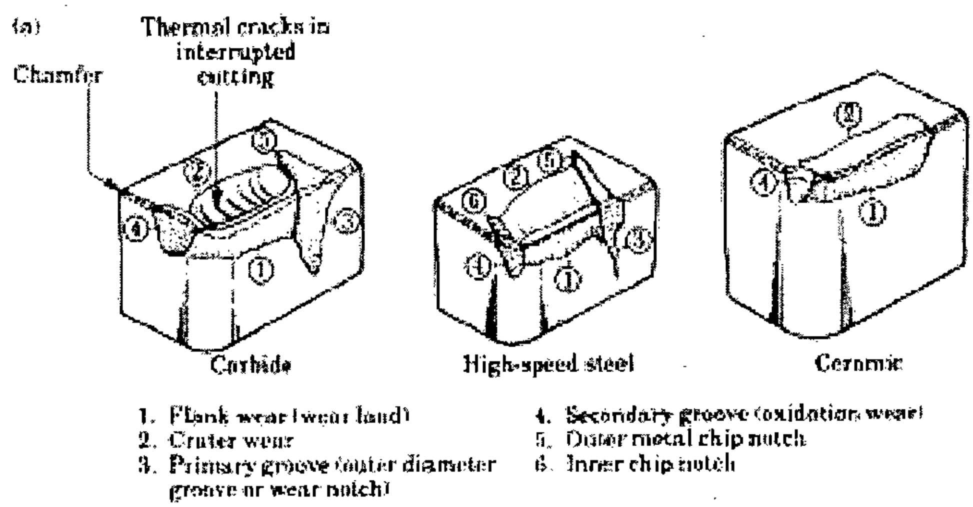



**Fig.2.2** Tool wear mechanisms **[Kalpakjian 1997]**

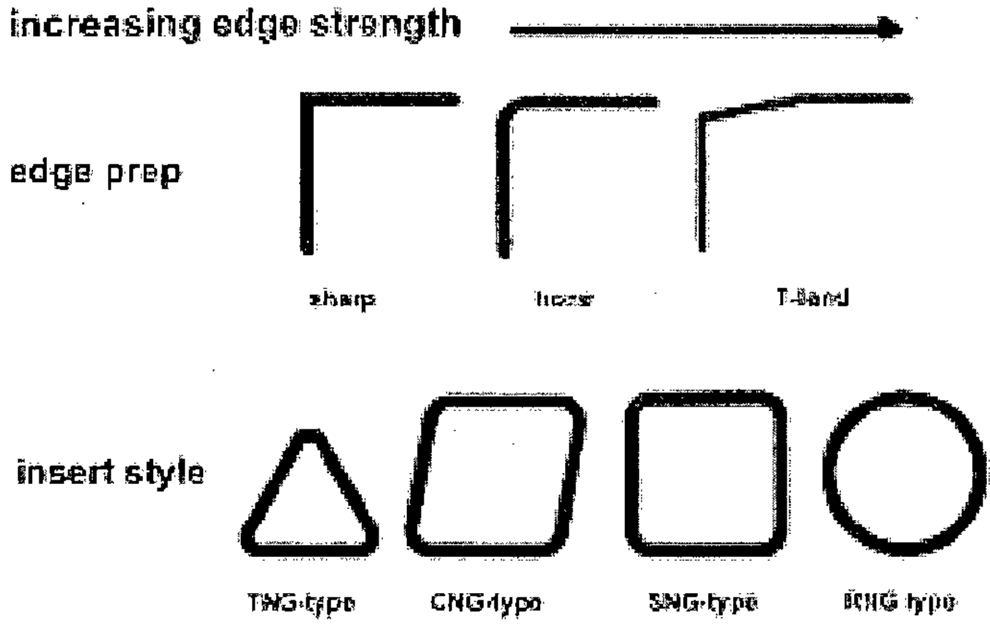



**Fig. 2.3** Insert geometries **[Mehrotra 1998]**

However, turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears. In general, wear due to adhesion, diffusion and oxidation are known to occur, but especially abrasion and attrition (adhesion) between the tool and the workpiece, as well as between the tool and the chip formed, for the case of machining of steel using carbide tools **[Ezugwu and Wang 1996; Wang 1997; Ezugwu and Machado 1988]**. With the progress of machining the tools attain crater wear at the rake surface and flank wear (on the major and minor flank of a tool) at the clearance surfaces due to continuous interaction and rubbing with the chips and the work surfaces, respectively **[Dhar et al. 2002]**. Among the aforesaid wears, the principal flank wear is the most important because principal flank wear generally causes an increase in the cutting force and the interfacial temperature, leading normally to dimensional inaccuracy in the workpieces machined and to vibration, which makes the cutting operation less efficient. Crater wear takes place on the rake face of the tool where the chip moves over the tool surface. A crater is usually formed at some distance from the cutting edge and it is most frequently observed when cutting steels and other high-melting-point metals at relatively high cutting speeds [**Trent 1979**]. This crater gradually becomes deeper with time and may lead to the breakage of the cutting edge, rendering the tool useless.

## 2.4 Methods and Effects of MQL in Machining

The use of cutting fluids in metal machining has long been considered to yield longer tool-life, better surface finish, greater part accuracy and improved chip control. Besides that, in some operations such as drilling, for example, cutting fluid is important to remove the chips from inside the holes, thus preventing drill breakage [**Klocke** and **Eisenblätter 1997** and **Derflinger et al. 1999**]. It is, therefore, important to find a way to accomplish machining processes without or with little cutting fluid and, at the same time, promoting long tool life and good workpiece quality. To reach this goal, it is necessary to find the suitable cutting conditions and also to develop new tool materials with lower friction coefficient and high heat resistance. Moreover, sometimes, the costs of tools may increase with the use of minimum lubrication, due to the increase of tool wear, even though the overall manufacturing cost may be lower when compared to the costs of using high amount of soluble oil in the processes [**Heisel et al. 1998** and **Kalhöfer 1997**].

Two techniques have been proven successful in minimizing the use of cutting fluids in machining processes. The first one is dry cutting or cutting with no fluid [**Lugscheider et al. 1997** and **Granger**]. For this to be possible without causing a large decrease in tool life and loss of workpiece quality, it is mandatory to have suitable tool materials and cutting conditions. Hard coatings of tool materials, including diamond coating, have been used to accomplish this purpose [**Machado** and **Wallbank 1997; Chiesa et al. 1995** and **Coelho et al. 1995**]. The optimization of cutting conditions to make them more suitable for dry cutting is done through the increase of feed and decrease of cutting speed. With this, roughly the same amount of heat is generated, but the area of the tool, which receives this heat, is bigger, making the temperature lower and the amount of chip removed per minute constant (without increasing cutting time). This action may damage the workpiece surface finish due to the increase of the feed. Therefore, it is also necessary to increase the tool nose radius in order to keep the surface roughness at the same level [**Klocke** and **Eisenblätter 1997**].

In those processes where dry cutting is either not possible or not economical, a second technique, minimum quantity of lubrication (MQL), can be tried to reach the goal of minimizing the amount of cutting fluid in machining process. This name is given to the process of pulverizing a very small amount of oil (50-500 ml/h) in a flow of compressed air. Some good results have been obtained with this technique [**Dhar** and **Islam 2005**; **Dhar**

**et al. 2004; Coelho et al. 1995; Tönshoff** and **Spintig 1994** and **Ferraresi 1974**]. Lugscheider et al. [**1997**] used this technique in the reaming process of gray cast iron (GG25) and aluminum alloy (AlSi12) with coated carbide tools and concluded that it caused a reduction of tool wear when compared to the completely dry process and, consequently, an improvement in the surface quality of the holes. The drilling of aluminum–silicon alloys is a process where dry cutting is impossible [**Derflinger et al. 1999**], due to the high ductility of the workpiece material. Without cooling and lubrication, the chip sticks to the tool and breaks it in a very short time during cutting.

However, Near-dry machining involving the use of minimum quantity lubricants (MQL) and dry machining applications are continuing to grow due to following reasons:

i. High cost of cutting fluids, ranging 7-16% of manufacturing cost, which in many cases is even higher than the tool cost [**Derflinger et al. 1999; Heisel et al. 1998** and **Kalhöfer 1997**]
ii. Health and environmental issues - Personal health, safety hazards, waste disposal, chip recycling, etc. [**Heisel et al. 1998** and **Kalhöfer 1997**]
iii. Continued innovation in cutting tool development involving advanced cutting tool materials and coatings [**Machado and Wallbank 1997; Chiesa et al. 1995** and **Coelho et al. 1995**]

### 2.4.1 Selection of Cutting Fluids for MQL Machining

For the low-emitting metal working with minimum quantity lubrication, the correct selection of the cutting fluid/lubricant is of decisive importance. In order to minimize emissions, cutting fluids/lubricants, which are toxicologically and dermatologically safe, should be applied, while having favorable lubricating properties and a high thermal stress capacity. Synthetic ester oils and fatty alcohols with low evaporation characteristics, being toxicologically harmless and with a high flash point have particularly proven themselves in practice [**Sefrin 1999; Freiler 1997**]

As reference values [**Freiler 1997** and **Sefrin 2000**] for the selection of a low emitting cutting fluid/lubricant, in particular flash point (DIN EN ISO 2592) as well as the Noack evaporation loss at 250°C (DIN 51581 T 01) are proven. The cutting fluid/lubricant should have a flash point of at least 150°C, an evaporation loss at 250°C of max. 65 % as well as a viscosity at 40°C (DIN 51562) of > 10 mm²/s.

**Table 2.1:** Reference values for the selection of a low emitting cutting fluid/lubricant

| Viscosity at 40°C [DIN 51562] [mm²/s] | Flash point open cup [DIN EN ISO 2592] [°C] | Noack evaporation loss 250°C [DIN 51581 T 01] [%] |
|---|---|---|
| > 10 | >150 | <65 |

However, fluids not applied for the minimum quantity lubrication [**Stäbler et al. 2003; Sefrin 1999** and **Hörner 1997**] are:

i. water mixed cooling lubricants and their concentrates

ii. lubricants with organic chlorine or zinc containing additives

iii. lubricants, which have to be marked according to the Decree on Hazardous Materials

iv. products basing on mineral base oils in the cooling lubricant > 3 ppm benzpyrene

### 2.4.2 Minimal Quantity of Cutting Fluid Application

The characteristic of the 'minimal quantity' application is to substitute all the effects of the coolant lubricant by using jet application to produce effects of equal values. Only a small amount of lubricant is needed if it is efficiently applied to the cutting zone. This lubricant is completely used and results in almost dry chips. However, all the effects provided by the usual cutting fluid flood-type lubricant are not possible with minimal quantity application or dry cutting alone. For example, the flushing effect is not supplied and the cooling effect is partially or not at all (with dry cutting) obtained. Then, additional use of minimum cooling system of the workpiece and a specially adapted blow-out technology for chip removal are required. Nevertheless, the results obtained with minimum quantities of cutting fluid application in drilling are excellent compared to the usual flood-type application, **[Popke et al., 1999]**. The 'minimal quantity' lubrication is a suitable alternative for economically and environmentally compatible production. It combines the functionality of cooling lubrication with an extremely low consumption of lubricant and therefore it has the potential to close the gap between overflow lubrication and dry cutting **[Brinksmeier et al., 1999]**.

Machado and Wallbank [1997] conducted experiments on turning medium carbon steel (AISI1040) using a Venturi to mix compressed air (the air pressure was of 2.3 bar) with small quantities of a liquid lubricant, water or soluble oil (the mean flow rate was between 3 and 5 ml/min). The mixture was directed onto the rake face of a carbide tool against the chip flow direction. The application of a mixture of air + soluble oil was able to reduce the consumption of cutting fluid, but it promoted a mist in the environment with problems of odours, bacteria and fungi growth of the overhead flooding system. For this reason, the mixture of air + water was preferred. However, even if the obtained results were encouraging, the system needed yet some development to achieve the required effects in terms of cutting forces, temperatures, tool life and surface finish.

In contrast, Varadarajan et al. [2002] developed alternative test equipment for injecting the fluid and used it with success in hard turning for which a large supply of cutting fluid is the normal practice. The test equipment consisted of a fuel pump generally used for diesel fuel injection in truck engines coupled to a variable electric drive. A high-speed electrical mixing chamber facilitated thorough emulsification. The test equipment permitted the independent variation of the injection pressure, the frequency of injection and the rate of injection. The investigations performed by the authors revealed that a coolant-rich (60%) lubricant fluid with minimal additives was the ideal formulation. During hard turning of an AISI 4340 hardened steel of 46HRC (460 HV), the optimum levels for the fluid delivery parameters were: a rate of 2 ml/min, a pressure of 20 MPa and a high pulsing rate of 600 pulses/min. In comparison, for the same cutting conditions, with dry cutting and wet cutting, the minimum quantity of cutting fluid method has led to lower cutting forces, temperatures, better surface finish, longer tool life. In addition, it was observed that tightly coiled chips were formed during wet turning and during minimal application, while long snarled chips were prevalent during dry turning. It must be noted that during minimal application, the rate of fluid was only 0.05% of that used during wet turning. The major part of the fluid used during minimal quantity application was evaporated; the remnant was carried out by work and chips and was too low in volume to cause contamination of the environment.

The paper of Klocke and Eisenblätter [**1997**] deals with drilling tests using minimum cooling lubrication systems, which are based on atomising the lubricant directly to the cutting zone. Small quantities of lubricant, in order of 10–50 ml/h, were mixed with compressed air for an external feeding via a nozzle or for internal feeding via spindle and tool. Internal feed systems with their ability to deliver the mixture very close to the drill–workpiece contact point may achieve very good results in terms of surface finish and tool life.

Lahres et al. [**1999**] presented dry machining of synchronizing cones for automotive application. The work material was austenitic 22Mn6 steel. In the first step of their study, dry machining was compared to machining with coolant and with minimal lubricant system. The used minimal lubricant system worked with special oil, which had food-grade quality. The air volume flow was about 50 l/min and the air volume oil was about 20 ml/h; hence, the produced chips were dry after leaving the contact zone of the cutting process. At this oil volume flow, a single chip can carry a maximum of 1 ml. Therefore, the chips could be declared as being almost dry and passed for metallic recycling without further treatment. The results exhibited an advantage for the minimal lubricant technique and for the dry machining.

In the second step, they **[Lahres et al. 1999]** investigated new tool coatings with a potential for dry machining: $TiAlNO_x$, TiAlN + $MoS_2$, single layer (Ti,Al)N and multilayer TiN + TiAlN. A new series of experiments were performed under minimal lubrication. The best performance was obtained with the double layer TiAlN + $MoS_2$ coating. Metallographic studies indicated that the solid lubricant $MoS_2$ is worn after a few machined parts. However, a small amount of solid lubricant exists further in the valleys of the tool surface profile and initiates a low friction at the tool–chip interface. Nevertheless, a small amount of solid lubricant exists perhaps also on the machined surface; this pollution is a problem for the aerospace components.

The $TiAlNO_x$ consists of two layers: the first layer on top of the substrate surface is a thick TiAlN-coating necessary to achieve good adhesion, the second is a thin $Al_2O_3$-coating used to reduce oxidation and wear. The performance of this coating was almost as good as the one of

$TiAlN + MoS_2$ - coating.

Wakabayashi et al. [**1998**], by model experiments, suggested that ester supplied onto a rake face of a tool decomposes to carboxylic acid and alcohol and its carboxylic acid forms a chemisorbed film with lubricity. In actual conditions with high machining load, however, existence of this kind of boundary film is uncertain [**Itoigawa et al. 2005**]. Therefore an investigation into the lubrication mechanism of MQL in actual conditions must be essential.

However, the concept of minimum quantity lubrication (MQL) presents itself as a possible solution for machining in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, provided that the MQL parameters can be strategically tuned.

## 2.5 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 application of cutting fluids helps in improving the life and function of cutting tools and in achieving the desired size, finish and shape of the workpiece. But the conventional types and methods of application of cutting fluid have been found to become less effective with the increase in cutting velocity and feed when the cutting fluid cannot properly enter the chip-tool interface to cool and lubricate due to bulk plastic contact of the chip with the tool rake surface. Further the use of conventional cutting fluid generally causes economy of tools and is not environment friendly as well.

Enormous efforts are, therefore, being made from the viewpoint of cost, technological and ecological issues to reduce or eliminate the use of cutting fluid or lubricant in metal cutting. In this context, minimum quantity lubrication (MQL) which uses a fine spray of cooling medium like soluble and vegetable oils appears to be a promising technique for effective cooling without the problems associated with conventional cutting fluid applications. However, MQL will only be acceptable on condition that the main tasks of coolants in machining processes can be successfully replaced. Keeping all these in mind, the performance and effectiveness of MQL by vegetable oil on machining a selected Ni-Cr steel have been investigated over both dry and wet machining in terms of heat, tool wear and dimensional deviation reduction, tool life increment and machined surface protection.

# Chapter-3

## *Objectives of the Present Work*

It is revealed from the aforesaid literature survey that MQL can substantially control the cutting temperature as compared to dry and wet machining, 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 been done systematically yet in this direction.

The main objective of the present work is to make a thorough and systematic experimental investigation on the roles of minimum quantity lubrication (MQL) by vegetable oil-based cutting fluid on the major machinability characteristics in respect of

i. chip tool interface temperature

ii. chip color and shape

iii. chip reduction coefficient

iv. tool wear and tool condition and

v. surface roughness

in turning alloy steel (AISI 9310 steel) by the industrially used uncoated carbide tool (SNMG 120408 TTS) at different cutting velocities and feeds combinations. The results are being expected to enable optimisation of the MQL process and machining conditions.

The scopes of the present work are

(a) Design and fabrication of a

i. MQL machining set up

ii. suitable nozzle for MQL jet and

iii. tool work thermocouple for measuring chip tool interface temperature

(b) Analysis of data by

i. measuring chip tool interface temperature

ii. observing chip shape, color and measuring chip reduction co-efficient ($\zeta$)

iii. measuring tool wear (flank wear) under microscope

iv. monitoring pattern and extent of tool wear under Scanning Electronic Microscope (SEM)

v. measuring surface roughness

# Chapter-4

## *Design and Fabrication of MQL System*

### 4.1 Introduction

The use of cutting fluids in metal machining has long been considered to yield longer tool-life, better surface finish, greater part accuracy and improved chip control. Besides that, in some operations such as drilling, for example, cutting fluid is important to remove the chips from inside the holes, thus preventing drill breakage. It is, therefore, important to find a way to accomplish machining processes without or with little cutting fluid and, at the same time, promoting long tool life and good workpiece quality.

Two techniques have been proven successful in minimizing the use of cutting fluids in machining processes. The first one is dry cutting or cutting with no fluid. But, in those processes where dry cutting is either not possible or not economical, a second technique, called minimum quantity of lubrication (MQL) can be tried to reach the goal of minimizing the amount of cutting fluid in machining process.

The characteristic of the 'minimal quantity' application is to substitute all the effects of the coolant lubricant by using jet application to produce effects of equal values. Only a small amount of lubricant is needed if it is efficiently applied to the cutting zone. This lubricant is completely used and results in almost dry chips. However, all the effects provided by the usual cutting fluid flood-type lubricant are not possible with minimal quantity application or dry cutting alone. For example, the flushing effect is not supplied and the cooling effect is partially or not at all (with dry cutting) obtained. Then, additional use of minimum cooling system of the workpiece and a specially adapted blow-out technology for chip removal are required.

Besides, the 'minimal quantity' lubrication is a suitable and proven alternative for economically and environmentally compatible production. It combines the functionality of cooling lubrication with an extremely low consumption of lubricant and therefore it has the potential to close the gap between overflow lubrication and dry cutting.

However, 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:

i. effective cooling by enabling MQL jet reach as close to the actual hot zones as possible

ii. avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes

iii. minimum consumption of cutting fluid by pin-pointed impingement and only during chip formation

## 4.2 Design and Fabrication of the MQL System

Minimum quantity lubrication (MQL) refers to the use of cutting fluids of only a minute amount-typically of a flow rate of 50 to 500 ml/hour-which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition, where, for example, up to 10 liters of fluid can be dispensed per minute.

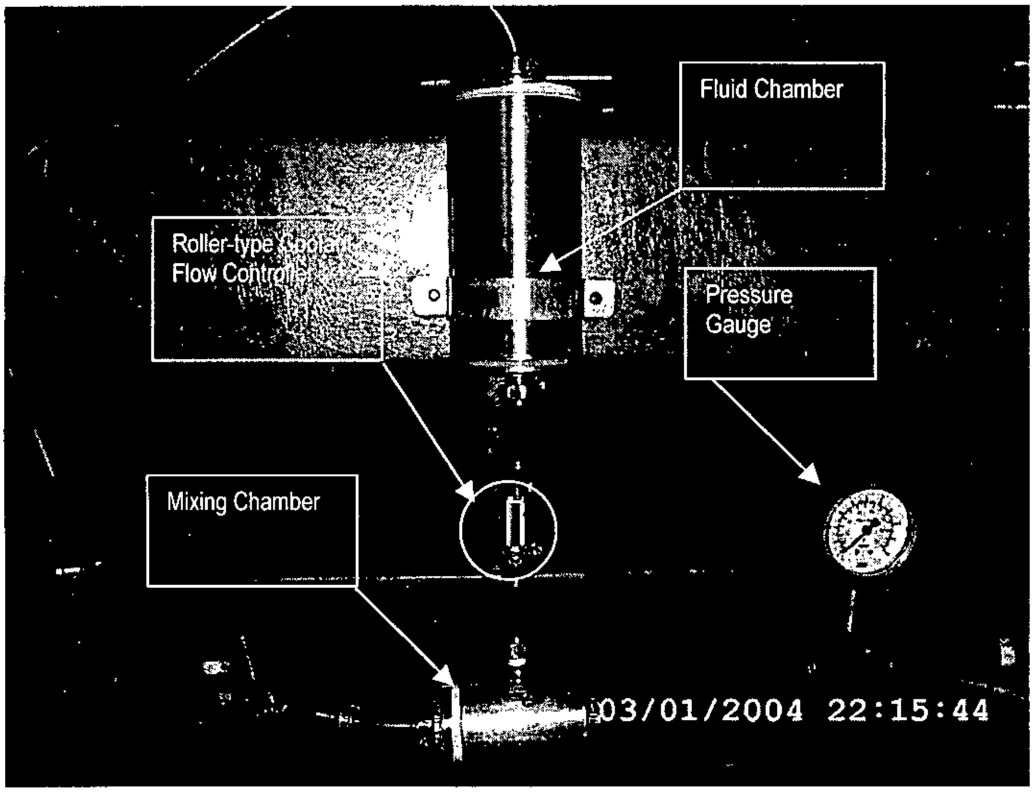



**Fig 4.1** Photographic view of the MQL Applicator

However, the MQL needs to supply at high pressure and impinged at high speed through the nozzle at the cutting zone. Considering the conditions required for the present research work and uninterrupted supply of MQL at constant pressure around 6 bar over a reasonably long cut; a MQL applicator has been designed, fabricated and used. The photographic view of the MQL applicator is shown in Fig 4.1.

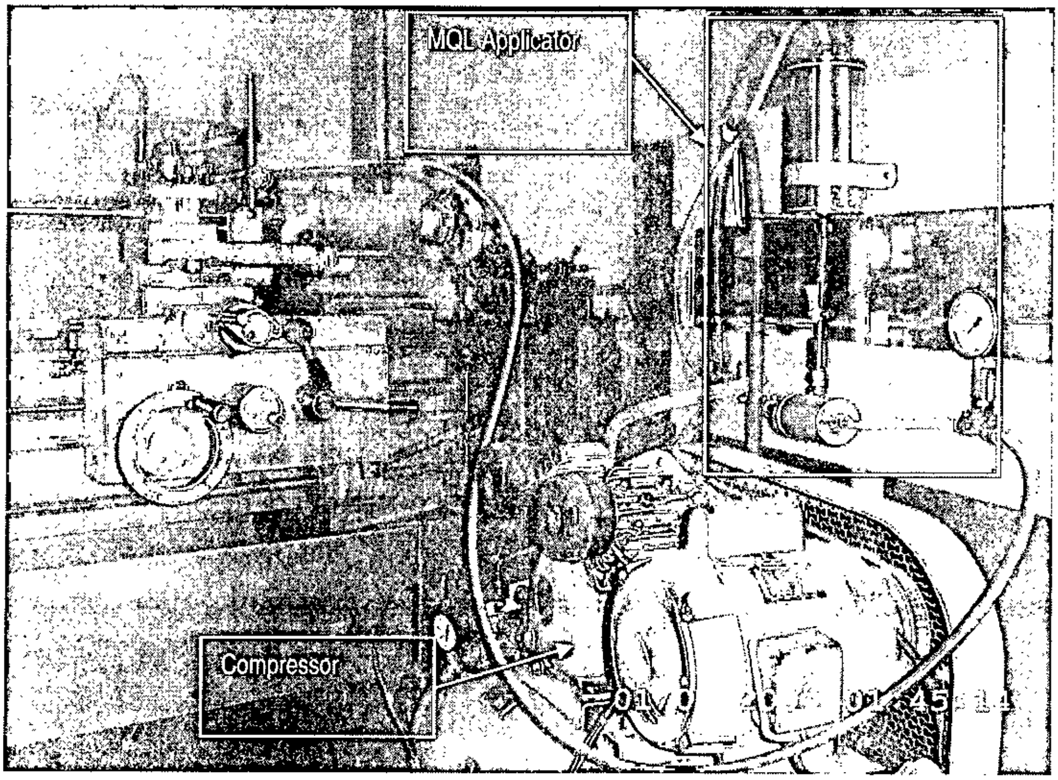



**Fig 4.2** Photographic view of the experimental set-up

The MQL system has two major components: Compressor and MQL applicator. Compressor used in this system acts as air supply unit and is able to develop a maximum pressure of 10 bar. However, the main purpose of the compressor is to supply air at a pressure, which is required to set in the different components of MQL applicator. MQL applicator consists of three such components as fluid chamber, mixing chamber and a nozzle.

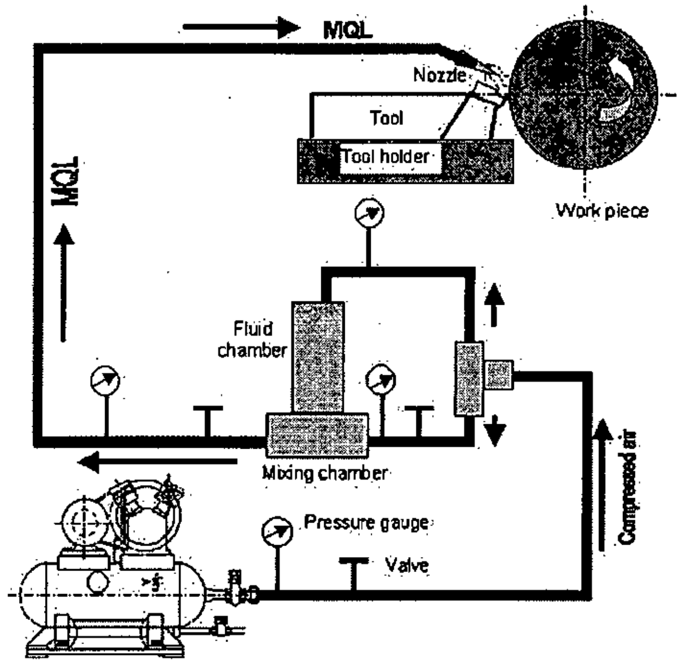



**Fig 4.3** Schematic views of the Experimental Set-up

The fluid chamber is used only to contain the cutting fluid selected for a particular machining. It has an inlet port and an outlet port at the top and the bottom respectively. It is connected to the compressor by a flexible pipe through the inlet port to keep the fluid inside chamber under a constant pressure of 10 bar. It is required to maintain the flow of cutting fluid into the mixing chamber at constant rate over a long period of time during machining. However, based on our research requirement, fluid chamber has been designed with capacity of one litre (1000 ml) so as to able to supply the cutting fluid continuously for five hours during machining at a flow rate of 200 ml/hr.

Mixing chamber, having two inlet ports and an outlet port, is connected with both the compressor by a flexible pipe at one inlet port which is inline with its outlet port and the fluid chamber at another inlet port at the top by a flexible tube that is very small in diameter. High-pressure air from the compressor enters into this chamber and mix with the minimum quantity of cutting fluid coming out from fluid chamber at a constant rate. This is worth mentioning that sudden expansion at the inlet port and contraction at the outlet port of the mixing chamber results in turbulence in the air-flow and ensures complete or proper mixing of air with cutting fluid in the chamber.

Nozzle, an important part of the MQL system, is connected to the mixing chamber by a long flexible pipe. It is located at the tip of the cutting tool along the auxiliary cutting edge making an angle $15^0$ with it using a magnetic stand.

## 4.3 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 auxiliary cutting edge of the tool are shown in Fig.4.5 and Fig.4.4 respectably.

The nozzle having bore diameter reduction ratio, i.e. inlet diameter to outlet diameter, 6:1 is attached to the tool post with a magnetic stand and is connected with flexible pipe to supply MQL in the form of jets to the chip-tool and work-tool interfaces of the cutting zone along auxiliary cutting edge. 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:

i. less interference with the flowing chips

ii. high speed MQL jet reaching quite close to the chip-tool contact zone

iii. simple and low cost.

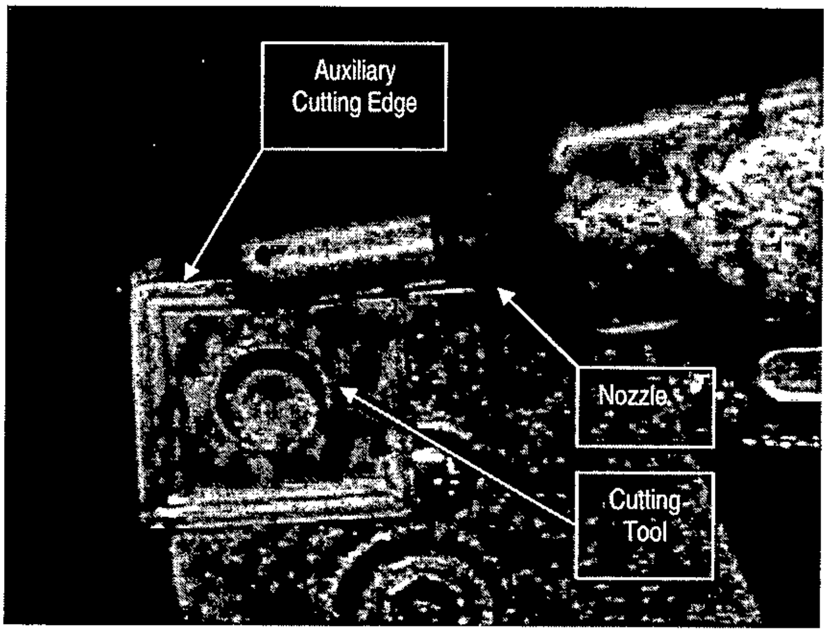



**Fig. 4.4** Photographic view of the nozzle used for MQL delivery at the cutting zone

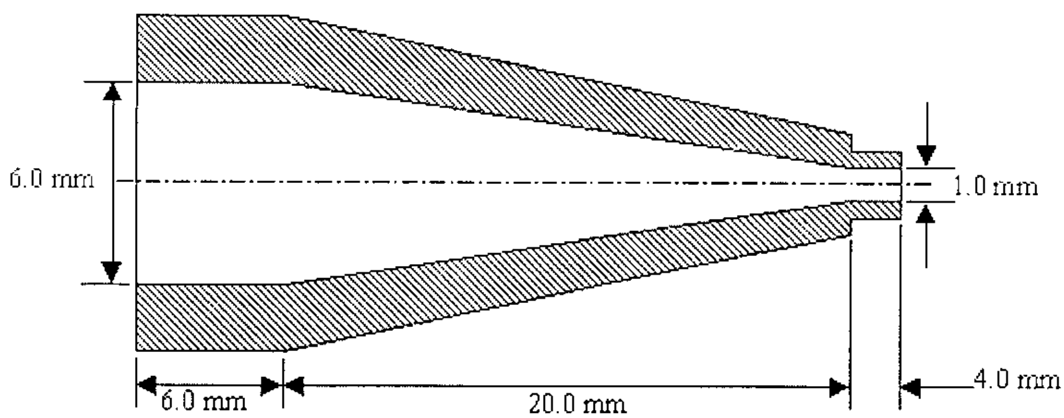



**Fig.4.5** Schematic view of the nozzle used for MQL delivery.

## 4.4 Working Principle of MQL System

In this system, a compressor is used to supply air at a high-pressure of 10 bar. This high-pressure air from the compressor enters into two chambers i.e. fluid chamber and mixing chamber at two different but pre-selected pressures of 10 bar and 6 bar respectively. The fluid chamber is connected at the bottom with the mixing chamber by very small diameter flexible tube. This tube is passed through a roller-type flow controller to permit a little amount of fluid to flow under high pressure. The compressed air entering into the inlet port creates pressure to cause the fluid to flow continuously to the mixing chamber through controller at a constant rate. The air and the vegetable oil are mixed in the mixing chamber so that the mixture of vegetable oil and air is impinged at a high velocity through the nozzle at the chip-tool interface. The photographic and schematic views of the experimental set-up are shown in Fig 4.2 and Fig 4.3 respectively. During experimentation the thin but high velocity stream of MQL is to be projected along the auxiliary cutting edge of the insert, so that the coolant reaches as close to the chip-tool and the work-tool interfaces as possible.

# Chapter-5

## Experimental Investigations

### 5.1 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:

i. ineffectiveness in desired cooling and lubrication
ii. health hazards due to generation of obnoxious gases and bacterial growth
iii. inconvenience due to uncleanliness of the working zone
iv. corrosion and contamination of the lubricating system of the machine tools

v. need of storage, additional floor space, pumping system, recycling and disposal

vi. 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:

i. effective cooling by enabling MQL jet reach as close to the actual hot zones as possible

ii. avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes

iii. minimum consumption of cutting fluid by pin-pointed impingement and only during chip formation

## 5.2 Experimental Procedure and Conditions

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

The machining tests have been carried out by straight turning of AISI 9310 steel in a rigid and reasonably powerful lathe (15 hp/11kW, France) by standard uncoated carbide inserts 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 9310 steel has been undertaken for the present investigations. The compositions, strength, hardness and industrial use of this steel are given in Table 5.1.

**Table 5.1** Characteristics of the used steel

| Work material | BHN | Chemical composition (wt %) | Applications |
|---|---|---|---|
| AISI 9310 steel | 257 | C-0.12%, Mn-0.55%,<br>P-0.025%, S-0.025%,<br>Si-0.25%, Cr-1.3%,<br>Ni-3.4%, Mo-0.14%o | • Shafts & crank shafts<br>• Automobile axles<br>• high strength studs and bolts<br>• 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 stabilized 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 the modern industries. But such tools are not only expensive but also require very rugged and powerful machine tools, which common industries cannot always afford. Diamond tools **[Hinterman** and **Chattopadhyay 1993**] are excellent performing for exotic materials excepting ferrous metals which 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 a standard tool configuration namely SNMG 120408 (SANDVICK) has been undertaken for the present investigation. The inserts were clamped in a PSBNR 2525 M12 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.4.4. During experimentation, the thin but high velocity stream of MQL was directed along the auxiliary cutting edge of the insert, so that the coolant reaches as close to the chip-tool and the work-tool interfaces as possible and cools the aforementioned interfaces and the auxiliary flank effectively as well. The photographic view of the experimental set-up is shown in Fig.4.2.

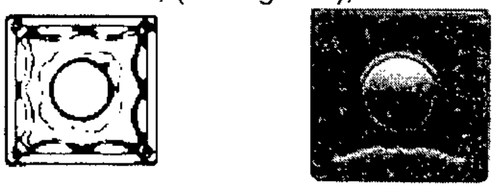
**Table-5.2** Machining responses investigated

| Work material: AISI 9310 steel (φ100 X 710 mm) | | | |
|---|---|---|---|
| **Tool insert** | **SNMG 120408 TTS** | | |
| **Investigation on** | **Working environment** | | |
| | **Dry** | **Wet** | **MQL** |
| Temperature calibration | √ | √ | √ |
| Cutting temperature | √ | √ | √ |
| Chip morphology | √ | √ | √ |
| Tool wear | √ | √ | √ |
| Surface roughness | √ | √ | √ |

The machining responses that have been studied and evaluated for assessing the machinability characteristics of the steel specimens under both dry, wet (flood cooling) and minimum quantity lubrication (MQL) conditions are indicated in Table 5.2. It has already been reported [**Dhar et al 2004; 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 5.3.

**Table 5.3** Experimental conditions

| | |
|---|---|
| **Machine tool** | : Lathe Machine (France), 15 hp |
| **Work material** | : AISI 9310 steel ($\varphi$100 X 710 mm) |
| **Cutting tool (insert)** | |
| Cutting insert | : Uncoated Carbide, (P-30 grade), Sandvick<br><br>SNMG 120408 |
| Tool holder | : PSBNR 2525M12(ISO specification) |
| Working tool geometry | : Inclination angle : $-6^{o}$<br>Orthogonal rake angle : $-6^{o}$<br>Orthogonal clearance angle : $6^{o}$<br>Auxiliary cutting edge angle : $15^{o}$<br>Principal cutting edge angle : $75^{o}$<br>Nose radius : 0. 8 mm |
| **Process parameters** | |
| Cutting velocity, $V_c$ | : 223, 246, 348 and 483 m/min |
| Feed rate, $S_o$ | : 0.10, 0.13, 0.16 and 0.18 mm/rev |
| Depth of cut, t | : 1.0 mm |
| **MQL supply** | : Air: 6 bar, Lubricant: Vegetable oil, 100 ml/h (through external nozzle). |
| **Environment** | : Dry, Wet 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 equipments and techniques as far as possible.

### 5.2.1 Calibration of Tool-work Thermocouple

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

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i. temperature sensitive powders [**Narutaki** and **Yamane 1979**]
ii. infrared measurement [**Prins 1971** and **Abrao et al. 1996**]
iii. the tool-work thermocouple techniques [**Stephenson 1993** and **Gottwein 1925**] and
iv. 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.

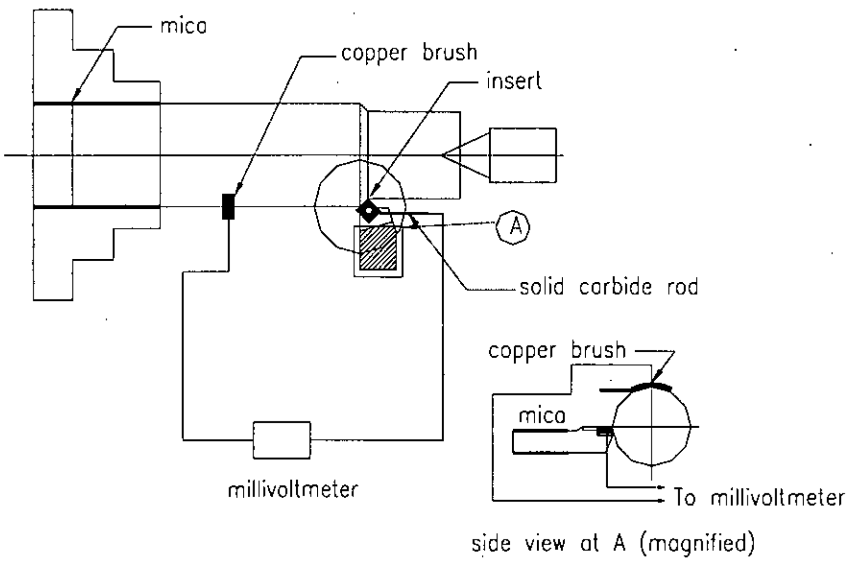



**Fig.5.1** Schematic view of the tool-work thermocouple loop

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 insulation of the tool and the job.

In the present work the average cutting temperature has been measured by tool-work thermocouple technique as indicated in Fig.5.1 taking care of the aforesaid factors.

Tool-work thermocouple can be calibrated in several ways, which include (a) furnace calibration **[Bus et al. 1971** and **Byrne 1965]** (b) resistance heating **[Alvedid 1970]** (c) embedded silver bit technique **[Barrow 1973]** (d) induction heating **[Braiden 1967]** (e) lead bath technique **[Shaw 1984]** and (f) flame heating **[Leshock** and **Shin 1997]**.

For the present investigation, the calibration of the work-tool thermocouple has been carried out by external flame heating. Fig.5.2 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 generation phenomena in machining and raised the temperature at the chip-tool interface. Standard thermocouple directly monitored the junction temperature (measured by a Eurotherm Temperature Controller and Programmer, model: 818P, made in UK) when the emf generated by the hot junction of the chip-tool was monitored by a digital multimeter (model: DH 334, Philips). Fig.5.3 shows the photographic view tool-work thermocouple set up.

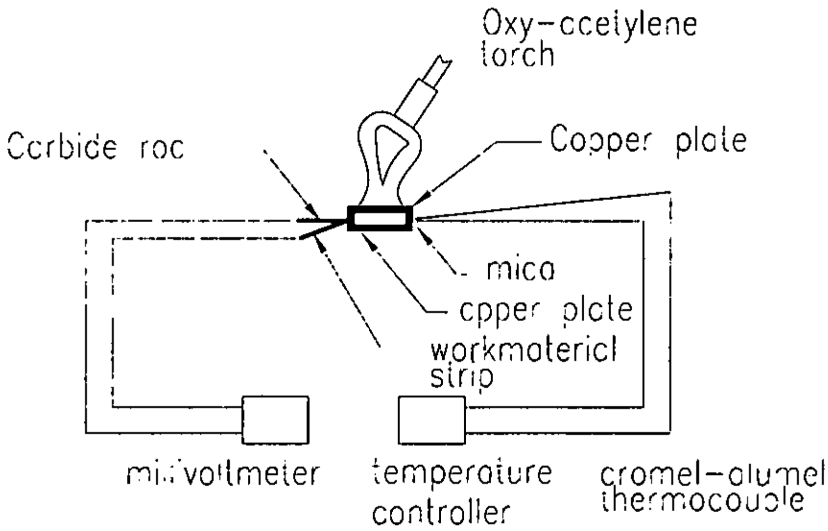



**Fig.5.2** Scheme of calibration of present tool work thermocouple

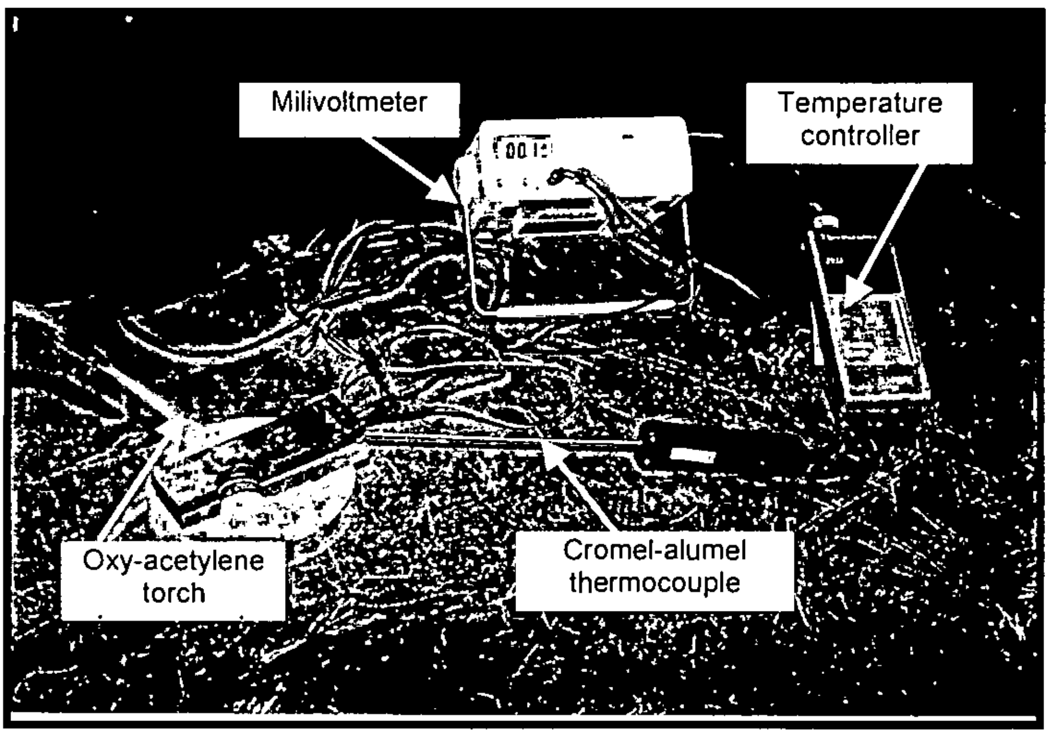



**Fig.5.3** Photographic view of the present tool-work thermocouple set up

Fig.5.4 shows the calibration curves obtained for the tool-work pair with tungsten carbide (P30 Grade, SANDVICK) as the tool material and the AISI 9310 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.

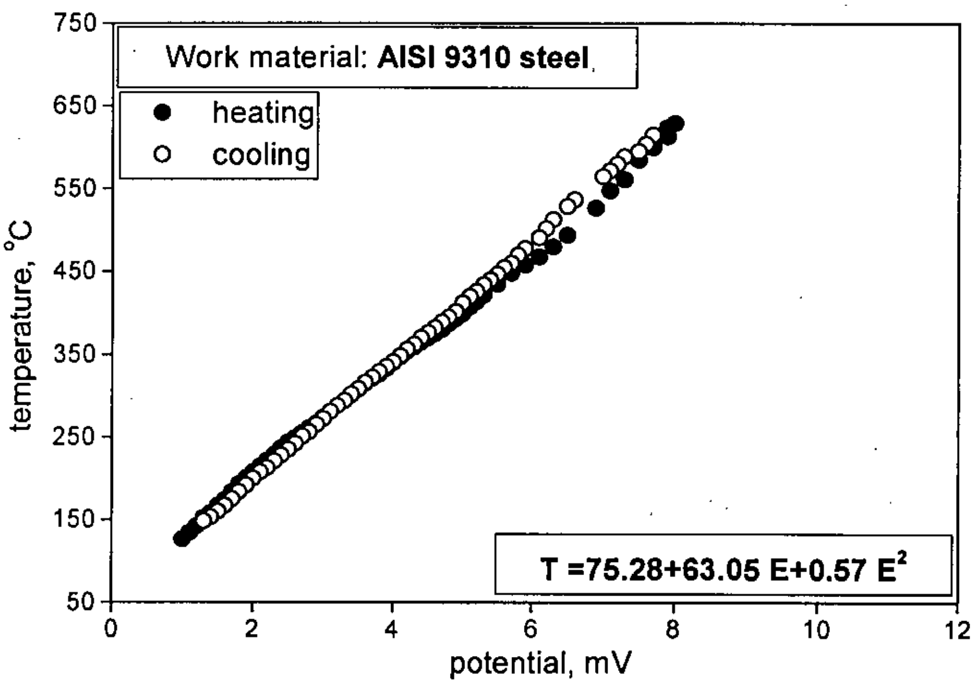



**Fig.5.4** Temperature calibration curve for uncoated carbide and AISI 9310 steel

## 5.2.2 Chip-Tool Interface Temperature

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

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

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

In the present work, the average chip-tool interface temperature could be effectively measured under dry, wet and MQL condition very reliably throughout the experimental domain. 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.5.5, Fig.5.6, Fig.5.7 and Fig.5.8 respectively.

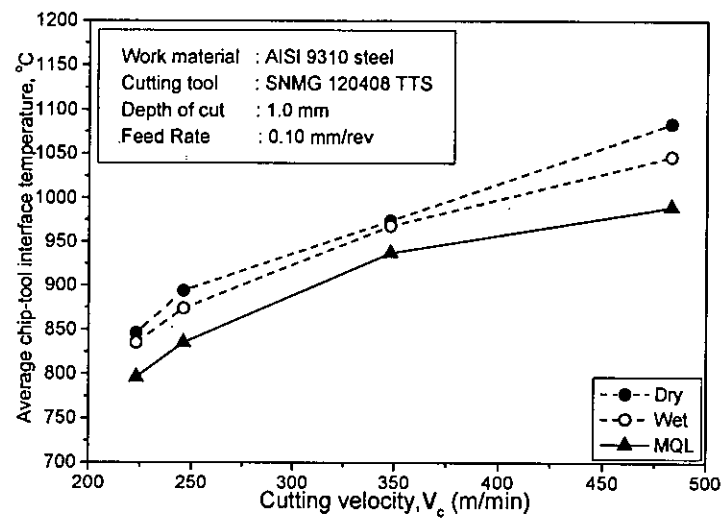



**Fig.5.5** Variation in $\theta_{avg}$ with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.10 feed rate

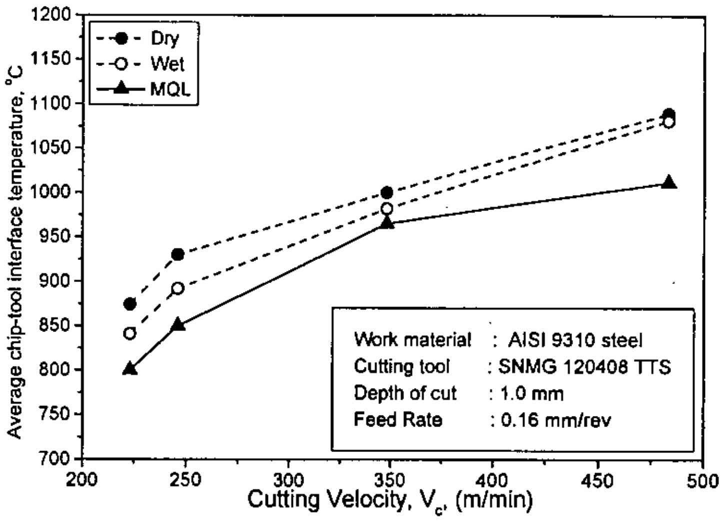



**Fig.5.6** Variation in $\theta_{avg}$ with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.13 feed rate

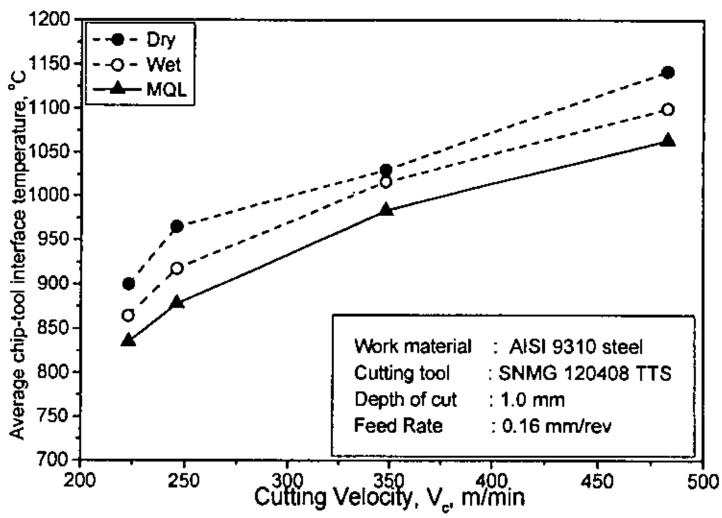



**Fig.5.7** Variation in $\theta_{avg}$ with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.16 feed rate

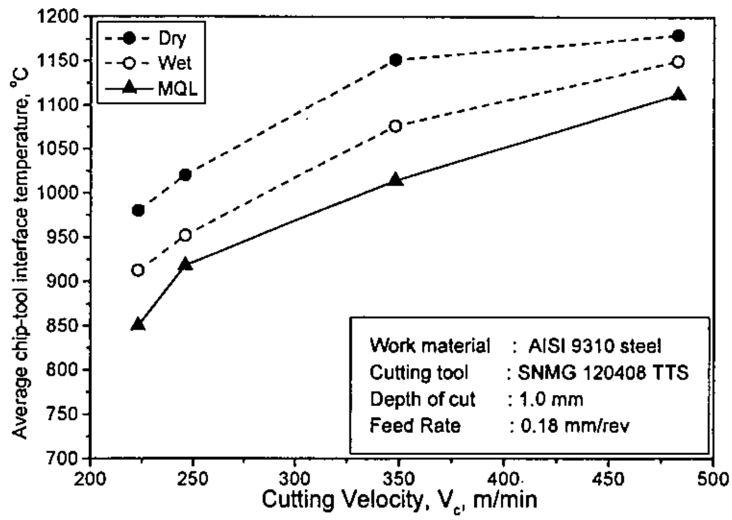



**Fig.5.8** Variation in $\theta_{avg}$ with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry, wet** and **MQL** cooling conditions at 0.18 feed rate

### 5.2.3 Study of Chip Morphology

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 all the work-tool and $V_c$-$S_o$ combinations under dry, wet and MQL conditions. The form and colour of all those chips were noted down. The thickness of the chips was repeatedly measured by a slide calliper to determine the value of chip reduction coefficient, $\zeta$ (ratio of chip thickness after and before cut), which is an important index of machinability.

The chip samples collected while turning the steel by the insert of configuration SNMG at different $V_c$-$S_o$ combinations under dry, wet and MQL by vegetable oil condition have been visually examined and categorized with respect to their shape and colour. The results of such categorization of the chips produced at different conditions and environments by the steel at different feed rates have been shown in Table-5.4.

**Table-5.4** Comparison of chip shape and colour at different $V_c$ and $S_o$ under **dry**, **wet** and **MQL** conditions

| Feed rate, $S_o$ (mm/rev) | Cutting velocity $V_c$ (m/min) | Environment | | | | | |
|---|---|---|---|---|---|---|---|
| | | Dry | | Wet | | MQL by vegetable oil | |
| | | Shape | Colour | Shape | Colour | Shape | Colour |
| 0.10 | 223 | Ribbon | Burnt blue | Ribbon | Golden & Burnt blue | Ribbon & Tubular | Burnt blue |
| | 246 | Ribbon | Burnt blue | Ribbon | Burnt blue | Tubular | Golden |
| | 348 | Ribbon | Burnt blue | Ribbon | Burnt blue | Ribbon | Burnt blue |
| | 483 | Ribbon | Burnt blue | Ribbon | Burnt blue | Ribbon | Burnt blue |
| 0.13 | 223 | Ribbon | Burnt blue | Tubular | Golden | Ribbon | Burnt blue |
| | 246 | Ribbon | Burnt blue | Ribbon | Golden & Burnt blue | Ribbon | Burnt blue |
| | 348 | Ribbon | Burnt blue | Ribbon | Burnt blue | Tubular | Golden |
| | 483 | Ribbon & Tubular | Golden & Burnt Blue | Ribbon | Golden & Burnt blue | Ribbon | Burnt blue |
| 0.16 | 223 | Ribbon & Tubular | Burnt blue | Helical | Golden | Ribbon | Golden |
| | 246 | Ribbon | Burnt blue | Ribbon | Golden | Ribbon & Tubular | Golden & Burnt Blue |
| | 348 | Tubular | Burnt blue | Ribbon & Tubular | Golden | Tubular | Golden |
| | 483 | Ribbon | Burnt blue | Ribbon | Golden & Burnt blue | Ribbon | Burnt blue |
| 0.18 | 223 | Tubular & Helical | Burnt Blue | Helical | Golden | Tubular | Golden & Burnt Blue |
| | 246 | Ribbon & Tubular | Burnt blue | Ribbon & Helical | Golden | Tubular & Helical | Golden & Burnt Blue |
| | 348 | Tubular | Golden & Burnt Blue | Ribbon | Golden | Tubular | Golden |
| | 483 | Ribbon | Golden | Ribbon | Golden | Ribbon | Burnt Blue |

| Chip shape |  |  |  |  |
|---|---|---|---|---|
| Group | Half turn | Tubular/helical | Spiral | Ribbon |

The actual forms of the chips produced by the different steels during machining by the SNMG type insert with a different feed rates and cutting velocities under dry and MQL conditions are shown in Fig.5.9, Fig.5.10, Fig.5.11 and Fig.5.12.

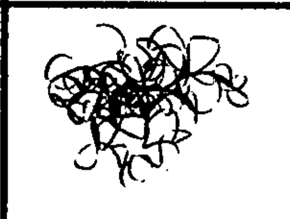
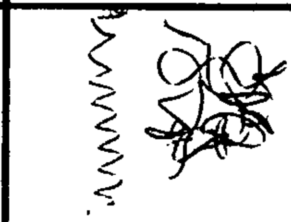
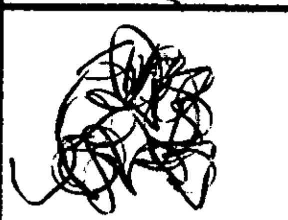
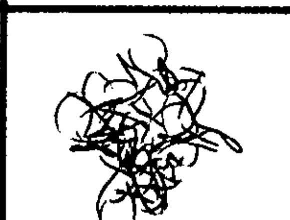
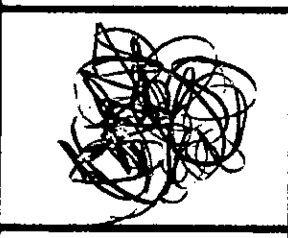
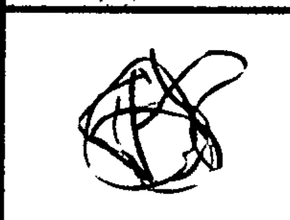
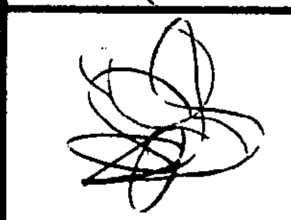
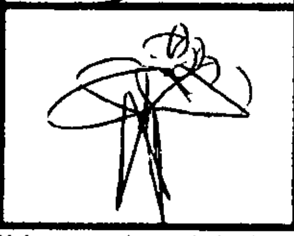
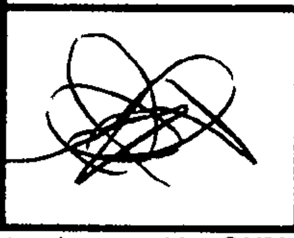
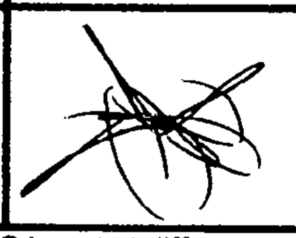
| Cutting velocity, $V_c$ (m/min) | Feed rate, $S_o$=0.10 mm/rev | | |
|---|---|---|---|
| | Environment | | |
| | Dry | Wet | MQL |
| 223 |  |  |  |
| 246 |  |  |  |
| 348 |  |  |  |
| 483 |  |  |  |

**Fig.5.9** Chips produced during turning steel by **SNMG** insert at different $V_c$ and 0.10mm/rev under **dry**, **wet** and **MQL** cooling conditions.

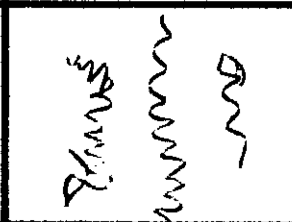
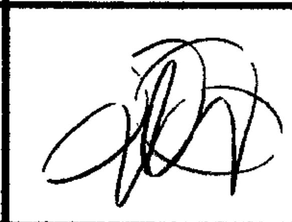
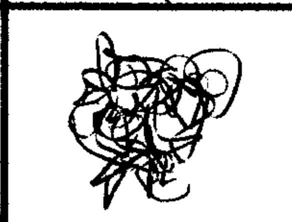
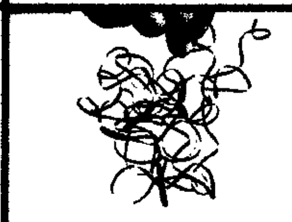
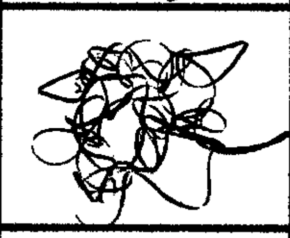
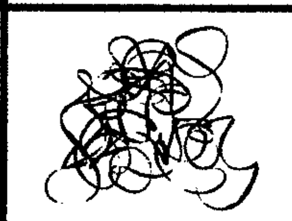
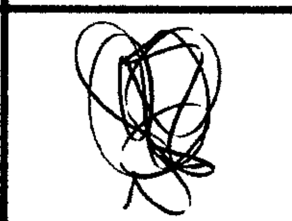
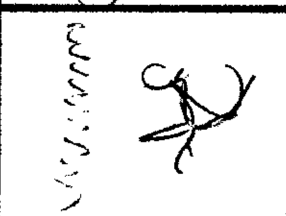
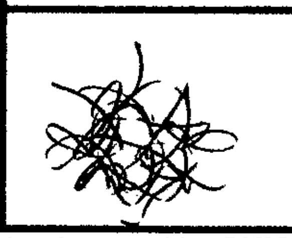
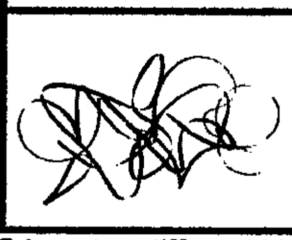
| Cutting velocity, $V_c$ (m/min) | Feed rate, $S_o$=0.13 mm/rev | | |
|---|---|---|---|
| | Environment | | |
| | Dry | Wet | MQL |
| 223 |  |  |  |
| 246 |  |  |  |
| 348 |  |  |  |
| 483 |  |  |  |

**Fig.5.10** Chips produced during turning steel by **SNMG** insert at different $V_c$ and 0.13mm/rev under **dry**, **wet** and **MQL** cooling conditions.

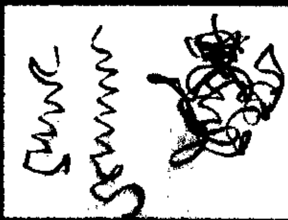
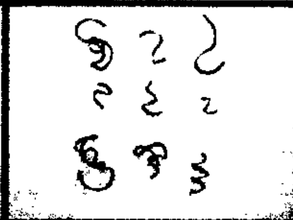
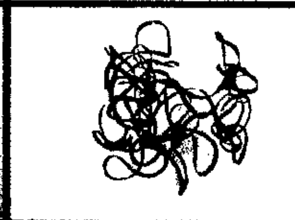
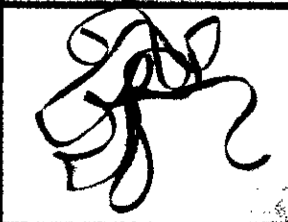
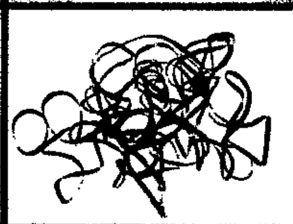
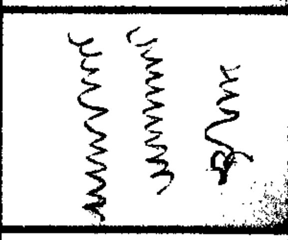
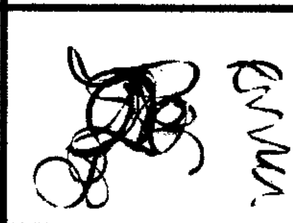
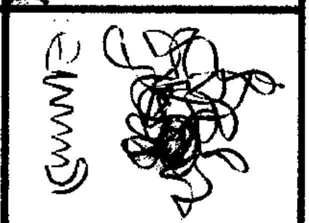
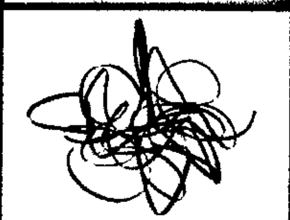
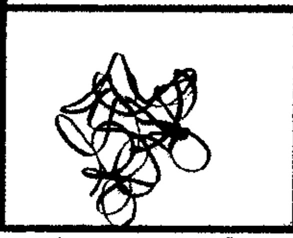
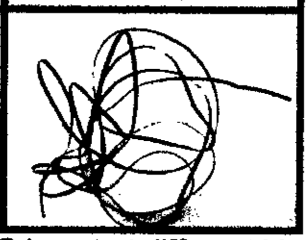
| Cutting velocity, $V_c$ (m/min) | Feed rate, $S_o$=0.16 mm/rev | | |
|---|---|---|---|
| | Environment | | |
| | Dry | Wet | MQL |
| 223 |  |  |  |
| 246 |  |  |  |
| 348 |  |  |  |
| 483 |  |  |  |

**Fig.5.11** Chips produced during turning steel by **SNMG** insert at different $V_c$ and 0.16mm/rev under **dry**, **wet** and **MQL** cooling conditions.

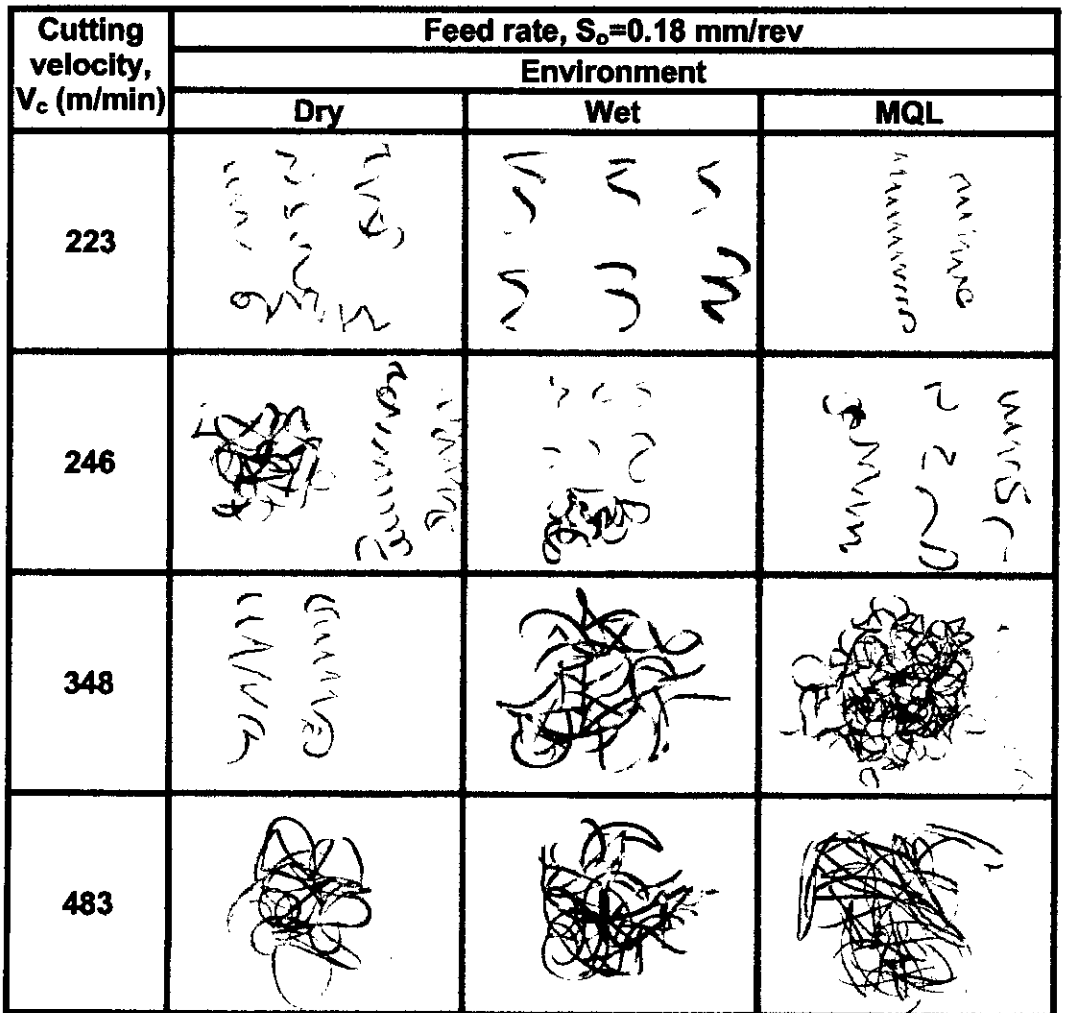



**Fig.5.12** Chips produced during turning steel by **SNMG** insert at different $V_c$ and 0.18mm/rev under **dry**, **wet** and **MQL** cooling conditions.

Another important machinability index is chip reduction coefficient, $\zeta$ (ratio of chip thickness after and before cut). For given tool geometry and cutting conditions, the value of $\zeta$ depends upon the nature of chip-tool interaction, chip contact length and chip form all of which are expected to be influenced by liquid nitrogen in addition to the levels of $V_c$ and $S_o$. The variation in value of ζ with $V_c$ and $S_o$ as well as machining environment evaluated has been plotted and shown in Fig.5.13, Fig.5.14, Fig.5.15 and Fig.5.16 respectively.

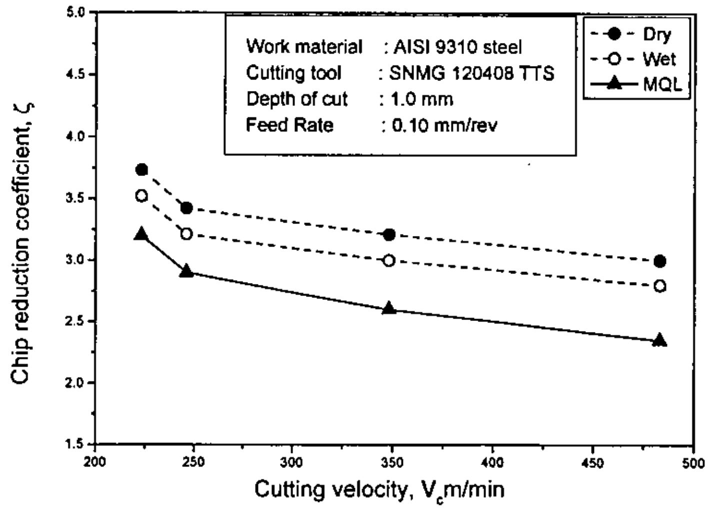



**Fig.5.13** Variation in chip reduction coefficient with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.10 feed rate

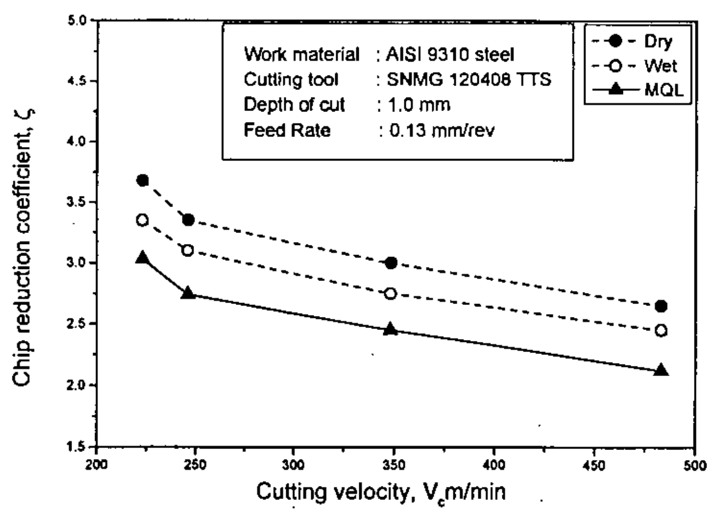



**Fig.5.14** Variation in chip reduction coefficient with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.13 feed rate

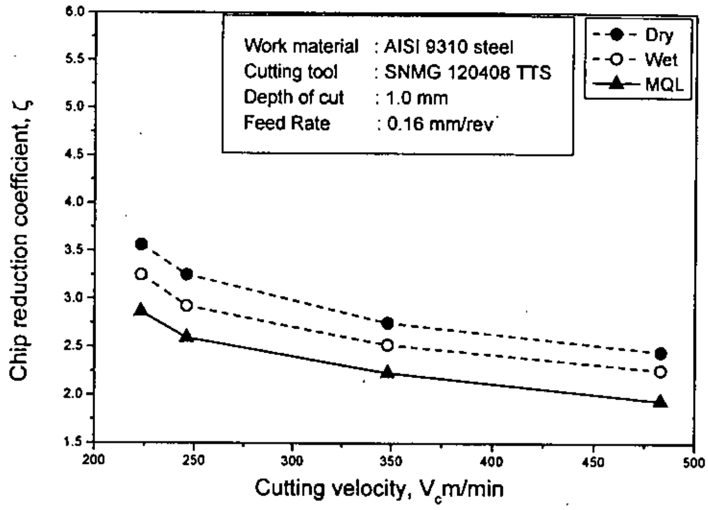



**Fig.5.15** Variation in chip reduction coefficient with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.16 feed rate

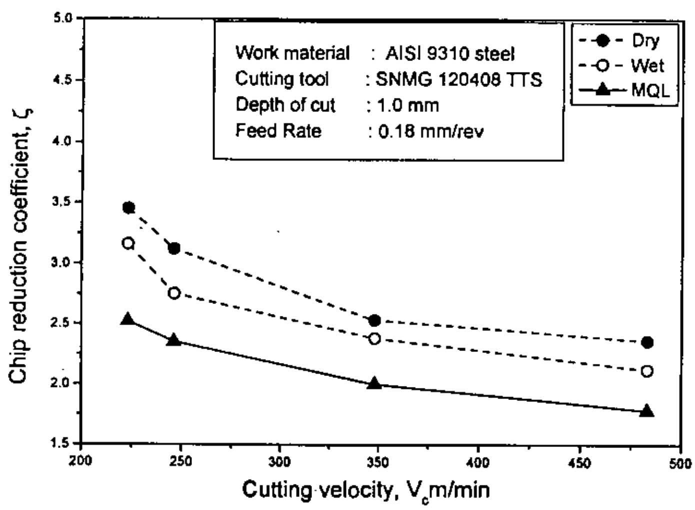



**Fig.5.16** Variation in chip reduction coefficient with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.18 feed rate

## 5.2.4 Cutting Tool Wear and Condition

Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tools. Cutting tools may fail by brittle fracture, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears. With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces, as schematically shown in Fig.5.17 due to continuous interaction and rubbing with the chips and the work surfaces respectively. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems.

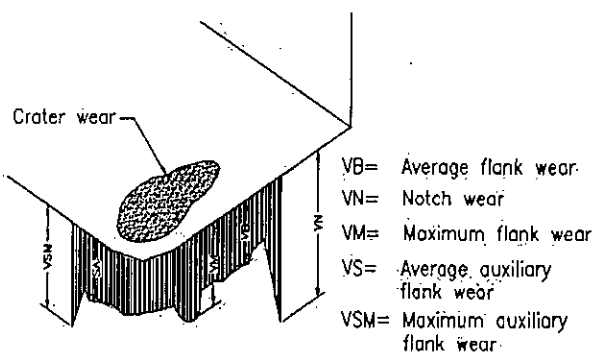



**Fig.5.17** Geometry of wear of turning tool

Again, 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.

However, tool rejection criteria for finishing operation were employed in this investigation. The values established in accordance with ISO Standard 3685 for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of rejection criteria **[Ezugwu et al. 2005]**:

| | | | |
|---|---|---|---|
| i. | Average Flank Wear | ≥ | 0.3 mm |
| ii. | Maximum Flank Wear | ≥ | 0.4 mm |
| iii. | Nose Wear | ≥ | 0.3 mm |
| iv. | Notching at the depth of cut line | ≥ | 0.6 mm |
| v. | Average surface roughness value | ≥ | 1.6 μm |
| vi. | Excessive chipping (flanking) or catastrophic fracture of cutting edge. | | |

Therefore, attempts should be made to reduce the rate of growth of flank wear ($V_B$) in all possible ways without much sacrifice in MRR.

During machining under each condition, the cutting insert was withdrawn at regular intervals and then the salient features like, $V_B$, $V_S$ etc. were measured under metallurgical microscope (Carl Żesis, 351396, Germany) fitted with micrometer of least count 1μm. At the end of machining and attaining sufficient wear the pattern and extent of wear of each tool was examined under Scanning Electron Microscope (Hitachi, S-2600N SEM, Japan) and the photographs are taken for onward comparative study.

Fig.5.18 clearly shows that average principal flank wear, $V_B$ decreased substantially by MQL by vegetable oil. Crater wear of carbide tools in machining steels particularly at higher $V_c$ and $S_o$ occur by adhesion and diffusion as well as post abrasion, whereas, flank wear occurs mainly by micro-chipping and abrasion and with increase in $V_c$ and $S_o$ adhesion and diffusion also come into picture due to intimate contact with the work surface at elevated temperature.

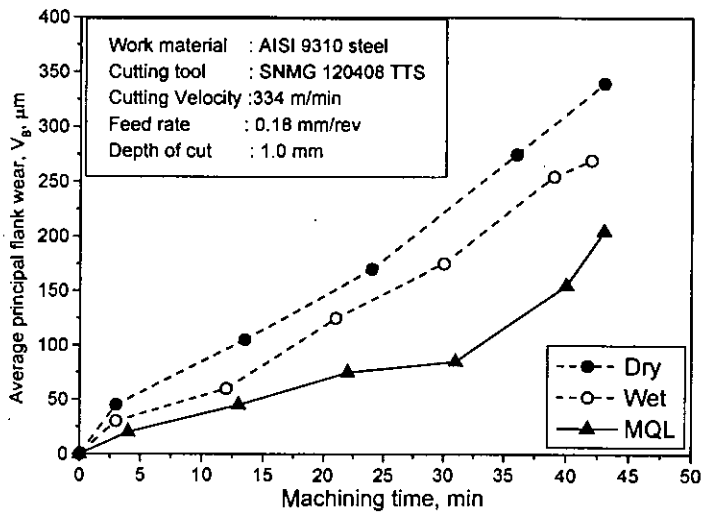



**Fig.5.18** Growth of average flank wear with time under **dry, wet** and **MQL** by vegetable oil conditions at cutting velocity 334 m/min

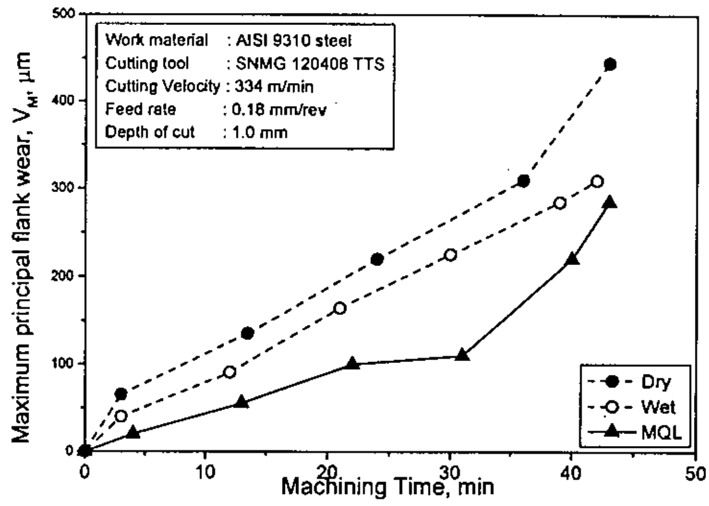



**Fig.5.19** Growth of maximum flank wear, $V_M$ with time under **dry**, **wet** and **MQL** by vegetable oil conditions at cutting velocity 334 m/min

The cause behind reduction in $V_B$ observed may reasonably be attributed to substantial reduction in the cutting temperature by MQL by vegetable oil particularly the jet impinged along the auxiliary cutting edge, which helped in reducing abrasion wear by retaining tool hardness and also adhesion and diffusion types of wear which are highly sensitive to temperature. Because of such reduction in rate of growth of flank wear the tool life would be much higher if MQL by vegetable oil is properly applied. Auxiliary flank wear ($V_S$), though occurs less intensively, also plays significant role in machining by aggravating dimensional inaccuracy and roughness of the finished surface. It appears from Fig.5.20 that auxiliary flank wear ($V_S$) has also decreased sizably due to proper temperature control under MQL by vegetable oil.

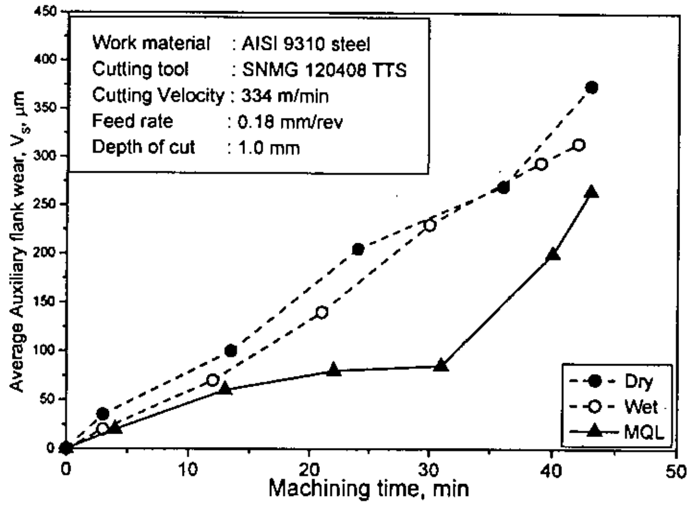



**Fig.5.20** Growth of auxiliary flank wear with time under **dry**, **wet** and **MQL** by vegetable oil conditions at cutting velocity 334 m/min

The favorable effect of MQL by vegetable oil on flank wear of insert has been briefly shown in Fig.5.21. After 43 minutes of machining the insert attained an average flank wear of around 340 μm under dry, 275 μm under wet machining whereas MQL by vegetable oil reduced flank wear to 205 μm only, whereas the insert attained an average auxiliary flank wear of round 375 μm under dry, 310 μm under wet machining and 285 μm under MQL by vegetable oil.

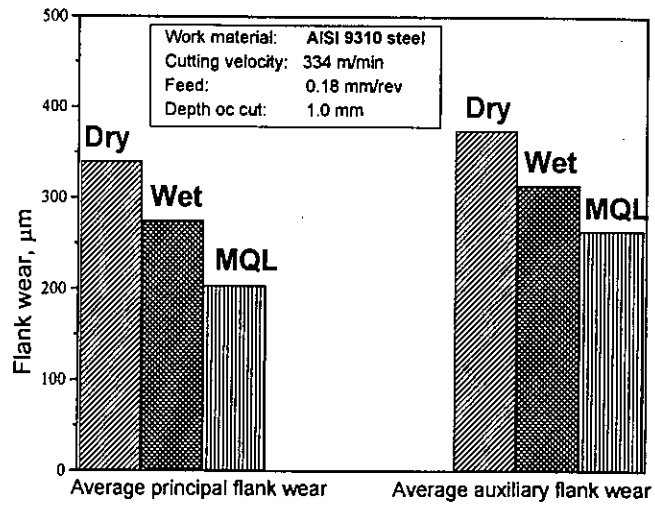
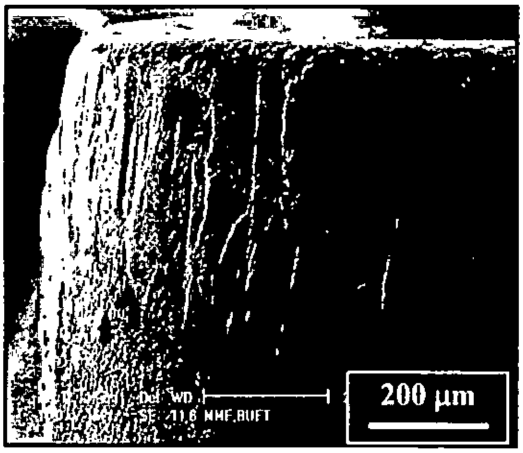
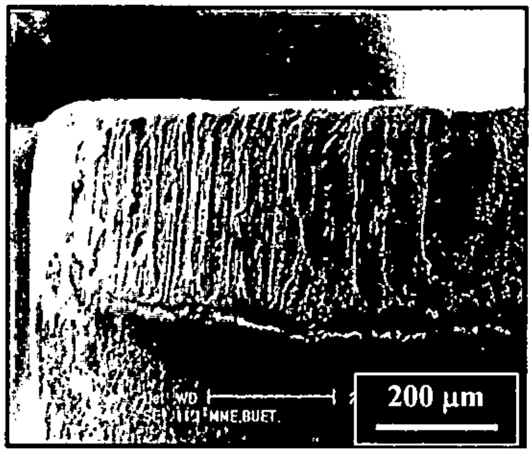



**Fig.5.21** Flank wear developed in insert after machining steel for 43 minutes under **dry**, **wet** and **MQL** by vegetable oil conditions.

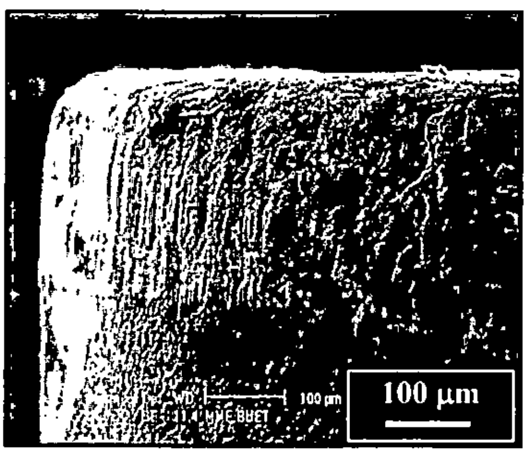
The pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining the AISI 9310 steel over reasonably long period have been observed under SEM to see the actual effects of different environments on wear of the carbide insert of present configuration. The SEM views of principal and auxiliary flank wear of the worn out insert after about 43 minutes of machining of the steel under dry, wet and MQL conditions have been shown in Fig.5.22 and Fig.5.23 respectively.




(a) Dry machining

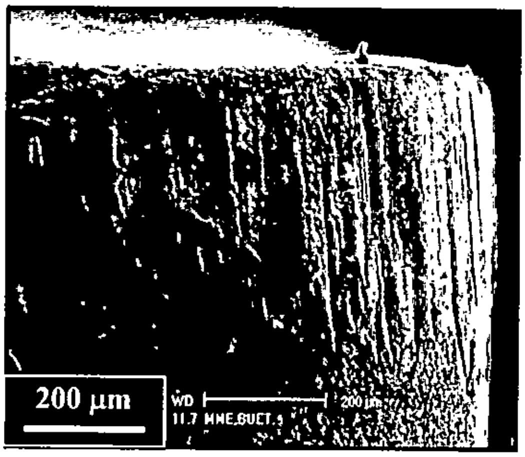



(b) Wet machining

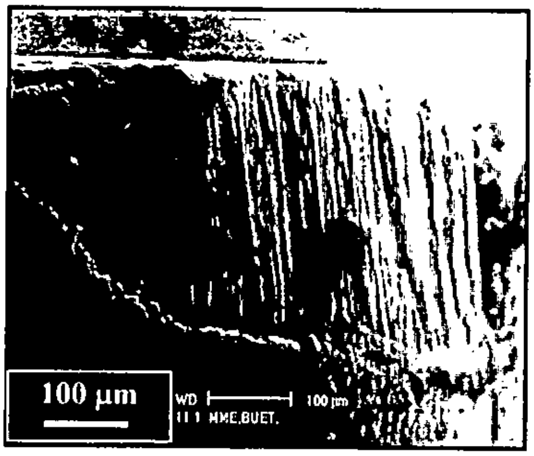



(c) MQL machining

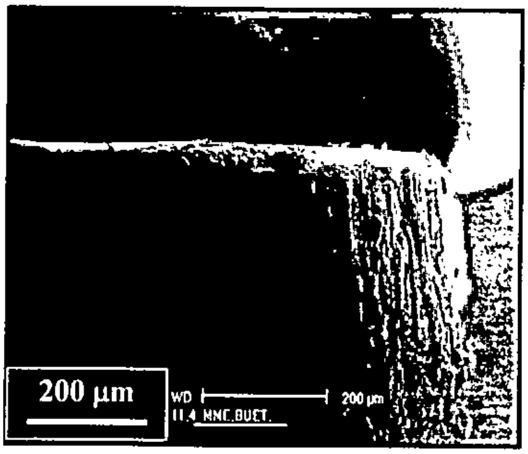
Fig.5.22 SEM views of principal flank wear of the worn out insert after machining 43 minutes under **dry**, **wet** and **MQL** conditions.




(a) Dry machining




(b) Wet machining




(c) MQL machining

Fig.5.23 SEM views of Auxiliary flank wear of the worn out insert after machining 43 minutes under **dry**, **wet** and **MQL** conditions.

### 5.2.5 Surface Roughness

After machining the steel bar by the insert, at different $V_c$-$S_o$ combinations under dry, wet and MQL conditions, the surface finish was measured respectively by a Talysurf (Surtronic 3+ Roughness Checker, Taylor Hobson, UK) using a sampling length of 0.8 mm. The photographic view of the surface roughness technique for measuring surface roughness is shown in Fig.5.24

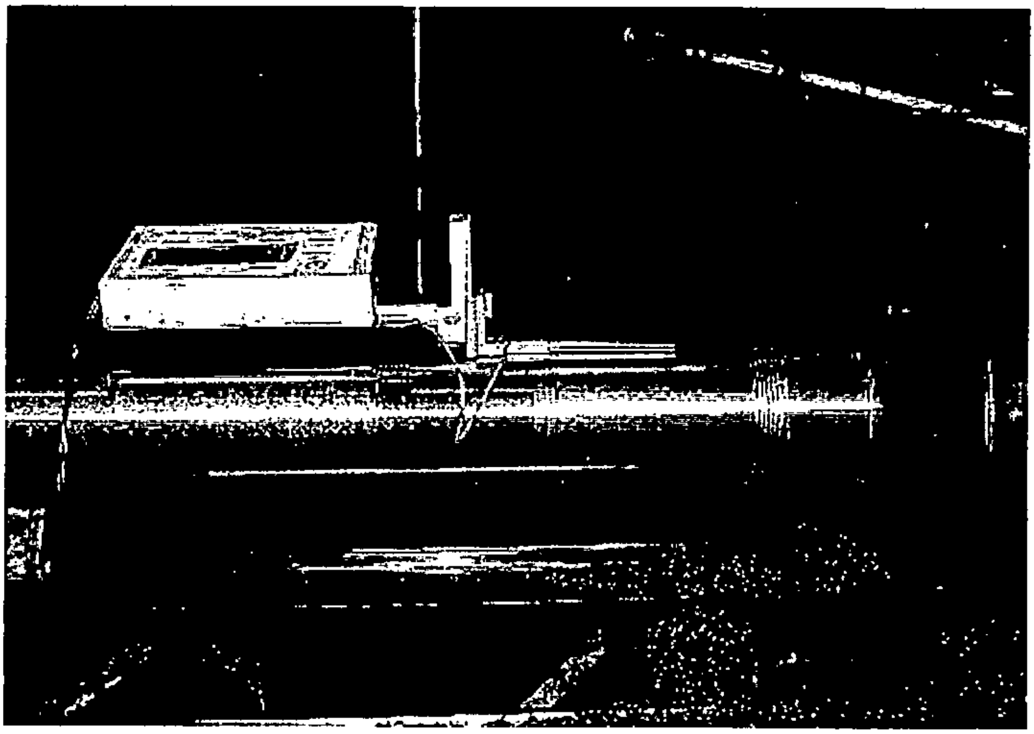


**Fig. 5.24** Photographic view of the surface roughness measuring technique

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.

Surface roughness is an important index of machinability, which is substantially influenced by the machining environment for given tool-work pair and speed-feed combinations. Surface roughness has been measured after a few seconds of machining with sharp tool while recording the chip-tool interface temperature. The photographic view of the surface roughness technique for measuring surface roughness is shown in Fig.5.24. The surface roughness attained after 45 seconds of machining of steel by the sharp carbide insert (SNMG 120408 TTS, Sandvick) at various $V_c$-$S_o$ combinations under dry, wet and MQL conditions are shown in Fig.5.25, Fig.5.26, Fig.5.27, Fig.5.28 and Fig.5.29.

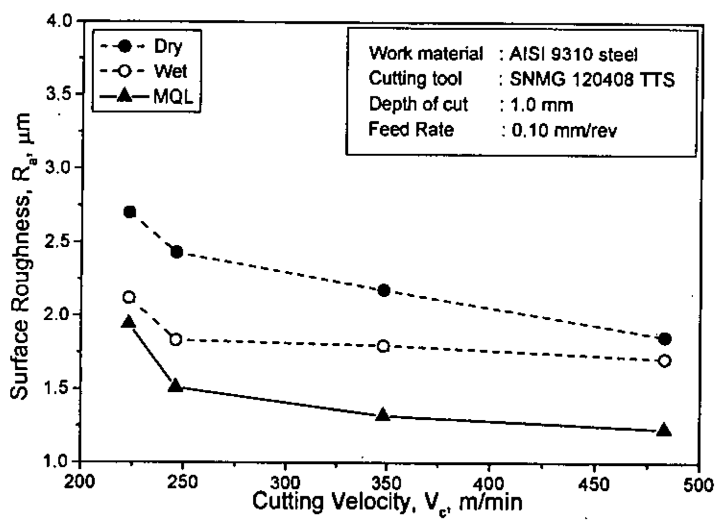



**Fig.5.25** Variation in surface roughness with that of $V_c$ and $S_o$ under dry, wet and MQL conditions in turning steel by **SNMG** insert under **dry, wet** and **MQL** cooling conditions at 0.10 feed rate

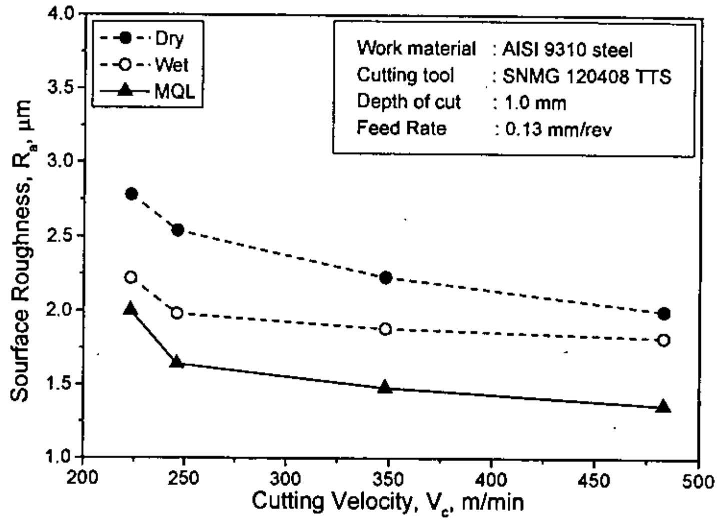



**Fig.5.26** Variation in surface roughness with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry, wet** and **MQL** cooling conditions at 0.13 feed rate

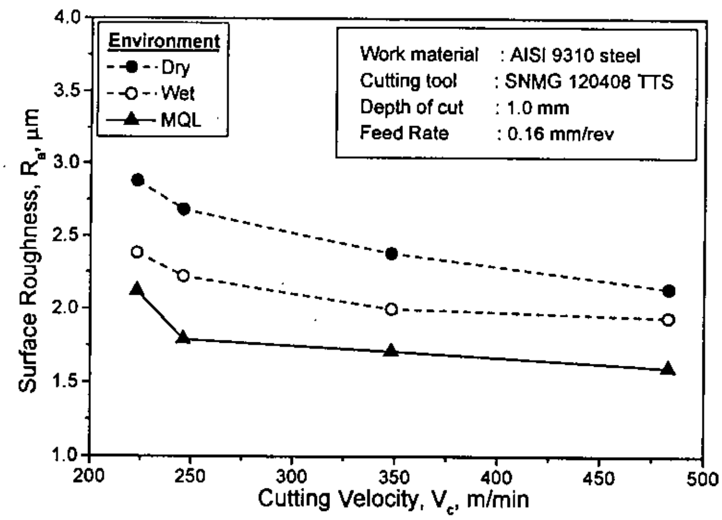



**Fig.5.27** Variation in surface roughness with that of $V_c$ and $S_o$ in turning steel by **SNMG** insert under **dry, wet** and **MQL** cooling conditions at 0.16 feed rate

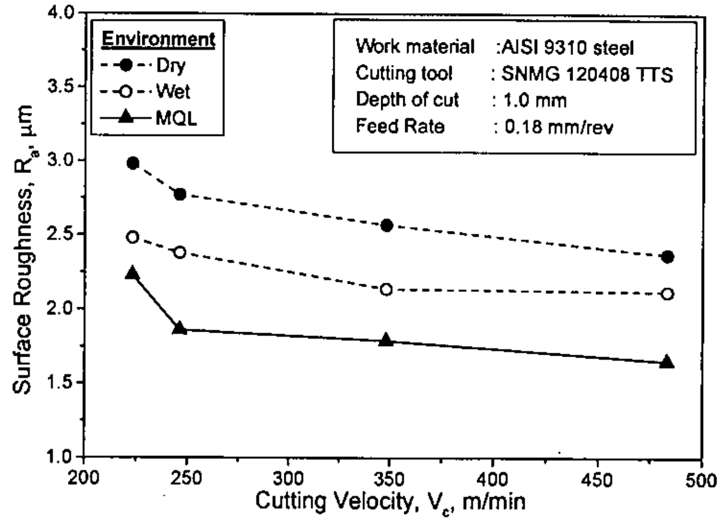



Fig.5.28 Variation in surface roughness with that of $V_c$ and $S_0$ in turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at 0.18 feed rate

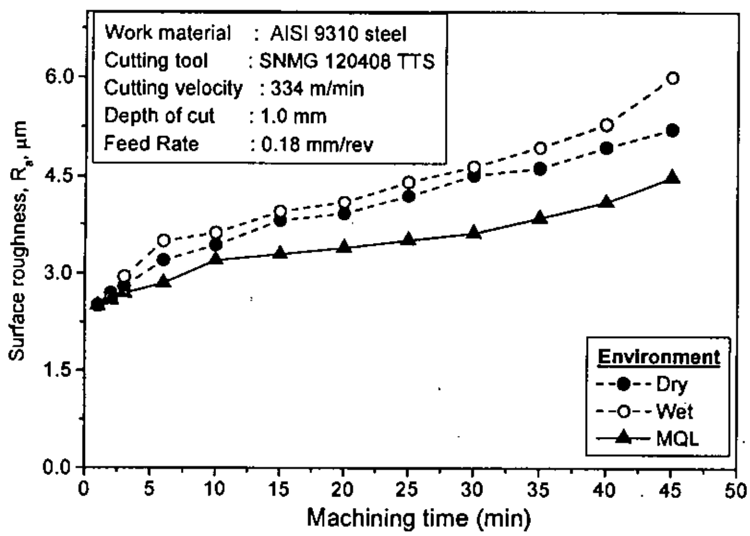



Fig.5.29 Variation in surface roughness with progress of turning steel by **SNMG** insert under **dry**, **wet** and **MQL** cooling conditions at cutting velocity 334 m/min and feed rate 0.18 mm/rev.

# Chapter-6

## Discussion on Experimental Results

### 6.1 Cutting Zone 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). During machining any ductile materials, heat is generated at the

(i) primary deformation zone due to shear and plastic deformation

(ii) chip-tool interface due to secondary deformation and sliding and

(iii) 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. That is why; 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 and effectively at the chip-tool interface where the temperature is maximum. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in $V_c$ when the chip-tool contact becomes almost fully plastic or bulk.

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.

The average chip-tool interface temperature, $\theta_{avg}$ have been determined using the tool work thermocouple technique and plotted against cutting velocity for different feeds and environments undertaken. The Fig.5.5, Fig.5.6, Fig.5.7 and Fig.5.8 are showing the effect of minimum quantity lubrication (MQL) on average chip-tool interface temperature, $\theta_{avg}$ under different cutting velocity, $V_c$ and feed rate, $S_o$ as compared to dry and wet conditions. However, it is clear from the aforementioned figures that with the increase in $V_c$ and $S_o$, average chip-tool interface temperature, $\theta_{avg}$ increased as usual, even under MQL condition, due to increase in energy input.

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 $\theta_{avg}$ to some extent depending upon the chip form and thermal conductivity of the work materials

Apparently, more reduction in average chip-tool interface temperature, $\theta_{avg}$ is expected by employing MQL but actually it is not so because the MQL could not reach the intimate chip-tool contact zone. However, during machining at lower $V_c$ when the chip-tool contact is partially elastic, where the chip leaves the tool, MQL is dragged in that elastic contact zone in small quantity by capillary effect and is likely to enable more effective cooling. With the increase in $V_c$ the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip-tool interface. As shown in Fig.5.5 and Fig.5.6, MQL cooling effect also improved to some extent with the decrease in feed particularly at lower cutting velocity. Possibly, the thinner chips, specially at lower chip velocity, are slightly pushed up by the high pressure MQL jet coming from opposite direction and enables it come closer to the hot chip-tool contact zone to remove heat more effectively. Further, at high cutting velocity, the coolant may not get enough time to remove the heat accumulated at the cutting zone resulting in less reduction in temperature under MQL condition. Besides, the effectiveness of the MQL by vegetable oil was found to decrease with the increase in feed also for more intimate chip-tool contact, but still more effective as compared to dry and wet conditions. With the increase in feed rate, $S_o$, shown in Fig.5.7 and Fig.5.8, the chip-tool contact length generally increases but the close curvature of the grooves parallel and close to the cutting edges of the insert has reduced the chip-tool contact length and thus possibly helped in reducing the chip-tool interface temperature further. 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 $S_o$. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

## 6.2 Chip Morphology

The form (shape and color) and thickness of the chips also directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The pattern of chips in machining ductile metals are found to depend upon the mechanical properties of the work material, tool geometry particularly 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 5.4 shows that the steel when machined by the pattern type SNMG insert under both dry and wet condition produced ribbon type continuous chips at lower feed rates and more or less tubular type continuous chips at higher feed rates. When machined with MQL the form of these ductile chips did not change appreciably but their back surface appeared much brighter and smoother. This indicates that the amount of reduction of temperature and presence of MQL application enabled favourable chip-tool interaction and elimination of even trace of built-up edge formation.

The color of the chips have also become much lighter i.e. metallic or golden from burnt blue depending upon $V_c$ and $S_o$ due to reduction in cutting temperature by minimum quantity lubrication.

Chip reduction coefficient, $\zeta$ (ratio of chip thickness after and before cut) is also an important machinability index. For given cutting conditions, the value of $\zeta$ 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 $\zeta$ with $V_c$ and $S_o$ as well as machining environment have been plotted and shown in Fig.5.9, Fig.5.10, Fig.5.11 and Fig.5.12.

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 (ratio of chip thickness after and before cut), $\zeta$, plays significant role on cutting forces and hence on cutting energy requirements and cutting temperature.

The value of $\zeta$ depends **[Kronenberg 1943]** mainly on apparent coefficient of friction, $\mu_a$ at the chip-tool interface and effective rake as,

$$\zeta = e^{\mu_a\left(\frac{\pi}{2}-\gamma_e\right)} \tag{6.1}$$

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

$$\tau_s = 0.74\sigma_u \varepsilon^{0.6\Delta} \tag{6.2}$$

where,

| | |
|---|---|
| $\sigma_u$ | Ultimate tensile strength of the work material |
| $\Delta$ | Percentage elongation of the work material |
| $\varepsilon$ | Average cutting strain = $\cot\beta + \tan(\beta - \gamma_e)$ |
| $\beta$ | Shear angle; where $\cot\beta = \zeta - \tan\gamma_e$ |
| $\tau_s$ | Dynamic yield shear strength of the work material |

The aforesaid figures clearly show that throughout the present experimental domain the value of $\zeta$ gradually decreased with the increase in

$V_c$ though in different degree under both dry and MQL by vegetable oil conditions. The value of $\zeta$ 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. The aforementioned figures also show that MQL by vegetable oil has reduced the value of $\zeta$ particularly at lower values of $V_c$ and $S_o$. By MQL applications, $\zeta$ 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.

From Fig.6.1, It is also noted that $\zeta$ decreased all along also with the increase in $S_O$ expectedly due to increase in average rake angle with increase in uncut chip thickness.

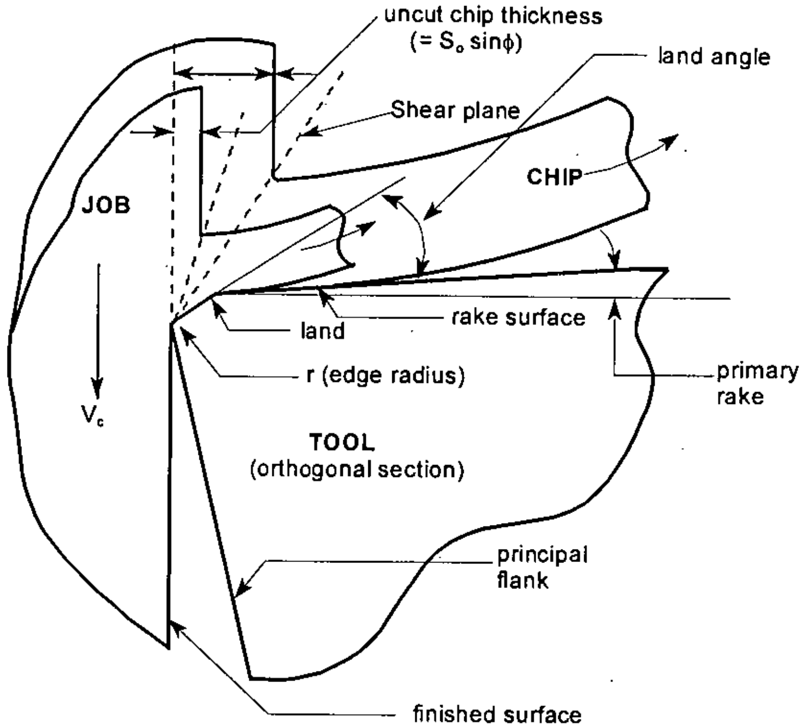



**Fig.6.1** Schematic view of machining with varying uncut chip thickness

## 6.3 Cutting Tool Wear and Condition

The cutting tools in conventional machining, particularly in continuous chip formation processes like turning, generally fail by gradual wear by abrasion, adhesion, diffusion, chemical erosion, galvanic action etc. depending upon the tool-work materials and machining condition. Tool wear initially starts with a relatively faster rate due to what is called break-in wear caused by attrition and micro-chipping at the sharp cutting edges.

Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature and/or dynamic loading at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness. However, in the present investigations with the tool and work material and the machining conditions undertaken, the tool failure mode has been mostly gradual wear. The geometrical pattern of tool wear that is generally observed in turning by carbide insert is schematically shown in Fig. 5.17. Among the aforesaid wears, the principal flank wear ($V_B$) is the most important because it raises the cutting forces and the related problems. The life of carbide tool, which mostly fail by wearing, is assessed by the actual machining time after which the average value ($V_B$) of its principal flank wear reaches a limiting value, like 0.3 mm. Therefore, attempts are to be made to reduce the rate of growth of flank wear ($V_B$) in all possible ways without sacrifice in MRR.

Fig.5.18 shows the growths of average principal flank wear, $V_B$, on the main cutting edge under dry and MQL by vegetable oil conditions. The gradual growth of average principal flank wear, $V_B$, the predominant parameter to ascertain expiry of tool life, observed under all the environments indicates steady machining without any premature tool failure by chipping, fracturing etc. establishing proper choice of domain of process parameters. Fig.5.18 also clearly shows that average principal flank wear, $V_B$ particularly its rate of growth decreased by MQL by vegetable oil. The cause behind reduction in $V_B$ observed may reasonably be attributed to reduction in the flank temperature by MQL, which helped in reducing abrasion wear by retaining tool hardness and also adhesion and diffusion types of wear which are highly sensitive to temperature. Because of such reduction in rate of growth of flank wear the tool life would be much higher if MQL is properly applied.

Another important tool wear criteria are average auxiliary flank wear, $V_S$, which governs the surface finish on the job as well as dimensional accuracy. Irregular and higher auxiliary flank wear leads to poor surface finish and dimensional inaccuracy.

The growth of average auxiliary flank wear, $V_S$ has been depicted in Fig.5.20 for all the trials undertaken. The nature of growth of average auxiliary flank wear, $V_S$ matches with that of $V_B$ expectedly. It appears from Fig.5.20 that auxiliary flank wear ($V_S$) has also decreased during MQL machining. Fig.5.21 clearly shows the amount of both average principal flank wear and auxiliary flank wear after machining for 43 minutes and depicts beneficial role of MQL, which is expected to provide better surface finish and dimensional accuracy.

The pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining the AISI 9310 steel over reasonably long period have been observed under SEM to see the actual effects of different environments on wear of the carbide insert of SNMG configuration. The SEM views of principal and auxiliary flank wear of the worn out insert after about 43 minutes of machining of AISI 9310 steel under dry, wet and MQL conditions have been shown in Fig.5.22 and Fig.5.23 respectively.

Under all the environments, abrasive scratch marks appeared in the flanks. There have also been some indications of adhesive wear in the insert. Severe groove wear at the flank surfaces were found in insert under dry and wet conditions. Some plastic deformation and micro chipping were found to occur under dry machining. Effective temperature control by MQL by vegetable oil almost reduced the growth of groove wear on the main cutting edge as well as auxiliary cutting edges. Further the figure clearly shows reduced average principal flank wear and average auxiliary flank wear under MQL by vegetable oil condition.

## 6.4 Surface Roughness

The quality of any machined product of given material is generally assessed by dimensional accuracy and surface integrity, which govern the performance and service life of that product. For the present study, only surface finish has been considered for assessment of quality of product under dry, wet and MQL machining.

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

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

i. regular feed marks left by the tool tip on the finished surface
ii. irregular deformation of the auxiliary cutting edge at the tool-tip due to chipping, fracturing and wear
iii. vibration in the machining system
iv. built-up edge formation, if any.

The variation in surface roughness observed with progress of machining of AISI 9310 steel by the SNMG insert at a particular set of cutting velocity, $V_c$, feed rate, $S_o$ and depth of cut, t under dry, wet and MQL conditions have been in shown in Fig.5.29. As MQL reduced average auxiliary flank wear and produced no notch wear on auxiliary cutting edge, surface roughness also grew very slowly under MQL conditions. Conventionally applied cutting fluid did not reduce tool wear compared to dry machining. But the surface roughness deteriorated drastically under wet machining compared to dry, which may possible be attributed to electrochemical interaction between insert and work piece. It appears from Fig.5.29 that surface roughness grows quite fast under dry machining due to more intensive temperature and stresses at the tool-tips. MQL appeared to be effective in reducing surface roughness. However, it is evident that MQL improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.

# Chapter-7

## Conclusions

Based on the results of the present experimental investigation the following conclusions can be drawn:

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

ii. The present MQL systems enabled reduction in average chip-tool interface temperature up to 10% depending upon the cutting conditions and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.

iii. The AISI 9310 steel when machined by SNMG type insert under both dry and wet condition produced ribbon type continuous chips at lower feed rates and more or less tubular type continuous chips at higher feed rates. When machined with MQL the form of these ductile chips did not change appreciably but their back surface appeared much brighter and smoother. This indicates that the amount of reduction of temperature and presence of MQL application enabled favourable chip-tool interaction and elimination of even trace of built-up edge formation.

iv. 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, $\zeta$ 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.

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

vi. Surface finishes also improved mainly due to reduction of wear and damage at the tool tip by the application of MQL.

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

# Chapter-8

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