PERFORMANCE EVALUATION OF DIFFERENT TYPES OF CUTTING FLUIDS IN MINIMUM QUANTITY OF LUBRICATION (MQL) MACHINING OF ALLOY STEEL BY COATED CARBIDE INSERT

By

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Declaration

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

Sonia Sultana

Sonia Sultana

This work is dedicated
to my loving

Father

&

Mother

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

MRR	Material removal rate
MWF	Metal working fluid
SEM	Scanning electron microscope
θ	Average chip-tool interface temperature

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Abstract

High cutting temperature is inherent during machining which shortens the tool life and deteriorates the job quality. This problem becomes more acute when the jobs are difficult to machine and are to be used under dynamic loading. Cutting fluid application is the most common strategy to improve the tool life and the product quality. But conventional cutting fluids are not that effective in high production machining particularly in continuous cutting of materials like steels. More over cutting fluids are the major source of environments pollution, soil contamination and inhalation problems. Minimum quantity lubrication (MQL) with vegetable oil or cutting oil is environment friendly machining technique. MQL refers to the use of cutting fluids of only a minute amount—typically of a flow rate of 50 to 500 ml/h which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition.

Effects of MQL on cutting performance of 42CrMo4 steel in respect of chip-tool interface temperature, chip formation, cutting forces, tool wear and product quality have been studied using coated carbide insert (SNMM-TN 2000). Three types of cutting fluids namely soluble oil, vegetable oil and VG 68 cutting oil have been used to compare the relative performance of those cutting fluids with each other as well as with that of dry condition.

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

Chapter-1

Introduction

1.1 Introduction

Machining is a material removal process that typically involves the cutting of metals using different types of cutting tools in which a tool removes material from the surface of a less resistant body through relative movement of the tool and application of force and is particularly useful due to its high dimensional accuracy, flexibility of process, and cost-effectiveness in producing limited quantities of parts. Due to removal of material in the form of chips, new surfaces are cleaved from the workpiece accompanied by a large consumption of mechanical energy which in turn transformed into heat, leading to conditions of high pressure, high temperature and severe thermal conditions at the tool-chip interface. The greater the energy consumption, the greater are the temperature and frictional forces at the tool–chip interface and which in turn increases tool wear.

The manufacturing company faces the challenges for higher production with superior quality and surface finish of product to meet the overall economy, global cost competitiveness by machining and grinding, insists high material removal rate, high stability and long life of the cutting tools. In high speed machining or grinding process, the desired products with actual size and shape are produced by gradually removing the excess material from the performed blank in the form of chips which is associated with the generation of high cutting temperature with high cutting velocity, feed, and depth of cut. High cutting temperature generation in machining not only reduces dimensional accuracy but also damages the surface finish of the product. But the performed parts essentially need finishing to the desired dimensional accuracy and surface integrity by these processes. Several engineering parts with dimensional accuracy and surface finish are essential not only for their ability to fulfill their functional requirements but also for their improved performance and prolonged service life.

The surface quality of the finished products deteriorates with the increase in cutting temperature due to built-up-edge formation, oxidation, rapid corrosion, induction of tensile residual stresses and surface. Such problems become more sensitive and serious when very hard, strong and heat resistive part is subjected to dynamic or shock loading during the functional operations. On the other hand, high cutting temperature accelerates the growth of tool wear and also enhances of premature failure of the tool by plastic deformation and thermal fracturing. Therefore it becomes very essential to reduce the cutting temperature as far as possible.

In general, the most important outcome in machining processes is the productivity, achieved by cutting the highest amount of material in the shortest period of time using tools with the longest life time. Combining all the parameters involved in the machining process to maximize productivity is, nevertheless, a very complex task and becomes much more difficult when working at high speed-feed condition as well as high cutting temperature. In industries, for sustainable development maintaining the highest productivity, the temperature generation 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. The cutting inserts 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.

Dry machining is a machining process in which no cutting fluid is used for the interest of lower cutting forces and environment friendliness. It is ecologically desirable and industries will be compelled to consider dry machining to enforce environmental protection laws for occupational safety and health regulations. Dry machining is now of great interest and actually some researchers meet with success in the field of environmentally friendly manufacturing [1, 2]. In reality, however, they are sometimes less effective when higher machining efficiency, better surface finish quality and severer cutting conditions are required. During dry machining at high cutting speed and feed, high temperature is generated which results in high tool wear rate, reduced tool life because these contact conditions become very severe and the tool wear is mainly caused by thermal softening, abrasion and a built-up edge (BUE) formation, which affects the quality of the generated surface and dimensional accuracy. On the other hand, in complete absence of coolant, chip transportation causes an increase of tool-chip and tool-workpiece friction, as a result increased cutting force as well as abrasive wear and attrition. Some recent techniques have enabled partial control of the machining temperature by using heat resistant tools like coated carbides, CBN, PCBN etc. The improvement in the coatings of carbide tools and in the chemical and mechanical properties of tool materials has caused the increase of tool working life in machining processes.

Due to the fact that the higher the tool temperature, the faster it wears. The use of cutting fluids in machining processes is the most common strategy, as its main goal, the reduction of the cutting zone temperature, either through lubrication reducing friction wear, or through cooling by conduction, or through a combination of these functions. The application of coolant during a machining operation is believed to reduce tool wear [3]. Cutting fluids also act as chip-breaker during machining and chip formation is also affected when coolant is applied during a machining operation. The chip curl changes with the temperature gradient along the thickness of the chip and affects the size of the crater wear and the strength of the tool cutting edge. The direction from which the cutting fluid is applied is therefore an important factor affecting the chip curl.

The applications of conventional cutting fluids have been found to become less effective with the increase in cutting velocity and feed as in this system the cutting fluid cannot properly enter in to the chip-tool interface due to elastic-plastic contact. It can not properly cool and lubricate the cutting zone due to bulk plastic contact of the chip with the tool rake surface. Besides this, it has some unfavorable effects on the operator, namely, toxic vapors, unpleasant odors, smoke, fumes and skin irritations. Large quantities of emulsion-based cutting fluids for machining are still widely used in the metal working industry, generating high costs of consumption and disposal and affecting the environment. The conventional cutting fluid systems can cool and lubricate the work-tool and chip-tool contact in a limited area and there are also restrictions in using much use of coolants in many countries because of environmental issues. Besides this, there are limits on the amount of coolant mist and some coolants and coolant-wetted chips have been treated as toxic materials. In some applications, the consumption of cutting fluids has been reduced drastically by using mist lubrication. However, mist in the industrial environment can have a serious respiratory effect on the operator [4, 5]. Consequently, high standards are being set to minimize this effect. Besides this, conventional coolants undergo film boiling at around 350^0C and loose their cooling property [6]. These combined factors have driven the industrial sector, research centers and universities to investigate alternative production processes, to create technologies that minimize or avoid the production of environmentally aggressive residues.

In line with growing environmental concerns involved in the use of cutting fluids in machining processes, as reported by several researchers and manufacturers of machine tools, strong emphasis is being placed on the development of environmentally friendly technology, i.e., on environmental preservation and the search for conformity with the ISO 14000 standard. On the other hand, despite persistent attempts to completely eliminate cutting fluids, in many cases cooling is still essential to the economically feasible service life of tools and the required surface qualities. In respect of the economical and environmental effects on the use of cutting fluids lead to the research of near dry machining several years ago [1, 7]. Near dry machining refers to the use of a small amount of cutting fluid, typically in the order of 100 ml/hr or less, which is about ten-thousandth of the amount of cutting fluid used in flood-cooling machining [8]. The principle of near dry machining is the application of less lubrication with dry surface after the machining process. Therefore, near dry machining is also recognized as minimum quantity lubrication (MQL) machining. According to Diniz et al. [9] machining processes with the minimum quantity lubrication (MQL) technique or without any cutting fluid (dry cutting) reduced the utilization of cooling lubricants, in order to improve environmental protection, safety of machining processes and to decrease time and costs related to the number of machining operations.

In various metal cutting processes, sawing, shaping, drilling and milling, minimum quantity lubrication (MQL) system has long been worked successfully. In this system, cutting fluids employed mainly that are non-soluble in water, especially mineral oils. According to Heisel et al. [10], these oils, inhaled in the form of aerosol, reduce the health hazard factor. Due to the very small amounts of cutting fluids used, one must consider that the costs should not prevent the use of high technology compositions in the field of additive oils. Over the years several researchers have employed minimum quantity of lubricants in machining and grinding of steels and advanced materials and reported that if employed effectively, minimum quantity of lubricants can successfully combat the high cutting temperature inherent in high production machining and grinding [11-17]. Different researchers also used vegetal-based coolants [18].

Typically, an MQL system supplies 0.3 ~ 0.5 ml/min of a metal working fluid (MWF) with pressurized air or other supplemental gases, whereas a conventional system supplies about several thousand ml/min of MWF. The conventional flood supply system demands more resources for operation, maintenance, and disposal, and results in higher environmental and health problems. MQL machining has many advantages in this regard [19, 20, 21]. Minimal quantity lubrication (MQL) is a technique of supplying lubrication in machining to achieve both environmental and economical benefits. The application of cryogenic coolant easily reduces cutting temperature, cutting forces with chip load, provides improved tool life and surface finish as a result increase all the machinability indices. But due to the high cost and difficult handling of cryogen, the use of cryogenic coolant is limited.

It is necessary to discover the knowledge over the performance of cutting fluids when applied to different work materials and operations in order to improve the efficiency of the most conventional machining processes. This efficiency can be measured, among other parameters, through cutting tool life and workpiece surface finish. However, the costs associated with the purchase, handling and disposal of cutting fluids are leading to the development of tool materials and coatings which do not require their application. In this work, the performance of three types of cutting fluids (soluble oil, vegetable oil and VG68 cutting oil) with MQL will be compared to dry cutting when continuous turning 42CrMo4 steel using coated carbide insert (SNMM-TN 2000) through the evaluation of the following parameters: cutting temperature, chips form, cutting forces, tool wear mechanism and surface finish.

1.2 Literature Review

Currently generous research and investigations have been done world wide on the machinability of different materials mainly in respect of chip-tool interface temperature, chip morphology, chip-tool interaction, cutting forces, wear and life of cutting tool, dimensional accuracy and surface integrity along with surface finish under different cutting environments with or without using cutting fluids. During machining the application of conventional cutting fluids arise severe alarm on environmental pollution and health hazard on workers. Research has also been initiated on control of such pollution by completely dry cutting using high heat and wear resistant cutting tools, Cryogenic machining, high-pressure coolant jet assisted machining and minimum quantity of lubricant (MQL) and their technological effects particularly in temperature intensive machining and grinding.

A brief review of some of the attractive and significant contributions in the closely related areas is presented in this section. This chapter also provides the background information relevant to this research. The ecological and economical dry machining and the problems of high temperature rises in dry machining, machining with conventional cutting fluids and the effects of cutting fluids on finish products and environment, other alternative lubrication system and finally the minimum quantity lubrication (MQL) system and its positive effects on the finished products with researchers remarks are described thoroughly in this chapter.

The advance metal machining industries are mainly paying attention on the achievement of high quality product, in terms of work part dimensional accuracy and surface finish, at high production rate and cost saving also with a reduced environmental impact. During machining high cutting temperature generation in very common and it deforms the tool cutting edge deformation which may result in poor machining performance in terms of form accuracy and surface quality. This generated high temperature is partially controlled by reducing heat generation and removing from the cutting zone. It can be done by selecting optimum machining parameters and geometry of the cutting tools, proper cutting tools, proper cutting fluid applications and using heat resistant cutting tool materials like carbides, coated carbides, and high performance ceramics.

1.2.1 Dry Machining

Dry cutting or cutting with no fluid may be a possible solution without causing a large decrease in tool life and loss of workpiece quality, but for this it is mandatory to have suitable tool materials and cutting conditions. During machining the heat generation raises the temperature of the cutting tool tips and the work-surface near the cutting zone [22] as there is no medium of heat removal from the cutting zone. Due to such high temperature and pressure acting on the cutting tool edge. results the deformation of cutting edge plastically. It also creates rapid tool wear which ultimately lead to dimensional inaccuracy, increase in cutting forces and premature tool failure. On the other hand, if the cutting temperature is high and is not controlled, it worsens the surface topography and impairs the surface integrity by oxidation and introducing residual stresses, micro-cracks and structural changes.

The magnitude of cutting temperature rises with the increase of cutting velocity, feed and depth of cut which constrained high production machining by rise in temperature. At such elevated temperature the cutting tool if not hot hard as much necessary may lose their permanence quickly or wear out rapidly which result in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. This problem increases further with the increase in strength and hardness of the work material. Hard coatings of tool materials have been used to accomplish this purpose. 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). The demand for producing large amount of product in target time insists high material removal rate during machining which increases cutting velocity, feed rate and depth of cut. For manufacturing product with good surface finish and dimensional accuracy it is eventually required to reduce the cutting zone temperature.

In machining ductile metals, the chip contact length plays a significant role on the chip and tool temperature which becomes highest almost at the center of the chip-tool contact surface [23] where then crater wear begins and grooves intensively. It was also observed by Jawahir and Luttervelt [24] that during machining ductile material produces long chips and the chip-tool contact has a direct influence on the cutting temperature and thermo-chemical wear of cutting tools. This cutting temperature becomes high on the rake face where cratering occurs, which also raise the temperature at the flank of the tool. The usual flank wear and crater wear of the cutting tools often attain notching on the flanks and grooving on the rake face at the outer ends of the engaged portions of the cutting edges. Kosa et al. [25] also commented that in machining ductile material the heat and temperature developed due to plastic deformation and rubbing of chips with tool. The generated heat and cutting temperature at the chip-tool interface may cause continuous built-up welded debris which causes fluctuation of cutting forces, increase power consumption along with increased surface roughness during machining operation.

Machining under high cutting velocity and unfavorable process parameters require high specific energy. This machining results in very high cutting temperature.

which reduces the dimensional accuracy and tool life by plastic deformation and rapid wears of the cutting points [26, 27]. Past researchers focused on the temperature and its distribution in the cutting zone because it is believed that it has a direct impact on tool life [28]. Due to high temperature and pressure the cutting edge deforms plastically and wears rapidly, which leads to dimensional inaccuracy, increase in cutting forces and premature tool failure. On the other hand, this uncontrolled high temperature worsens the surface topography and the surface integrity by oxidation, and introducing residual stresses and surface or sub-surface micro-cracks. Currently, this problem is tried to control by reducing heat generation and removing heat from the cutting zone through optimum selection of machining parameters, proper selection and application of cutting fluids.

Cutting force is an important criterion in increasing cutting temperature during machining. In turning operation the resultant force is divided into three components, feed force, radial force and main cutting force. Usually, in finishing operations the radial force is the largest of all, since the depth of cut is very small, compared to the tool nose radius [29] and with the increasing of cutting velocity both, radial and feed forces tend to decrease, for most of the metallic parts machined with carbide tools. The lubricants are considered to act in the slightly loaded region where the chip leaves the tool. They decrease the friction there and thereby causing the contact length and the chip thickness to reduce, but even at very low speeds it never penetrates the highest loaded region. However, a lubricant does not have to penetrate the whole contact by attacking at the edge and it can reduce the whole contact [30, 31] attributes such behavior partly to the softening effect of the workpiece material, due to temperature increase, and partly to the decreasing of the chip-tool contact length. Additionally, the depth of cut (d) evidently has an influence larger than the cutting velocity and feed rate has a moderate effect on forces.

Although surface roughness of the finished product is usually undesirable, it is difficult and expensive to control in manufacturing. To decrease surface roughness, it is necessary to increase manufacturing cost. This often results in a trade-off between the manufacturing cost of a component and its performance in application. Several factors will influence the surface roughness in a machining operation. The surface roughness might be considered as the sum of two independent effects: i) the ideal surface roughness is a result of the geometry of the tool and feed rate and ii) the nature of surface roughness is a result of the irregularities in the cutting operation [32]. Even in the occurrence of the chatter or vibrations of the machine tool, defects in the structure of the work material, wear of tool or irregularities of chip formation contribute to the surface damage in practice during machining.

Shaw [3], Komanduri et al. [33] and Stephenson et al. [34] agree that most of the energy applied to the cutting process is converted into heat in the main zone of plastic deformation, the shearing plane, where the workpiece material turns itself into chip and in the secondary zone of plastic deformation, where chip slides on the rake face. Finally, some heat also arises on the tertiary zone, where the tool relief face slides on the newly machined surface. This last source is, however, not considered in most cases, either for simplicity, or because the heat generated is very small when using sharp cutting edges. The heat generated in those zones is distributed among the tool, the workpiece, the chip, and after that to the environment. Heat generated at the shearing plane can make the cutting action easy, but it can flow into the cutting edge and that will negatively affect tool life by shortening it.

1.2.2 Machining with Conventional Cutting Fluids

Conventional machining prevails plastically deformation in generating chips whereas in high speed machining chip generation is followed by segmentation process. Usually the high cutting temperature is controlled by profuse cooling [35, 36, 37]. 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. During machining cutting fluids carry out many useful functions which include cooling of the cutting tool at higher speeds, lubrication at low speeds and high loads, increasing tool life, improve the surface finish, reducing the distortion due to temperature rise in the workpiece, chip handling and disposal, providing a protective layer on the machined surface from oxidation and protection of the machine tool components from rust [38, 39, 40]. Compared with the cost of the cutting tools the cutting fluids cost is significantly high and it is necessary to reduce the use of cutting fluids. It was reported that metal-working fluids cost ranges from 7 to 17% of the total machining cost. On the other hand tool cost is less in respect of total manufacturing cost which ranges from 2 to 4%. The more the consumption of cutting fluids in manufacturing process, the more cost increased due to some additional process for handling and disposal the cutting fluids.

While primarily dependent on the cutting speed and the workpiece material properties, the cutting temperature is also affected by the cutting tool properties. Almost all of the mechanical energy in metal cutting is transformed into heat. The major portion of the produced heat is conducted into and removed with the chips from the cutting region with nearly the entire remaining portion conducted into the workpiece and cutting tool. At elevated temperature the cutting tool if not enough hard may lose their form stability quickly or wear out rapidly resulting in increased cutting force, dimensional inaccuracy of the product and shorter tool life [41]. Longer cut under high cutting temperature causes 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 chance of premature failure of the tool by plastic deformation and thermal fracturing. It has already been reported [42, 43] that the use of conventional cutting fluids (wet machining) does not serve the desired purpose in machining steels by carbides, rather reduce tool life and often may cause premature failure of the insert by brittle fracture. Cutting with the excess amount of cutting fluids is still very common in conventional machining to control high cutting temperature which adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products.

1.2.3 Alternative Lubrication Systems in Machining

During machining cutting temperature is an apprehensive element and it is essential to control this cutting temperature for lesser tool wear and good surface finish. Cutting fluid reduces cutting temperature and also provides lubrication effect between the tool and work interface. There are different types of lubrication as well as cooling system available to reduce the cutting temperature. Many researchers also made their investigations using these different types of cooling and lubrications systems like flood cooling, near dry cooling, or micro lubrication, high pressure jet cooling, cryogenic cooling and MQL cooling. Flood cooling reduces temperature to some extent by bulk cooling but is not very much effective because without reaching into the interface where maximum temperature attains, it cools only the top surface of the job due to its overhead application. It has some bad effects too; when cooling fluid comes in contact with the human body it creates skin irritation, bronchitis, lung cancer etc.

Cryogenic machining with liquid nitrogen machining [44] and with minimum quantity lubrication (MQL) [45] has improved machinability of steel to a certain extent under normal cutting conditions. It has also been reported that the machining of steel with liquid nitrogen improves the machinability index such as less cutting forces, reduce cutting temperature, better surface finish and improve tool life compared to dry machining. Ding et al. [46] commented on the favorable role of cryogenic cooling in chip breaking and in reducing cutting temperature in turning. Cryogenic machining is costly due to high cost of liquid nitrogen. It also accelerated notch wear on the principal flank of the carbide insert under nitrogen rich atmosphere of cryogenic machining.

High-pressure coolant is a possible solution for high speed machining in achieving intimate chip-tool interaction, low cutting temperature and slow tool wear while maintaining cutting forces/power at reasonable levels if the high pressure cooling parameters can be strategically tuned [47]. With the use of high-pressure coolant during machining under normal cutting conditions, the tool life and surface finish are found to improve significantly. Mazurkiewicz et al. [48] reported that a coolant applied at the cutting zone through a high-pressure jet nozzle can reduce the contact length and coefficient of friction at chip-tool interface and thus can reduce cutting forces and increases tool life to some extent. But reaching to the boiling temperature the fluid produces harmful smoke that is injurious to health. Splashing and spreading of coolant during injection creates a dirty working zone.

MQL machining is environmental friendly and also capable to reduce the huge amount of heat generated in machining process if level of pressure and velocity of the issuing jet can be maintained effectively accordingly to the desired cutting. In order to decrease the economical and environmental impacts, near dry machining was addressed as an alternative to the traditional flood cooling application a decade ago [7, 49]. Near dry machining refers to the process of using a small amount of cutting fluid, typically in the order of 100 ml/hr or less, which is about ten-thousandth of the amount of cutting fluid used in flood cooling machining [8, 50]. The concept of near dry machining is based on the principles of less lubrication or minimum quantity lubrication in the machining process. Near dry machining is also recognized as minimum quantity lubrication (MQL) machining. Many researches have suggested that MQL shows its potential competitiveness in terms of tool life, surface finish and cutting forces in turning, milling, reaming and taping. Most documented studies thus far relating to MQL are constructed upon experimental observations with individual and separate treatment of machining performance measures such as cutting force, cutting temperature, tool wear progress, chip formation, surface roughness, or air quality. Therefore, using MQL technique, which reduces remarkable machining costs, can be obtained reducing the quantity of lubricant used in machining.

1.2.4 Machining with Minimum Quantity Lubrication (MQL)

The minimization of cutting fluid 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 semi-dry machining recently and minimum quantity lubrication (MQL) machining in particular has been accepted as a successful semidry application because of its environmentally friendly characteristics. Minimum quantity lubrication (MQL) systems employ mainly cutting fluids that are non-soluble in water, especially mineral oils. Due to very small amounts of cutting fluids used, one must consider that the costs should not prevent the use of high technology compositions in the field of additive oils. Vegetable-based materials are being increasingly used. These oils, inhaled in the form of aerosol, reduce the health hazard factor [11].

Minimum quantity lubrication is a recent technique introduced in machining particularly, in turning and grinding to obtain safe, environmental and economic benefits, reducing the use of coolant lubricant fluids in metal cutting. 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 less than the amount commonly used in flood cooling condition. A number of studies have been shown that MQL machining can show satisfactory performance in practical machining operations [7, 8, 13, 49, 50, 51].

Lugscheider et al. [52] used MQL technique in reaming process of gray cast iron and aluminium alloy with coated carbide tools and concluded that it caused a reduction of tool wear when compared with the completely dry process and, consequently, an improvement in the surface quality of the holes.

Dhar et al. [45] also employed MQL technique in turning process of AISI-1040 steel. He investigated the influence of near dry lubrication on cutting temperature, chip formation and dimensional accuracy and concluded that cooling ability of MQL increased the tool life compared to dry machining and wet machining. Based on the experimental results, the authors found that near dry lubrication resulted in lower cutting temperatures compared with dry and flood cooling. The dimensional accuracy under near dry lubrication presented notable benefits of controlling the increase of the work piece diameter when the machining time elapsed where tool wear is observed. Dimensional accuracy was improved with the use of near dry lubrication due to the reduction of tool wear and damage.

Braga et al. [13] reported that the holes obtained during drilling of aluminum-silicon alloys with uncoated and diamond-coated K10 carbide tools using MQL technique presented either similar or better quality than those obtained with flood lubricant system. The investigations carried out by Kelly et al. [53] on aluminum alloy revealed that the MQL technique is preferable for higher cutting speeds and feed rates.

Davim et al. [54] carried out experimental investigations on machining of brass under different conditions of lubricant environments. The influence of cutting speed and feed rate on machinability aspects were studied and concluded that flood lubrication can be successfully replaced by MQL type of lubrication.

Machado et al. [55] applied 200-300 ml/hr of lubricant in a venturi-mixed air stream when turning steel bars. The results showed that surface roughness, chip thickness and cutting forces variations were improved compared to the conventional flood cooling situation. It was also found that the cutting and feed forces were reduced with the use of cutting fluids when turning medium carbon steel bars under low cutting speeds and high feed rates. Cutting with near dry lubrication had better results than conventional flood cooling in reducing the variation of cutting forces and extending the tool life. The effect of near dry lubrication on surface finish and chip thickness was only noticeable at low cutting speeds and high feed rates. The application of near dry lubrication also reduced the cost of cutting fluids and related equipments. However, the aerosol concentration increased compared with traditional flood cooling case.

Varadaranjan et al. [56] found that during hard turning of AISI 4340 steel under near dry lubrication had better performance than that in dry or wet cutting in terms of cutting forces, temperatures, surface roughness, tool life, cutting ratio and tool chip contact length. Lower cutting forces, lower cutting temperatures, better surface finish, shorter tool chip contact length, larger cutting ratio and longer tool life were observed in near dry turning compared with those in dry or wet cutting.

The effects of oil-water combined mist on turning had been investigated by Chen et al. [57] on the stainless steel with the use of 17 ml/hr oil and 150 ml/hr water mixture. The use of oil water combined mist could prevent the production of built-up edge (BUE), while BUE was observed when cutting dry or with oil mist. Lower cutting temperatures were also observed with the use of oil-water combined mist compared to cutting dry or with oil mist.

Diniz et al. [58] applied 10 ml/hr oil in turning SAE 52100 steel with CBN tools. The lubricant was delivered in a supplying air pressure of 4.5 bars. The experimental outputs are concluded as follow: (i) Dry and near dry machining had similar performance in terms of CBN tool flank wear, always better than the tool life under flood cooling. (ii) The work piece surface roughness measured in near dry cutting was close to that obtained from dry cutting.

Wakabayashi et al. [59] suggested that ester supplied onto a rake face of a tool decomposes to carboxyl acid and alcohol and its carboxylic acid forms a chemisorbed film with lubricity. Itoigawa et al. [60] suggested that in practical condition when high machining load is applied, this type of boundary film is uncertain. Therefore the investigation for the minimum lubrication mechanism in actual conditions must be essential.

Minimum quantity lubrication (MQL) has been applied in grinding by Brinksmeier et al. [61] on two different work materials, one was hardened steel (16MnCr5) and another was tempered steel (42CrMo4V). The author observed that though both dry and near dry grinding would cause thermal damage on the hardened material with the creep feed grinding operation, acceptable surface finish was obtained under minimum quantity lubrication.

1.2.5 MQL Machining with Heat and Wear Resistant Tools

Cutting tool selection is an important criterion in machining all types of metals so that it can withstand the high cutting speed where the high cutting temperature generation is occurred. There are primarily three problems occurred in the cutting tool faces such as heat generation in the chip-tool contact zone, wear at the cutting edge, and thermo-mechanical shock. The correct hardness, toughness, wear resistance, and chemical stability of any cutting tool material will stay long run with machining materials. In general, increased hardness improves wear resistance but is associated with decreased toughness. Reed et al. [62] 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. Depending on machining conditions and workpiece properties, different degree of hardness or toughness is required.

When machining steel with coated carbide tools different tool wear mechanisms occur, such as: abrasion, adhesion, oxidation and even some diffusion, which act simultaneously and in proportions depending mainly on the temperature [63]. The task of defining which of those mechanisms is the predominant one has become a very complex task. However, some researches relating wear mechanisms to the cutting speed have been made and some important results have been published. For example, the raise in temperature at the cutting zone occurs basically due to the cutting speed increase. The abrasion phenomenon occurs predominantly at low cutting speeds, adhesion at medium ones and oxidation/diffusion at high ones. The limit of growing for cutting speed depends on several other factors, such as tool-workpiece combination, contact time between them and the presence of cutting fluids. However, those findings are only indications and may not offer more than recommendations for practical applications.

In machining of steels the use of proper coating structure can contribute to substantial reduction of the friction action between the rake and chip and result in a decrease in heat generation and lower the tool-chip interface temperature. The improvement in the coatings of carbide tools and in the chemical and mechanical properties of tool materials has caused the increase of tool working life in machining processes [64]. The selection of work piece material with low thermal conductivity and low heat capacity and coating material with low thermal conductivity leads to a reduction in the contact length, resulting in the effect of a thermal barrier. As a consequence, heat is concentrated within the thin top layer of the coating to protect the tool against diffusion.

The application of high cooling type water base cutting fluids is generally avoided in machining steels by brittle type cutting tools like carbides and ceramics due to close curling of the chips and thermal shocks. But it is also a vital concern to continue the environmental friendly machining system which is caused by the use of cutting fluid, particularly oil-based type. Due to the several negative effects the conventional cutting fluids utilized in machining are considered a problem for manufacturers. Moreover, large quantities of emulsion based cutting fluids for machining are still widely used in the metal working industry which generates high costs of consumption and disposal. These fluids are seriously harmful for the environment and day by day these environmental concerns have become an important issue to production process associated with their economic and technological aspects. These combined aspects have been forced the industrial sector, research centers and universities to investigate alternative production processes, to create technologies that minimize or avoid the production with environmentally aggressive residues. This increasing need for environmentally friendly production techniques and the rapid growth of cutting fluid disposal costs have justified the demand for alternate machining processes without using fluids [65, 66]. The goal of research in the use of lesser amount of cutting fluids or lubricants in metal production processes has not been achieved so much over the last decades. In comparison to the application of MQL assisted jet, conventional cutting fluids, have less thermal stability and lubricating capability. However, despite its advanced lubrication capability compared to conventional flood cooling, Wahl [67] assumes that in many cases the decrease in temperature due to a reduction in friction is not sufficient to keep the tool at a tolerable temperature level. Barrow [68] states that lubrication is most effective at low cutting speeds, whereas cooling becomes increasingly important at higher cutting speeds as the lubricant cannot penetrate into the tool–workpiece interface quickly enough. During machining with MQL some researchers used water insoluble mineral oils or synthetic oils or ester. For this experimentation, VG 68 hydro clear straight run cutting oil and vegetable oil are selected as MQL oil.

1.2.6 Summary of Literature Review

A review of the literature highlights the immense potential on the machinability of different commercial steel in controlling the machining temperature and also its detrimental effects on machined products. It is realized that the machining temperature has a significant influence on chip configuration, cutting forces, tool wear, tool life and surface roughness. These all responses are very essential in deciding the overall performance of the tool. The modern manufactnring industries face the demand for high production rate which insists the higher MRR. For getting high MRR it is necessary to increase cutting velocity and other process parameters which result higher cutting zone temperature. At such 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 deteriorates due to high temperature. Cutting fluids are essential to reduce the elevated temperature. But the conventional cutting fluids are not that effective for machining with high cutting velocity particularly continuous cutting of materials like steel. Besides this there are some other limitations in using and disposal of cutting fluids to be environmentally harmful and health hazards to the workers. Recycling and reuse of conventional cutting fluids create further problems. Though cryogenic machining improves machinability indices, it is limited by the high cost of cryogen.

In high production machining and grinding, minimum quantity lubrication (MQL) allows for a practicable solution in respect of economic terms and health concerns. In this process minimum quantity lubrication (MQL) is impinged through a nozzle precisely at the narrow cutting zone with a spray of air and cutting oil. Minimum quantity lubrication (MQL) gives the significant performance in machining and grinding process. MQL caused a reduction of tool wear when compared to the completely dry processes and consequently improvement of surface finish. However, even though the results got are encouraging it is required to make further development to achieve the required effects in terms of temperatures, cutting forces, tool wear, tool life and surface finish.

The thesis work was carried out with a view to study the effects of minimum quantity lubrication (MQL) of different cutting fluids on the cutting performance of 42CrMo4 steel in terms of average chip-tool cutting temperature, chip thickness ratio, cutting forces and tool wear by coated carbide SNMM-TN2000 insert as compared to completely dry machining. An approach based on the process parameters (speeds, feeds and depth of cut) will be performed to identify the suitable MQL nozzle position for better cooling action. In the study, the lubricant is supplied from a pressurized reservoir and transmitted to the cutting zone as a mixture of fluid and air.

1.3 Objectives of the Present Work

It is exposed from the aforementioned literature review that minimum quantity lubrication (MQL) assisted machining is starting to be established as a method for substantial increase of removal rate and productivity in the metal cutting industry. The economy of machining steel is strongly connected to effective chip control, for higher utilization of machines and temperature reduction in the tool, for raising the rates of metal removal. 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 minimum quantity lubrication (MQL) in such cases. But enough work has not been done systematically yet in this direction.

The main objective of the present research work is to make a thorough and systematic experimental investigation on the roles of minimum quantity lubrication (MQL) by different types of cutting fluids (soluble oil, vegetable oil and VG 68 cutting oil) on the major machinability characteristics in respect of

a. average chip-tool interface temperature

b. chip morphology

   i. chip thickness ratio (r_c) and

    ii. chip shape and color

c. cutting forces (main cutting force, F_c and feed force, F_f)

d. tool wear

    i. principal flank wear, VB

    ii. notch wear, VN

    iii. auxiliary flank wear, VS

e. quality of the finished surface (surface finish, R_a)

in turning alloy steel (42CrMo4 steel) by the industrially used coated carbide insert (SNMM TN 2000) at different cutting speeds, feeds, depth of cut and machining environments combinations.

In this study, the minimum quantity lubrication (MQL) was provided with a spray of air and cutting fluids at a pressure 25 bars and coolant flow rate of 150 ml/hr. The results indicated that the use of minimum quantity lubrication (MQL) by VG 68 cutting oil leads to reduce surface roughness, delayed tool wear and lowered cutting temperature significantly in compare to other environments.

1.4 Scope of the Thesis

There is a lot of scope and necessity to carry out intensive research and development work for more effective and efficient machining of such increasingly used alloy steels. Such research and development work through understanding of mechanism and mechanics of machining of this critical alloy will essentially enable enhanced productivity, product quality, tool life and overall economy in machining though optimum selection of process parameter, tool material and geometry and environment. Minimum quantity lubrication is the possible solution in the machine shops in respect of environmental friendliness, workers health consciousness, cost effectiveness and in limiting the space requirements which can not be fulfilled by the conventional application of cutting fluids. Considering the overall economical feasibility MQL application does not affect the essentially important technological requirements rather works favorable in respect of power consumption, product quality and tool life. From that point of view, the present thesis work has been taken up to explore the role of minimum quantity lubrication (MQL) on the major machinability characteristics in machining (turning) 42CrMo4 steel by coated carbide tools under different machining conditions.

Chapter 1 presents the general requirements in machining industries, role of cutting tools and problem associated with high cutting temperature, selection of cutting fluids, the conventional cooling practices and expected role of minimum quantity lubrication (MQL). Literature review and objectives of the present work are also presented in this chapter.

Chapter 2 presents the procedure and conditions of the machining experiments carried out. The experimental results on the effects of MQL (VG 68 cutting oil and vegetable oil) relative to dry machining on cutting temperature, chip morphology, cutting forces, cutting tool wear and surface roughness in turning alloy steel (42CrMo4 steel) under different cutting conditions. Calibration results of tool-work thermocouple comprising of experimental steel and cutting insert are also presented in this chapter.

Chapter 3 presents the discussion on experimental results obtained under different environments during turning the concerned steel with referred insert on cutting temperature, chip morphology, cutting forces, cutting tool wear and surface roughness to evaluate the effect of dry and MQL conditions on the performance of cutting tool.

Chapter 4 contains the concluding remarks and also provides some recommendations for future work. References are included at the last chapter.

Chapter-2

Experimental Investigations

2.1 Introduction

The economy of machining steel is strongly connected to effective control of the cutting zone temperature and control of chip thickness for higher utilization of machines and for raising the metal removal rate with temperature reduction in the tool. Minimum quantity lubrication (MQL) with its ability to provide excellent cooling at relatively lower cost is an attractive and viable option in this regard. The effectiveness, efficiency and overall economy of machining any work material by given tool depend largely on the machinability characteristics of the tool-work material under the recommended conditions. The conditions are

i. cutting temperature; that affects product quality and cutting tool performance

ii. chip formation mode and pattern of machined chip

iii. magnitude of cutting forces; which affects power requirements, vibration and dimensional accuracy

iv. surface finish

v. tool wear and tool life

The beneficial role of minimum quantity lubrication on environmental friendliness has already been established. The aim of the present work is to study the machining responses in terms of cutting temperature, chip-forms, cutting forces, tool life, and surface finish which governs productivity, product quality and overall economy and to assess the machinability characteristics of alloy steel (42CrMo4 steel) specimen under both dry and minimum quantity lubrication (MQL) conditions. For achieving substantial technological and economical benefits in addition to environmental friendliness, minimum quantity lubrication needs to be properly designed considering the following important factors:

i. effective cooling by enabling MQL jet reach as close to the actual hot cutting 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 of jet during chip formation.

It is necessary to mix air and lubricant to obtain the mixture to be spread on the cutting surface. Pressurized air and lubricant are mixed in the mixing chamber. The mixture of the air and cutting fluid is impinged at a high speed through the nozzle at the chip- tool interface. Fig. 2.1 shows the schematic view of the mixing chamber along with nozzle used for the present work.

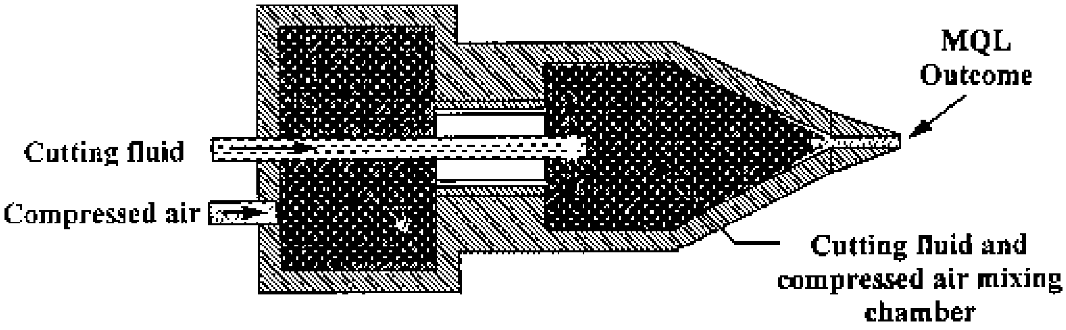


Fig. 2.1 Schematic view of Mixing Chamber for MQL Supply [69]

2.2 Experimental Procedure and Conditions

Machining steel by coated carbides is a major activity in the manufacturing industries. Machining of steel involves more heat generation for their ductility and production of continuous chips having more intimate and wide chip-tool contact. In this experiment MQL conditions are used during machining to compare the results with that of obtained under dry condition. Minimum quantity lubrication (MQL) based machining has been accepted as a successful semidry application because MQL has positive part on environment friendliness as well as techno-economical benefit. To evaluate and explore the role of different cutting fluids on the machinability of a tool-work combination, frequently used in machining industries, mostly in terms of cutting temperature, chip morphology, cutting forces, tool wear and surface finish, which manage product quality, productivity and overall economy is endeavor of the present work.

The machining tests have been carried out by turning 42CrMo4 steel in a lathe (7.5 kW) at different cutting speed-feed condition under dry and MQL environments at a constant depth of cut by coated carbide insert (SNMM-TN2000). The conditions under which the machining tests have been carried out are briefly given in Table 2.1. A number of cutting speed, feed and depth of cut have been taken over relatively wider ranges keeping in view the industrial recommendations for the tool-work materials undertaken and evaluation of role of variation in V and f on effectiveness of MQL. Keeping in view less significant role of depth of cut (d) on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.0 mm, which would adequately serve the present purpose.

Table 2.1 Experimental conditions

Machine tool	:	Lathe (China), 7.5 kW
Work material	:	42CrMo4 steel
Composition	:	C=0.38-0.45%, Si=0.40%, Mn=0.60-0.90%, P=0.025%, S=0.035%, Cr=0.90-1.20%, Mo=0.015-0.030%
Size	:	Φ 160 X 550 mm
Cutting tool	:	Coated carbide SNMM -TN2000, WIDIA 
Tool geometry	:	-6°,-6°,6°,15°,75°,0.8 (mm)
Coating	:	TiCN
Tool holder	:	PSBNR 2525 M12 (WIDIA)
Process parameters		
Cutting speed, V	:	175, 247 and 352 m/min
Feed rate, f	:	0.10, 0.12 and 0.14 mm/rev
Depth of cut, d	:	1.00 mm
MQL supply	:	Air pressure 23 bars, oil pressure 25 bars and flow rate 150 ml/hr
Environment	:	i. Dry ii. MQL with Vegetable oil iii. MQL with VG 68 Cutting oil and iv. MQL with Soluble oil

Cooling effectiveness and the related benefits depend on how closely the MQL jet can reach the chip-tool and work-tool interfaces where, apart from the primary shear zone, heat is generated. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Coated carbide insert has been used for the present work considering common interest and time constraint only. A standard tool configuration namely SNMM-TN2000 has been undertaken for the present work. The insert has been clamped in a PSBNR 2525 M12 type tool holder. The orientation of nozzle tip regarding the cutting insert has been settling after a few trials. The thin but high velocity stream of MQL has been heading for along the auxiliary cutting edge of the insert, so that the coolant reaches as close to the chip-tool and work-tool interfaces as possible and cools the above mentioned interfaces and both the principal and auxiliary flanks effectively as well. Fig. 2.2 shows the photographic view of the experimental set up used in the present investigation.

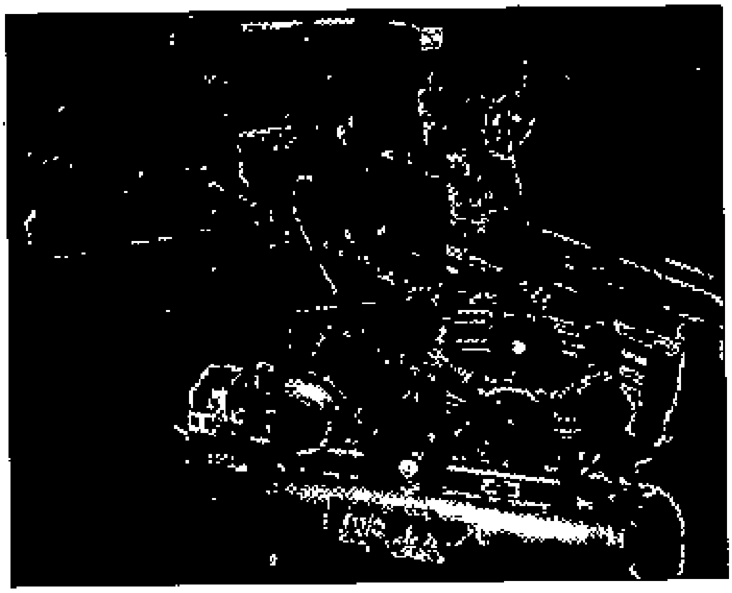


Fig. 2.2 Photographic view of the experimental set up [69]

Minimum quantity lubrication (MQL) system consists of a compressor for compressing and delivering compressed air at the desired pressure, mixing chamber for mixing cutting fluid and compressed air, suitable nozzle to impinge MQL to the cutting zone, pressure and flow control valves for effective economical use of cutting fluid. Compressor and MQL applicator are the two major components of MQL system. Compressor acts as air supply unit and is able to develop a maximum pressure of 23 bars. However, the main purpose of the compressor is to supply air at a pressure, which is required to set in the different components of MQL applicator. The fluid chamber is used to contain the cutting fluid selected for a particular machining. The high pressure air from the compressor enters into two chambers, one is fluid chamber and other is mixing chamber. Fluid chamber has an inlet port and an outlet port at the top and the bottom respectively. It is connected to the compressor by a flexible pipe through the inlet port to keep the fluid inside chamber under a constant pressure of 25 bars. It is required to maintain the flow of cutting fluid into the mixing chamber at constant rate over a long period of time during machining. For this a flow control valve is used in between the fluid chamber and the mixing chamber. In this study, MQL jet was provided with a spray of air and cutting fluids at a pressure 23 bars and coolant flow rate of 150 ml/hr.

The average chip-tool interface cutting temperature was measured under dry and MQL conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. This method is very useful to specify the effects of the cutting speed, feed rate and cutting parameters on the temperature. Thermocouples are conductive, rugged and inexpensive and can operate over a wide temperature range. But proper functioning of this technique needs care about parasitic emf generation. To avoid generation of parasitic emf, a long carbide rod was used to extend the insert during calibration. Tool and workpiece have been insulated from the machine tool. To record emf as milivolt a digital multi-meter (Rish Multi, India) has been used where one end of multi-meter has been connected to the workpiece and other end to the tool. The graphical view of variation of temperature with different emf (mV) has been shown in Fig. 2.3.

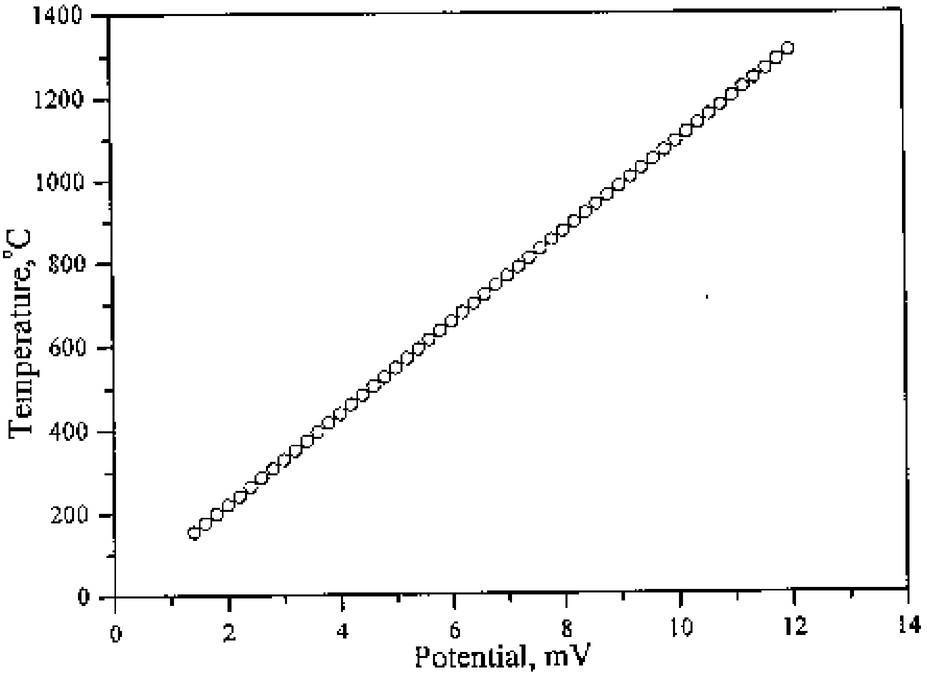


Fig. 2.3 Temperature calibration curve for 42CrMo4 steel and carbide [69]

The cutting insert was withdrawn at regular intervals to study the pattern and extent of wear on main and auxiliary flanks under both dry and MQL conditions. The average width of the principal flank wear, VB and auxiliary flank wear, VS were measured using metallurgical microscope (Carl Zeiss, Germany) fitted with micrometer of 1μm resolution. No notch wear was observed during measuring under optical microscope. The surface roughness of the machined surface after each cut was measured by a Talysurf roughness checker(Surtronic 3^+, Rank Hobson, UK) using a sampling length of 0.8mm.

2.3 Experimental Results

2.3.1 Cutting temperature

During machining 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 and (c) work-tool interface due to rubbing during machining of any ductile materials. Maximum temperature has been produced at the chip-tool interface by all such heat sources which substantially influence the chip formation mode, cutting forces and tool life. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting speed, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. Conventional cutting fluid application, may or to some extent cool the tool and job in bulk but can not cool and lubricate expectedly at the chip-tool interface where the temperature is maximum. This may be happened due to the bulk contact of flowing chips with the tool rake surface or due to elastic contact with the tool before leaving the chips. 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 cutting speed when the chip-tool contact becomes almost fully plastic or bulk. Besides this, at elevated temperature the cutting tool if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. In the present work the average chip-tool interface temperature has been measured under both dry and MQL conditions by tool-work thermocouple techniques during turning of 42CrMo4 steel by coated carbide (SNMM TN-2000) insert at different V-f combinations have been shown graphically in Fig. 2.4, Fig. 2.5, Fig. 2.6 and Fig. 2.7.

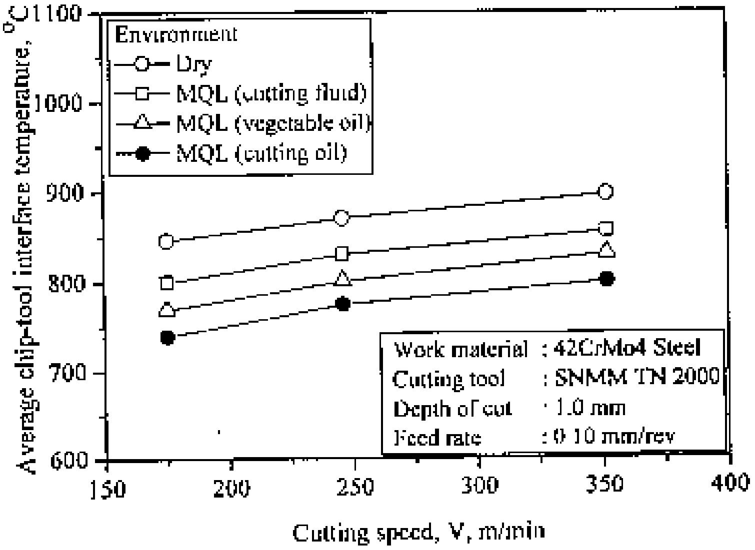


Fig. 2.4 Variation of average chip-tool interface temperature (θ) with cutting speed (V) under different environments at f = 0.10 mm/rev

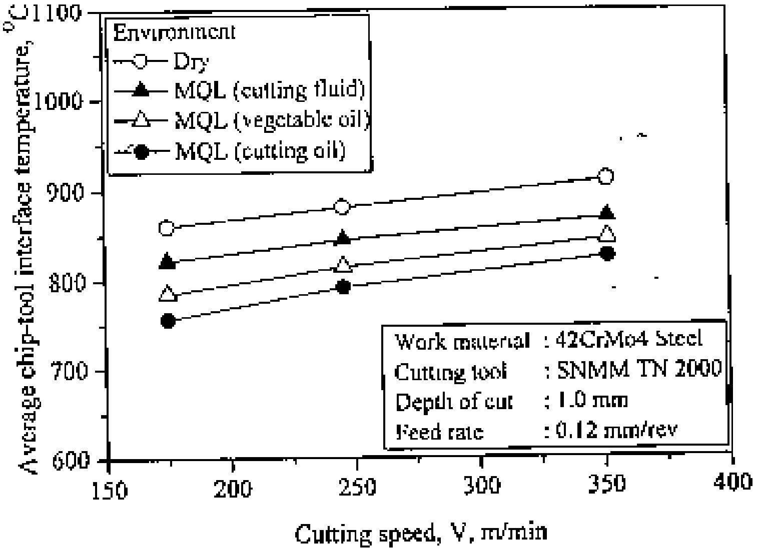


Fig. 2.5 Variation of average chip-tool interface temperature (θ) with cutting speed (V) under different environments at f = 0.12 mm/rev

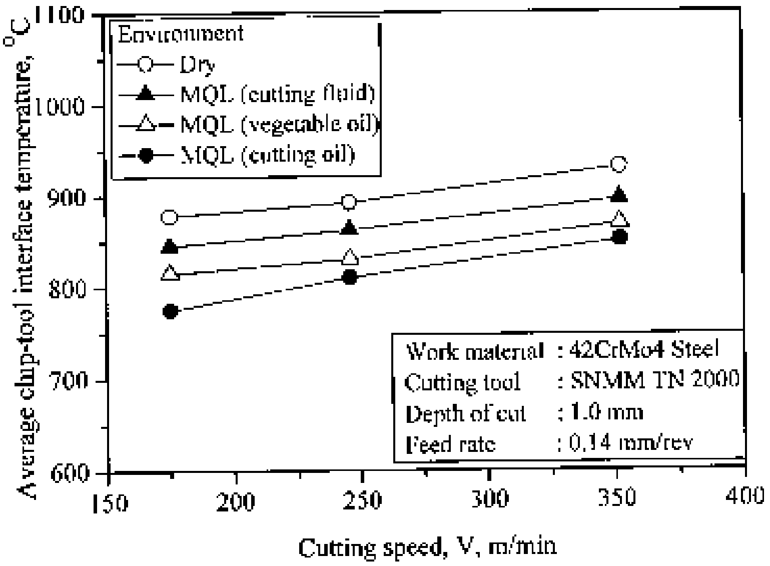


Fig. 2.6 Variation of average chip-tool interface temperature (θ) with cutting speed (V) under different environments at f = 0.14 mm/rev

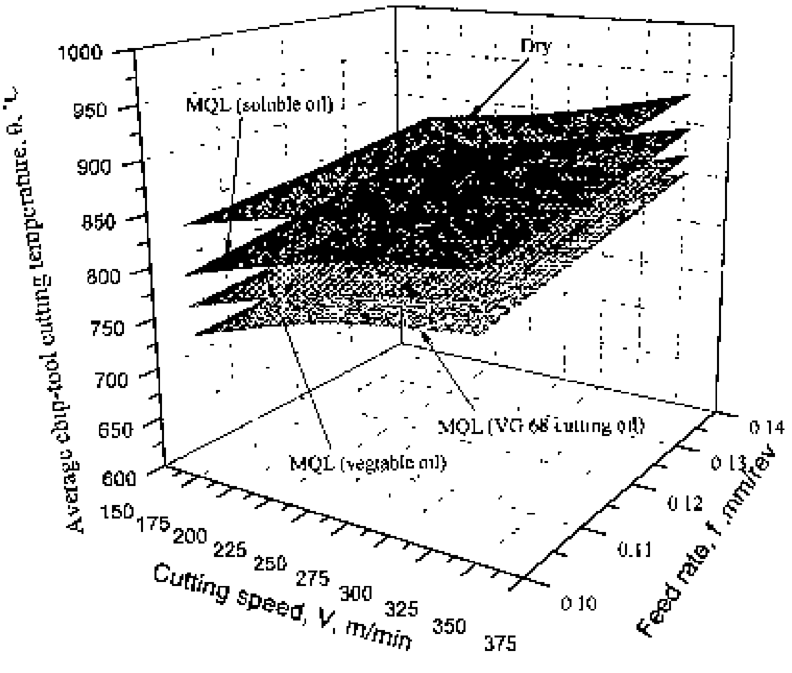


Fig. 2.7 Effect of environments on chip-tool interface temperature (θ) evaluated by regression analysis of the experimental data

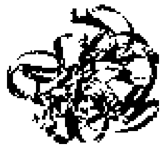
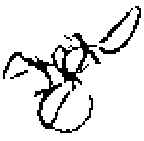
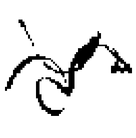
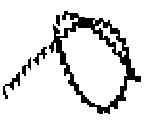
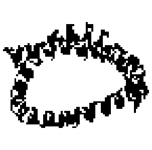
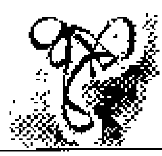
2.3.2 Machining Chips

Machining is a process of shaping by the removal of material which results in chips and the geometrical and metallurgical characteristics of these chips are very representative of the performance of the process because the form (Shape, color) and thickness of the chips directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples were collected during short run turning the 42CrMo4 steel by SNMM-TN2000 insert at different V-f combinations under MQL conditions by three types of cutting fluids (soluble oil, vegetable oil and VG 68) have been visually examined and categorized as per ISO standard 3685 [70] with respect to their shape and color. The results of such categorization of the chips produced at different V-f combinations and environments by the 42CrMo4 steel have been shown in Table 2.2 and Table 2.3 show the actual shape and color of machining chips under different MQL conditions compare to dry condition.

Table 2.2 Shape and color of chips produced during machining 42CrMo4 steel by coated carbide insert (SNMM TN-2000) under different environments

Feed rate, f, mm/rev	Cutting speed, V, m/min	Different MQL environments							
		Dry		MQL (Soluble oil)		MQL (Vegetable oil)		MQL (VG 68 cutting oil)	
0.10	175	snarled ribbon	blue	snarled ribbon	golden	short ribbon	metallic	short ribbon	metallic
	246	snarled ribbon	blue	long tubular	golden	short ribbon	golden	short ribbon	metallic
	352	snarled ribbon	blue	snarled ribbon	blue	short ribbon	blue	short ribbon	metallic
0.12	175	snarled ribbon	deep blue	long tubular	metallic	short ribbon	metallic	short ribbon	metallic
	246	snarled ribbon	blue	long tubular	golden	short ribbon	metallic	short ribbon	metallic
	352	long tubular	deep blue	long tubular	golden	short ribbon	golden	short ribbon	golden
0.14	175	snarled ribbon	deep blue	long tubular	golden	short ribbon	metallic	short ribbon	metallic
	246	snarled ribbon	blue	long tubular	golden	short ribbon	golden	short ribbon	golden
	352	long tubular	deep blue	long tubular	golden	short ribbon	metallic	short ribbon	golden

Table 2.3 Actual shape and color of chips produced during machining 42CrMo4 steel by coated carbide insert (SNMM TN-2000) under Different environments

Feed rate, f, mm/rev	Cutting speed, V, m/min	Environments			
		Dry	MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.10	175				
	246				
	352				
0.12	175				
	246				
	352				
0.14	175				
	246				
	352				

The thicknesses of the chips has been repeatedly measured by a slide calliper to determine the value of chip-thickness ratio, r_c, which is an important index of machinability. Chip thickness ratio, r_c (ratio of chip thickness before and after cut) is another important machinability index. For given tool geometry and cutting conditions, the value of r_c depends upon the nature of chip-tool interaction, chip contact length and chip form, all of which are expected to be influenced by MQL in addition to the levels of V and f. The variation in value of r_c with change in V and f and as well as machining environment evaluated for 42CrMo4 steel which have been shown in Fig. 2.8, Fig. 2.9, Fig. 2.10 and Fig. 2.11.

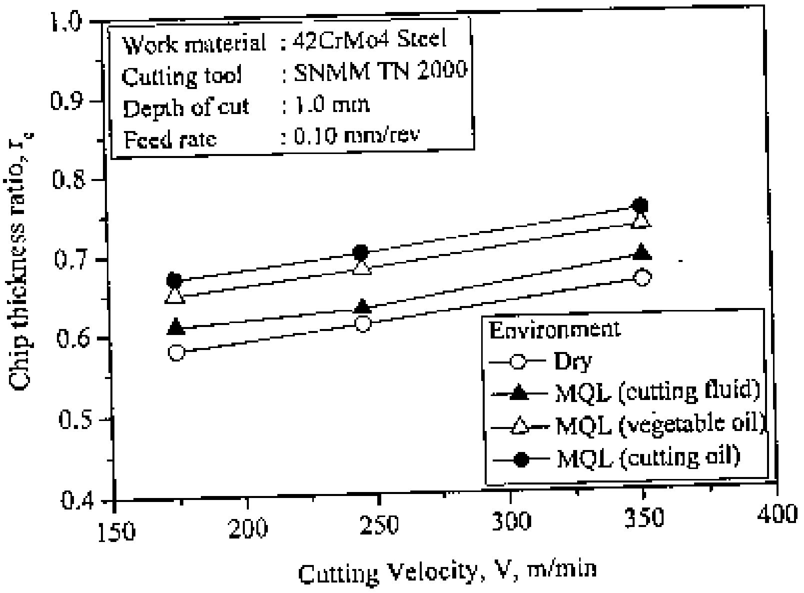


Fig. 2.8 Variation of chip-thickness ratio (r_c) with cutting speed (V) under different environments at f = 0.10 mm/rev

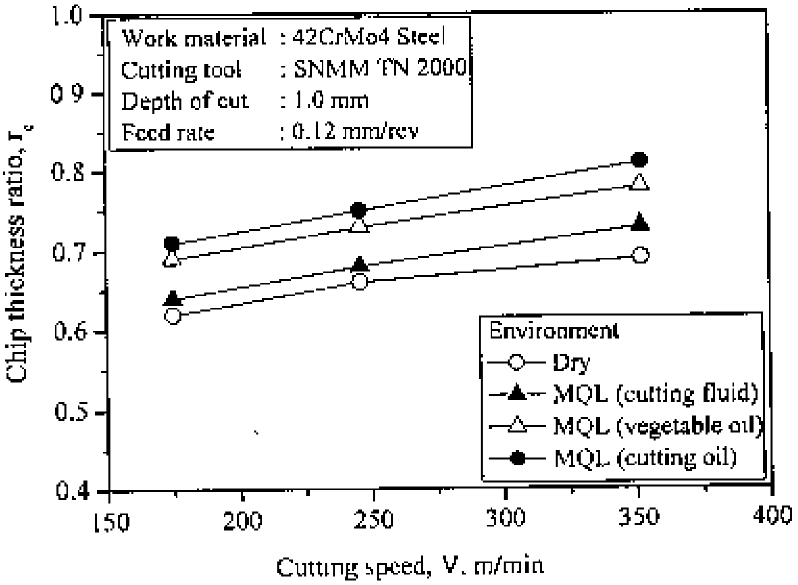


Fig. 2.9 Variation of chip-thickness ratio (r_c) with cutting speed (V) under different environments at f = 0.12 mm/rev

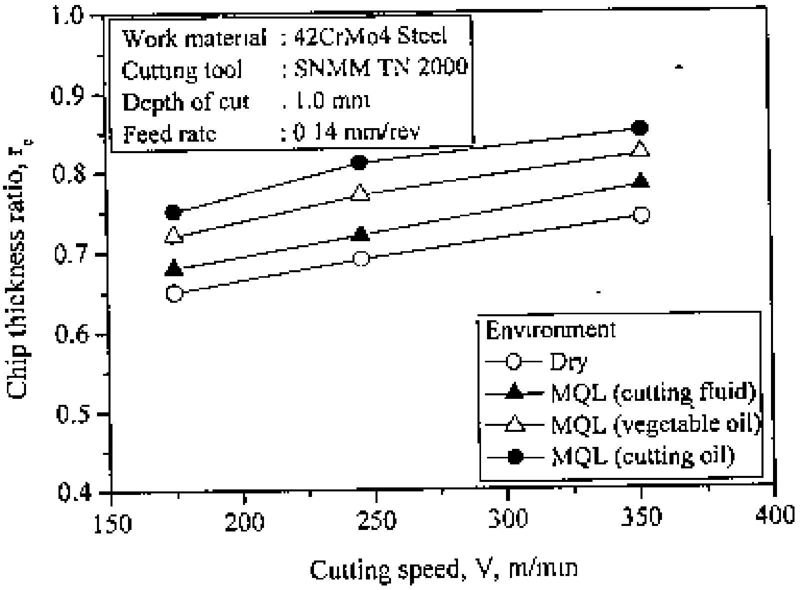


Fig. 2.10 Variation of chip-thickness ratio (r_c) with cutting speed (V) under different environments at f = 0.14 mm/rev

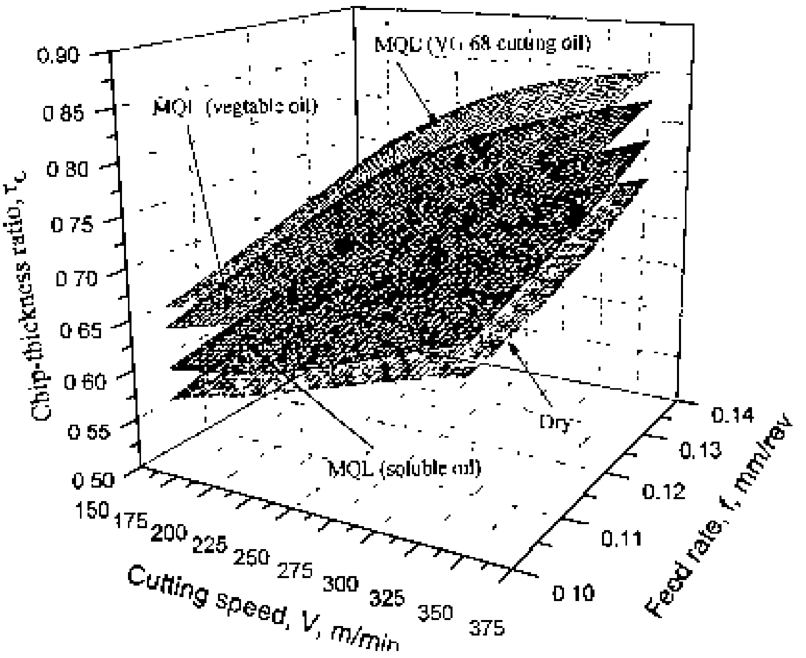


Fig. 2.11 Effect of environment on chip thickness ratio (r_c) evaluated by regression analysis of the experimental data

2.3.3 Cutting Forces

The deformation of a work material means that enough force has been applied by the tool for permanently reshape or fracture the work material. During applying force the plastic limit of material has been exceeded and chip is formed as the excess material. The deformed chip is separated from the parent material by fracture. The cutting action and the chip formation can be more easily analyzed if the edge of the tool is set perpendicular to the relative motion of the material. When a solid bar is turned by single point cutting tool like insert, there are three forces acting on the cutting tool namely as tangential force or main cutting force (F_c), axial force or feed force (F_f), and radial force (F_r) as indicated in

Fig. 2.12 The major deformation starts at the shear zone and diameter determines the angle of shear.

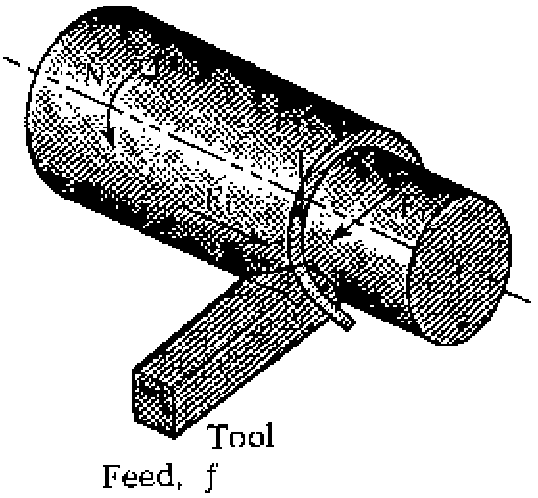


Fig. 2.12 Typical turning operation showing the forces acting on the cutting tool

The tangential force acts direction tangential to the revolving workpiece and represents the resistance to the rotation of the workpiece. In a normal operation, tangential force is the highest of the three forces and accounts for maximum portion of the total power required by the operation. Longitudinal force acts in the direction parallel axis of the work and represents resistance to the longitudinal feed of the tool. Longitudinal force is usually about 50 percent as great as tangential force. Since feed velocity is usually very low in relation to the velocity the rotating workpiece, longitudinal force accounts for only about 1 percent of total power required. Radial force acts radial direction from the center line of the workpiece. The radial force is generally the smallest of the three, often about 50 percent as large as longitudinal force. Its effect on power requirements is very small because velocity in the radial direction is negligible.

Longitudinal turning tests have been studied in depth by a large number of research workers all over the world. Effects of independent parameters (Viz., cutting speed, feed rate, depth of cut, tool angles etc) on dependent machining parameters (Viz., shear angle, cutting forces, shear flow stress, tool chip interface temperature) have been studied during longitudinal turning and also during accelerated cutting [71]. During machining the cutting tool generally undergoes both flank wear and crater wear [24]. Flank wear generally causes an increase in 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 The tool material composition and properties are also crucial to the behavior of the machining forces [72], which in turn affect tool life and surface roughness.

In the present work, the magnitude of main cutting force, F_C and feed force, F_f have been monitored by dynamometer for all the speed-feed combinations under dry, MQL (soluble oil), MQL (cutting oil) and MQL (vegetable oil) machining by coated carbide insert (SNMM-TN2000) which have been shown graphically from Fig. 2.13, Fig. 2.14, Fig. 2.15, Fig. 2.16, Fig. 2.17, Fig. 2.18, Fig. 2.19 and Fig. 2.20.

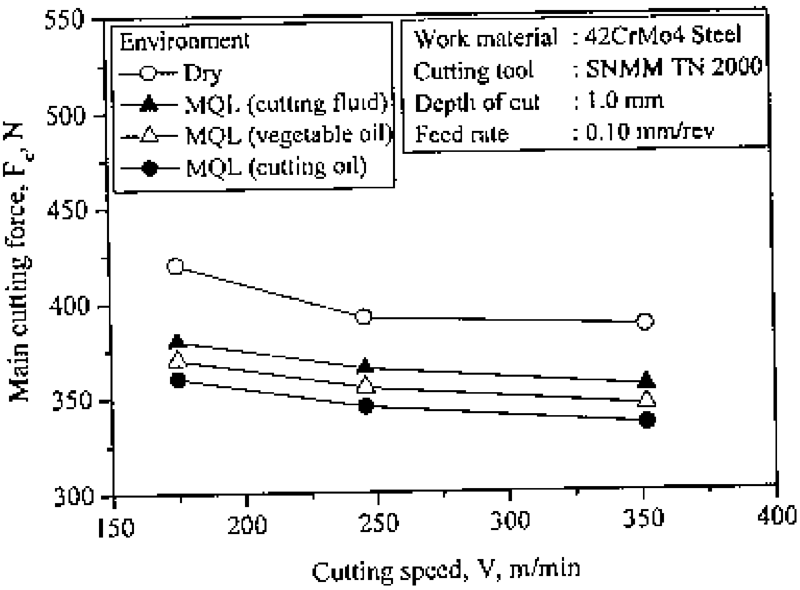


Fig. 2.13 Variation of main cutting force (F_c) with cutting speed (V) under different environments at f = 0.10 mm/rev

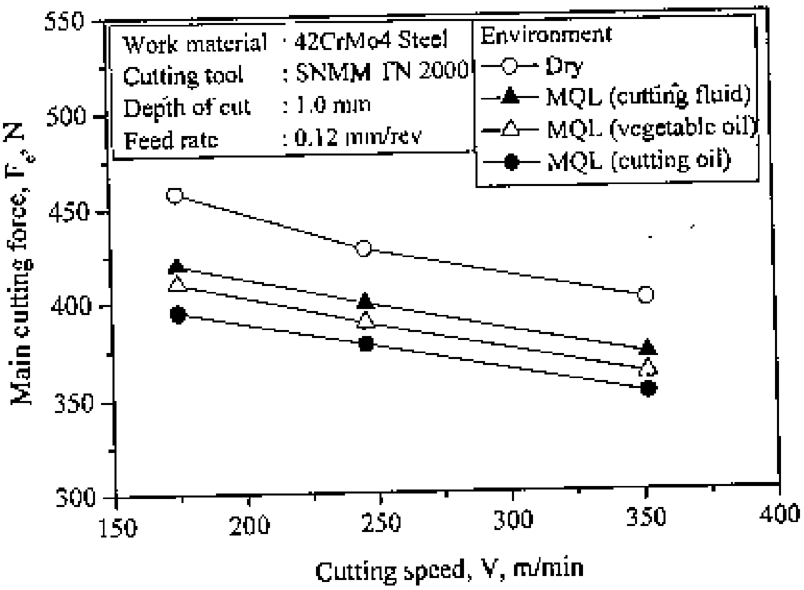


Fig. 2.14 Variation of main cutting force (F_c) with cutting speed (V) under different environments at f = 0.12 mm/rev

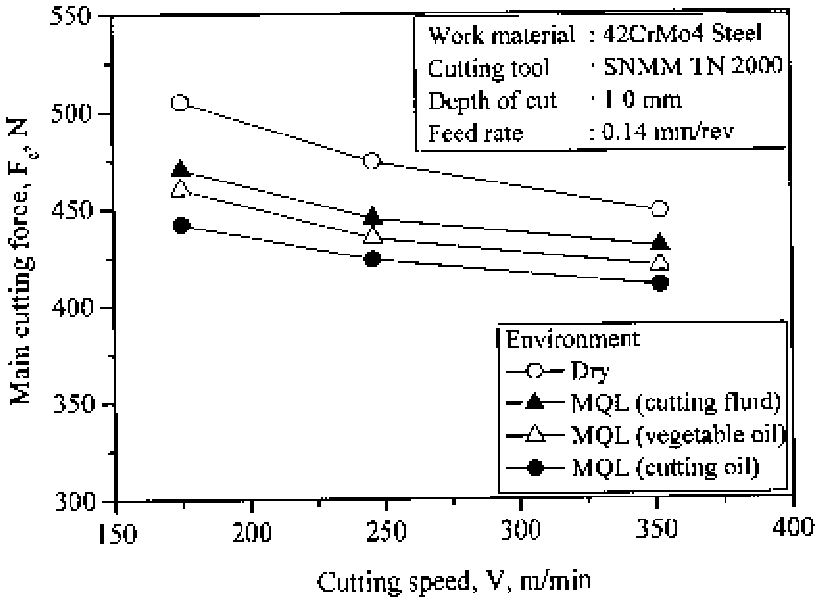


Fig. 2.15 Variation of main cutting force (F_c) with cutting speed (V) under different environments at f = 0.14 mm/rev

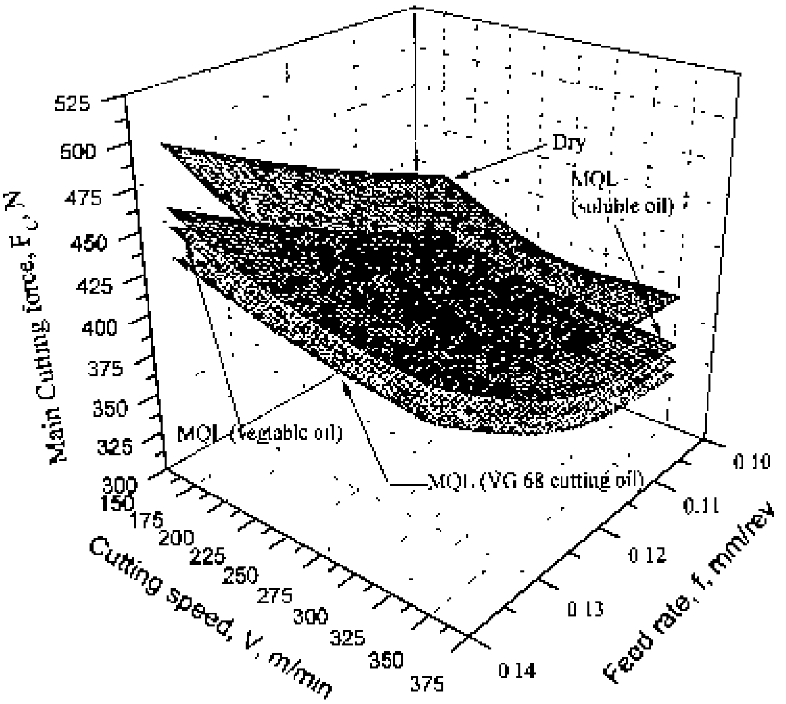


Fig. 2.16 Effect of environment on main cutting force (F_c) evaluated by regression analysis of the experimental data

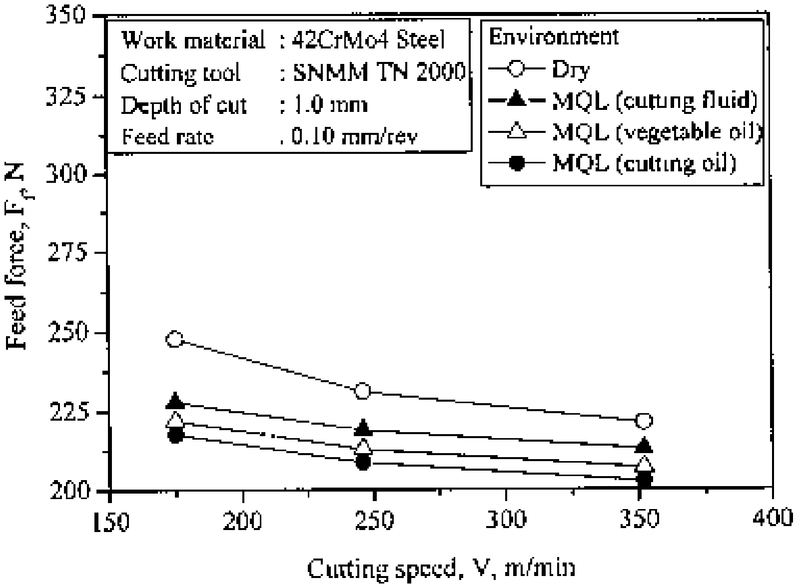


Fig. 2.17 Variation of feed force (F_f) with cutting speed (V) under different environments at f = 0.10 mm/rev

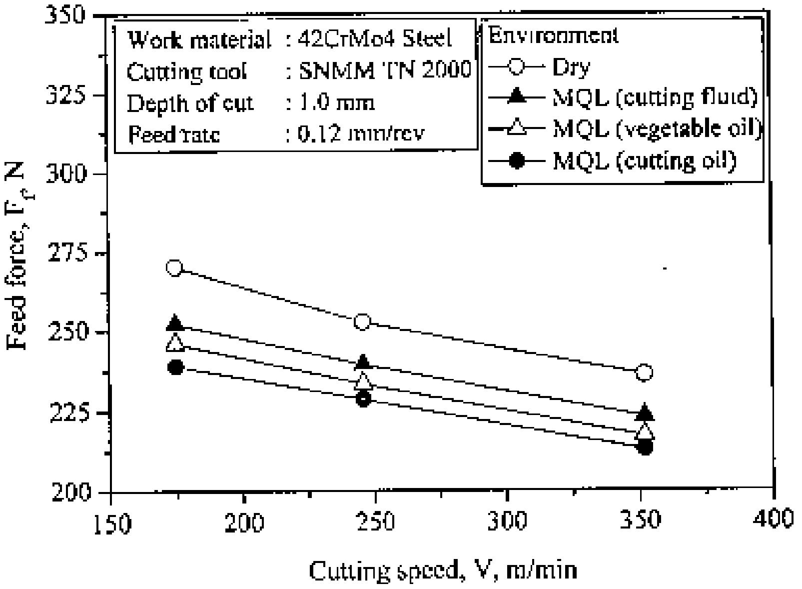


Fig. 2.18 Variation of feed force (F_f) with cutting speed (V) under different environments at f = 0.12 mm/rev

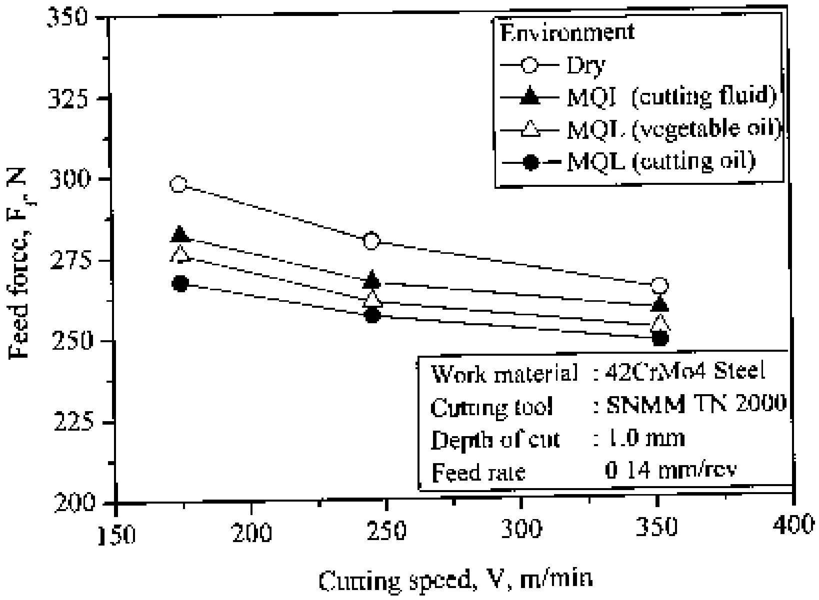


Fig 2.19 Variation of feed force (F_f) with cutting speed (V) under different environments at f = 0.14 mm/rev

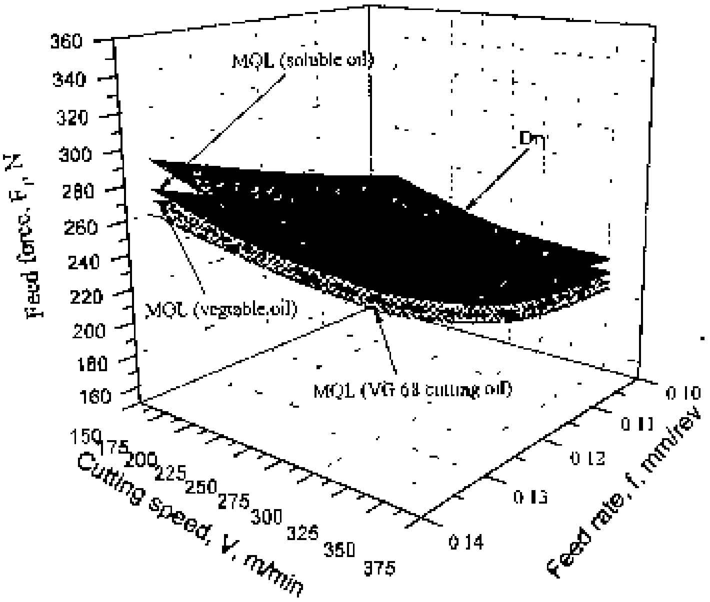


Fig. 2.20 Effect of environment on feed force (F_f) evaluated by regression analysis of the experimental data

2.3.4 Cutting Tool Wear

Tool wear generated due to high cutting temperature could have significantly effects on dimensional, forms and surface roughness errors. As a tool becomes worn, the geometry of the tool tip is changed. The wear of the tool tip on the clearance side will result in loss of the effective depth of cut, which can generate both dimensional and form errors of the workpiece by change of alignment between the tool and the workpiece. In machining tool wear depends on the following parameters:

- The material and shape of the tool
- The material of the machined parts
- Cutting conditions and coolant
- The machining process (turning, milling or drilling etc.)

Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tool. Any tool or work material improvements that increase tool life without causing unacceptable drops in production will be beneficial. In order to form a basis for such improvements, efforts have been made to understand the behavior of the tool, how it physically wears and the wear mechanisms and forms of tool failure. Cutting tools may fail by brittle fracture, plastic deformation or gradual wear. In conventional machining, particularly in continuous chip formation processes like turning, generally the cutting tools fail by gradual wear by abrasion, adhesion, diffusion, chemical erosion. galvanic action etc. depending upon the tool-work materials and machining condition.

Tool wear initially starts with a relatively faster rate due to what is called break-in wear caused by attrition and micro-chipping at the sharp cutting edges. With the progress of machining tools attain crater wear at the rake surface and flank wear at the clearance surfaces respectively due to continuous interaction and rubbing with the chips and the work surfaces respectively. Turning with carbide inserts having enough strength; toughness and hot hardness generally fail by gradual wears. Fig. 2.21 shows the schematic view of general pattern of wear.

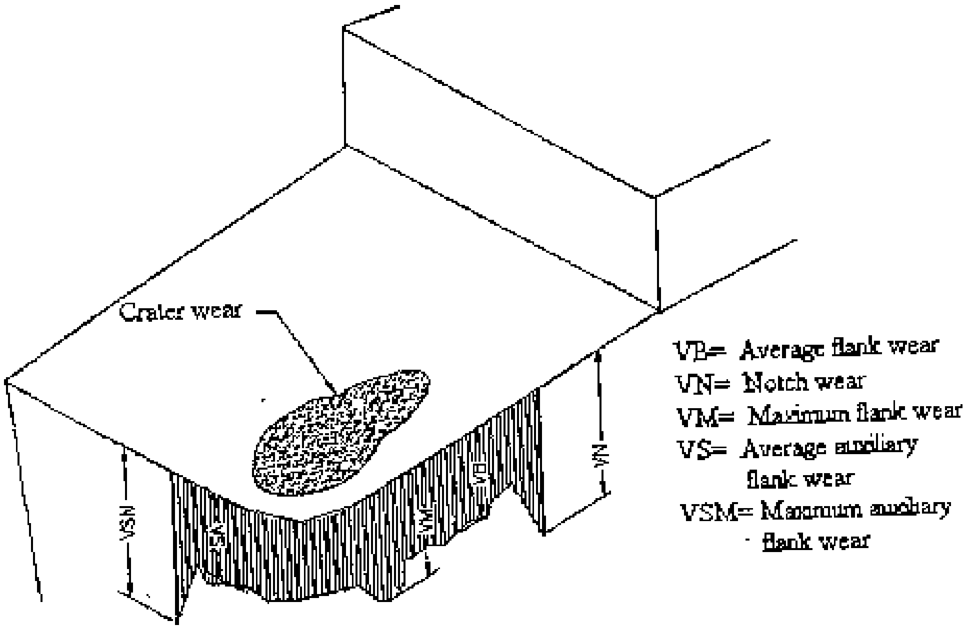


Fig. 2.21 Schematic view of general pattern of wear [69]

Among the aforesaid wears, the principal flank wear is the most important because it aggravates cutting forces and temperature and may induce vibration with progress of machining which influences the dimensional accuracy of finished product. The pattern and extent of the auxiliary flank wear (VS) affects surface finish and dimensional deviation of the machined parts. Growth of tool wear is sizeable influenced by the temperature and nature of interactions of the tool-work interfaces, which again depends upon the machining conditions for given tool-work pairs. Wear may grow at a relatively faster rate at certain locations within the zones of flank wear apart from notching. The width of such excessive wear are expressed by VM (maximum flank wear), VS (average auxiliary flank wear) and VSM (maximum auxiliary flank wear).

In the present investigations the given insert attained significant values of VM and VS in different degrees under different conditions. During machining under each condition, the cutting insert was withdrawn at regular intervals and then the salient features like, VB and VS were measured under metallurgical microscope fitted with micrometer of least count 1.0 μm.

The growth of principal flank wear, VB with progress of machining recorded while turning steel, undertaken by coated carbide insert (SNMM-TN2000) at feed rate f =0.12mm/rev and depth of cut d=1.00 mm and cutting speed V =175m/min under dry, MQL (soluble oil), MQL (vegetable oil) and MQL (Cutting oil) conditions has been shown in Fig. 2.22.

The auxiliary flank wears which affect dimensional accuracy and surface finish have also recorded at a regular interval of machining under all the conditions undertaken. The growth of average auxiliary flank wear, VS with machining time of 42CrMo4 steel under dry, MQL (soluble oil), MQL (vegetable oil) and MQL (Cutting oil) conditions has been shown in Fig. 2.23.

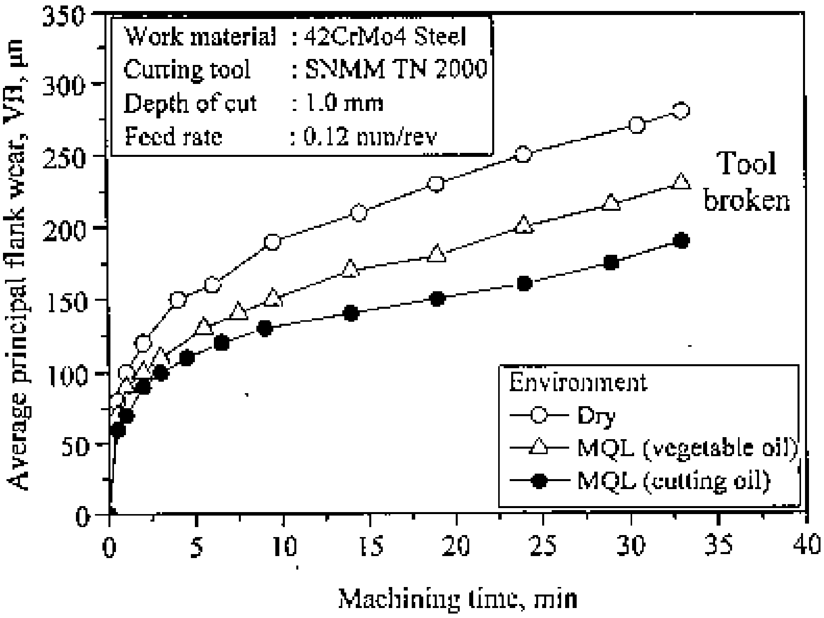


Fig. 2.22 Growth of average principal flank wear (VB) with time recorded during turning 42CrMo4 steel by coated carbide insert (SNMM) under different environments

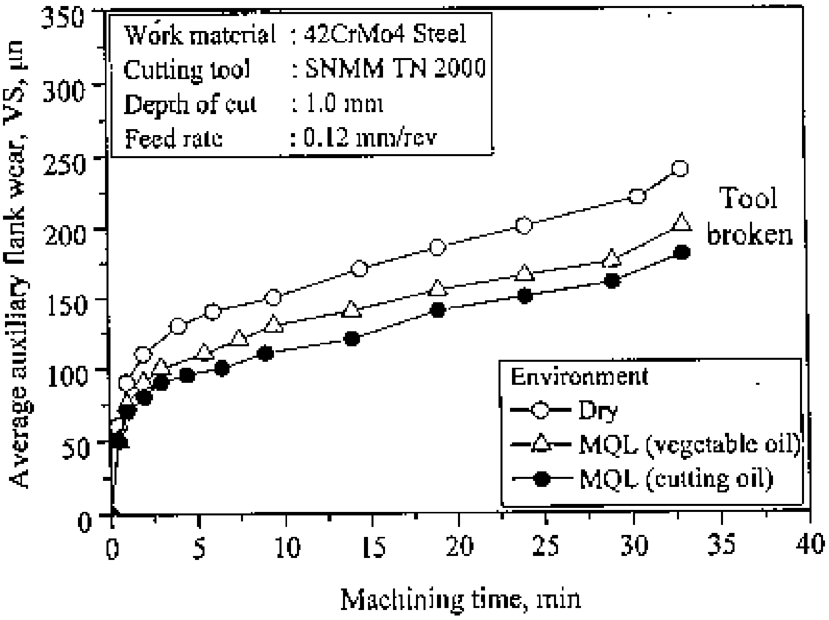


Fig. 2.23 Growth of average auxiliary flank wear (VS) with time recorded during turning 42CrMo4 steel by coated carbide insert (SNMM) under different environments

After machining the steel over reasonably long period the pattern and extent of wear that developed at different surfaces of the tool tips have been observed under SEM in different magnification power. The SEM views represent the actual effects of different environments on wear of the coated carbide inserts of present configurations.

The SEM views of the principal flank of the worn out SNMM insert after about 33 minutes of machining of 42CrMo4 steel under dry, MQL (vegetable oil) and MQL (Cutting oil) conditions have been shown in Fig. 2.24. The SEM views of the auxiliary flank of the worn out SNMM insert after about 33 minutes of machining of 42CrMo4 steel under dry, MQL (soluble oil), MQL (vegetable oil) and MQL (Cutting oil) conditions have been shown in Fig. 2.25.

[illegible]

[illegible]

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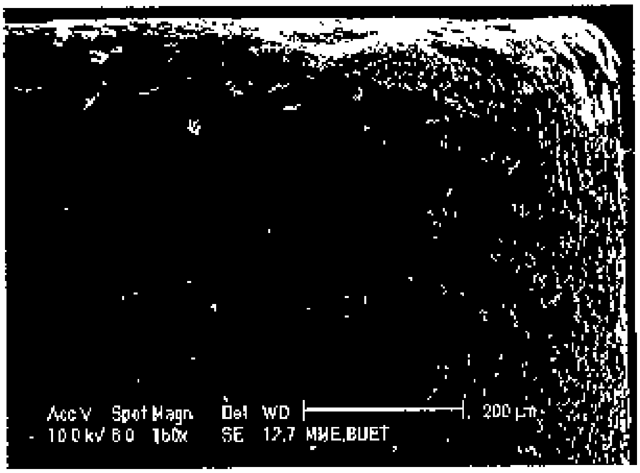
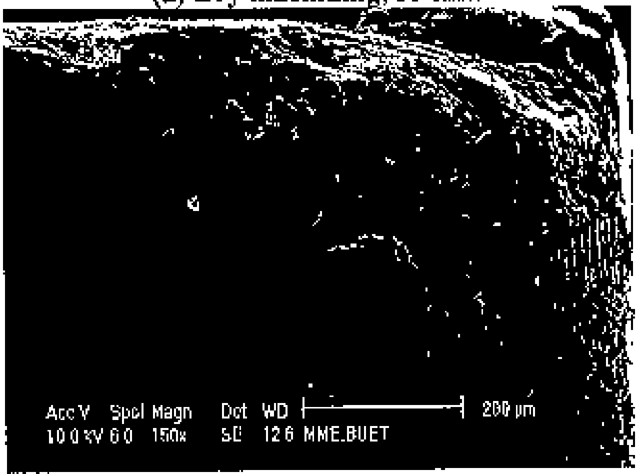
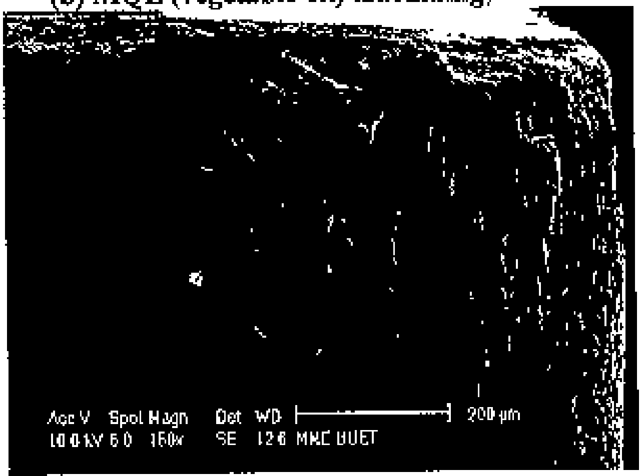
Fig. 2.24 SEM views of principal flank of worn out insert under (a) dry (b) MQL (vegetable oil) and (c) MQL (VG 68 cutting oil) conditions



(a) Dry machining, 33 min



(b) MQL (vegetable oil) machining, 33 min



(c) MQL (VG 68 cutting oil) machining, 33 min

Fig. 2.25 SEM views of auxiliary flank of worn out insert under (a) dry (b) MQL (vegetable oil) and (c) MQL (VG 68 cutting oil) conditions.

2.3.5 Surface Roughness

The performance and service life of any machined part are regularized by the quality of that product, which for a given material is generally assessed by dimensional accuracy and surface integrity of the product in respect of surface roughness, oxidation, corrosion, residual stresses and surface or subsurface micro cracks. Surface roughness is predominantly considered as the most important feature of practical engineering surfaces due to its crucial influence on the mechanical and physical properties of machined parts. So, characterization of surface topography is essential in applications involving friction, lubrication, wear and contact resistance [73]. Surface finish is also important index of machinability or grindability which is substantially influenced by the machining environment for given tool-work pair and speed-feed condition. The 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 particularly when the component is to be used under dynamic loading or in conjunction with some other mating parts.

Surface roughness has been measured at two stages- i) after a few seconds of machining with the sharp tool while recording the cutting forces and ii) with the progress of machining while monitoring growth of tool wear with machining time. The variation in surface roughness observed with advancement of machining 42CrMo4 steel by the coated carbide SNMM insert at a particular set of cutting speed (V), feed rate (f), and depth of cut (d), under dry and different MQL conditions which have been shown in Fig. 2.26, Fig. 2.27, Fig. 2.28 and Fig. 2.29 respectively.

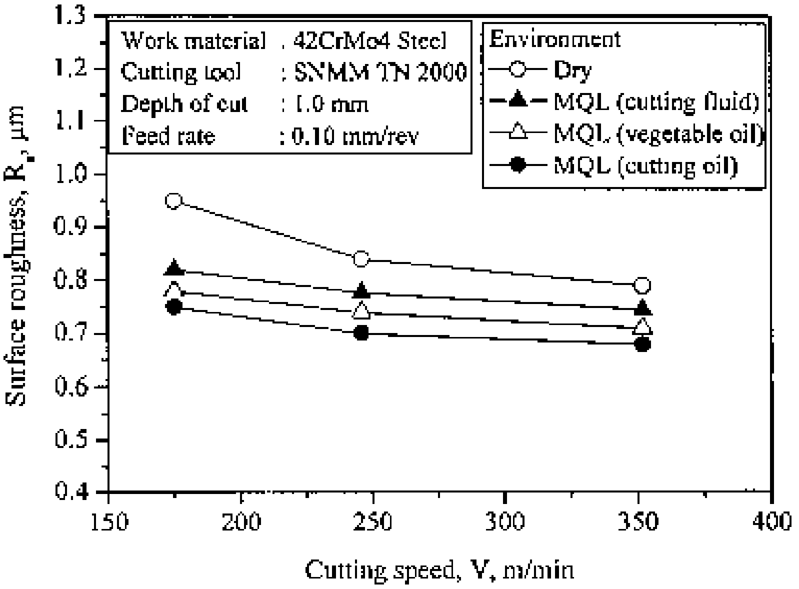


Fig. 2.26 Variation of surface roughness (Ra) with cutting speed (V) under different environments at f = 0.10 mm/rev

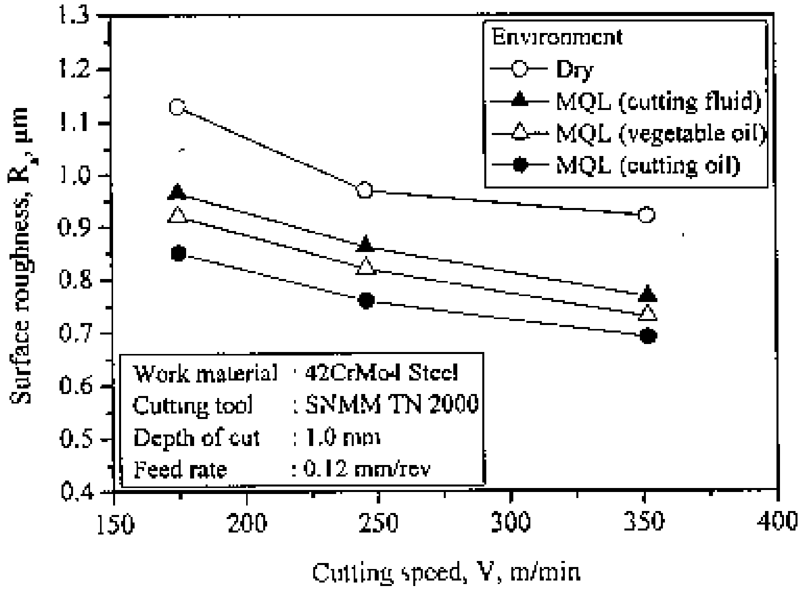


Fig. 2.27 Variation of surface roughness (Ra) with cutting speed (V) under different environments at f = 0.12 mm/rev

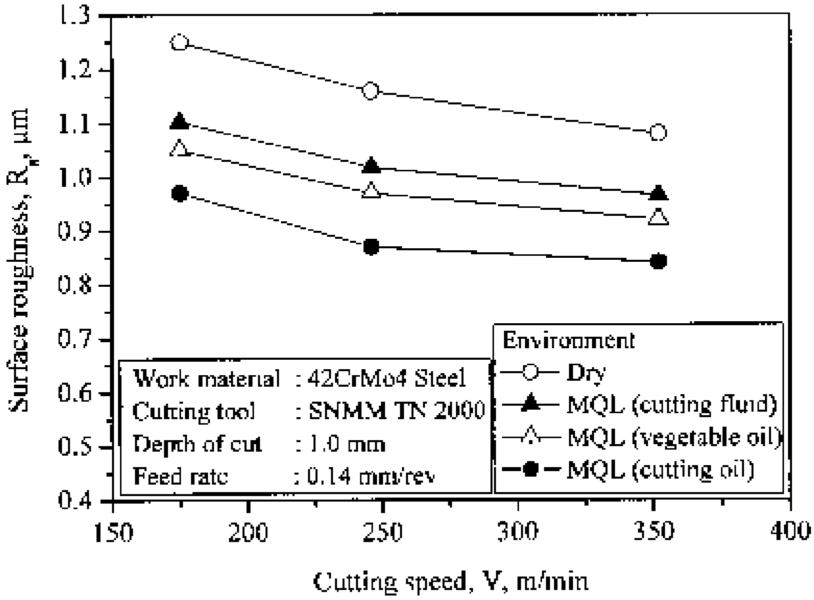


Fig. 2.28 Variation of surface roughness (Ra) with cutting speed (V) under different environments at f = 0.14 mm/rev

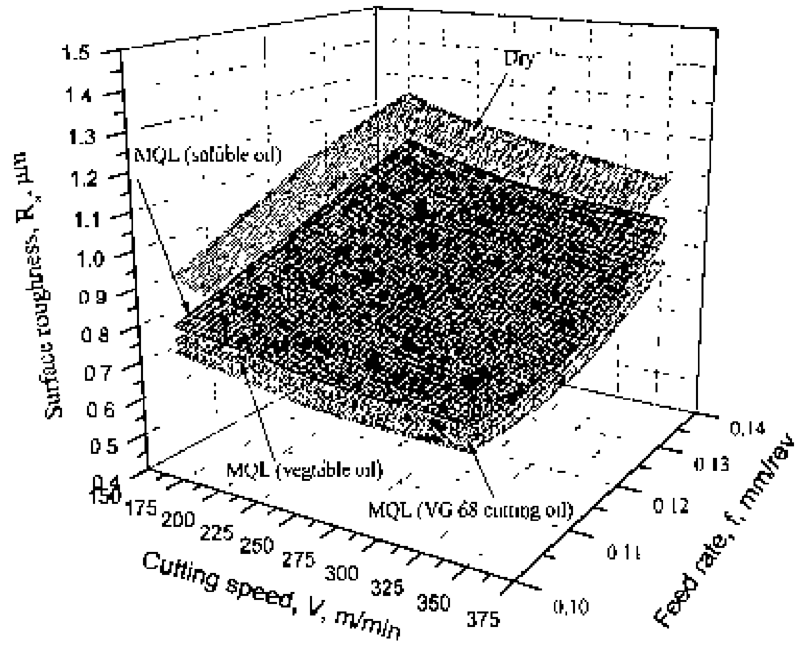


Fig. 2.29 Effect of environment on surface roughness (R_a) evaluated by regression analysis of the experimental data

The variation in surface roughness observed with progress of machining 42CrMo4 steel at a particular set of cutting speed V, feed rate f and depth of cut d, by the coated carbide SNMM insert under dry and different MQL conditions has been shown in Fig. 2.30.

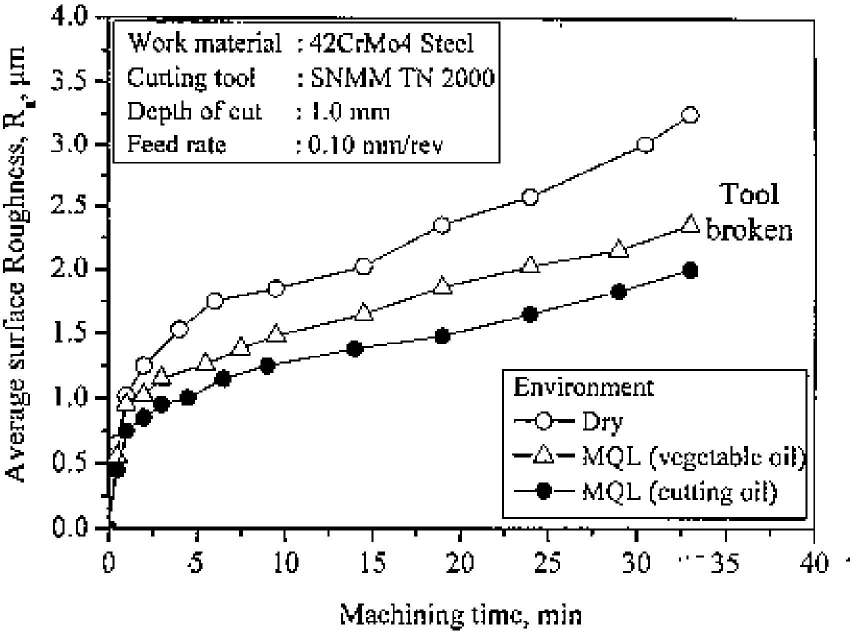


Fig. 2.30 Surface roughness (R_a) developed with progress of machining 42CrMo4 steel under different environments

Chapter-3

Discussion on Experimental Results

3.1 Cutting Temperature

Cutting temperature increases with the increase in specific energy consumption and material removal rate (MRR). Such high cutting temperature affects, directly and indirectly, chip formation, cutting forces, tool life, dimensional accuracy and surface integrity of the products. Many Attempts have been made to reduce this prejudicial high cutting temperature. Application of conventional cutting fluid during machining may, to some extent, cool the tool and the workpiece in bulk but cannot cool and lubricate expectedly and effectively at the chip-tool interface where the temperature is maximum. This is because the flowing chips make principally bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. This type of bulk contact does not allow the cutting fluid to penetrate in the interface. On the other hand, the 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 cutting speed when the chip-tool contact becomes almost fully plastic. The application of minimum quantity lubrication (MQL) at chip-tool interface is expected to improve machinability characteristics that play a vital productivity, product quality and overall economy in addition to environment-friendliness in machining particularly when the cutting temperature is very high.

The average chip-tool interface temperature has been determined by using the tool work thermocouple technique and plotted against different cutting speeds under dry and MQL environments in turning 42CrMo4 steel by coated carbide insert (SNMM-TN2000). The variation in average chip-tool interface temperature at different cutting speed, feed and environment combinations have been shown in Fig. 2.4, Fig. 2.5, Fig. 2.6 and Fig. 2.7. The cutting temperature generally increases with the increase in V and f though in different degree due to increased energy input. It could be expected that MQL would be more effective at higher values of V and f. Fig. 2.4, Fig. 2.5, Fig. 2.6 and Fig. 2.7 show that MQL is better than dry machining for all the V-f combinations but among three cutting fluids used for MQL, cutting oil shows the best results, vegetable oil shows inferiority than cutting oil. Though soluble oil shows the better result than dry, it is the worst among the three MQL conditions. This may be attributed to the higher lubricating and cooling capability of cutting oil than other two which reduce the heat generation due to friction as well as reduce the generated heat effectively. Coefficient of friction between the contact surface of the tool, flowing chips and the finished surface of the work-piece is reduced by the formation of the lubrication film, consequently reduce the frictional heat generation and drastically reduce the cutting temperature. Less viscous vegetable oil usually forms thin film and rate of temperature reduction is lower in comparison to cutting oil when it is employed as MQL. Though the cooling capacity of soluble oil increases due to mixing with water, lubricating capacity of soluble oil decreases that makes water miscible cutting fluid ineffective in reducing cutting temperature at the chip-tool interface.

It is apparent from Fig. 2.4, Fig. 2.5, Fig. 2.6 and Fig. 2.7 that as the cutting speed and feed rate increase, the percentage reduction in average cutting temperature decreases. It may be for the reasons that, the bulk contact of the chips with the tool increases with the increase in V and f which do not allow significant entry of coolant jet. Only possible reduction in the chip-tool contact length due to the dragging of the chip by MQL jet particularly that comes along the auxiliary cutting edge, can give access the jet towards the interface, reduce the temperature to some extent particularly when the chip velocity is high due to higher V. This small amount of reduction in average cutting temperature is quite significant in pertaining tool life and surface finish at industrial speed-feed conditions.

The percentage saving in average chip-tool interface temperature (θ) attained by different MQL application for a set of V-f combinations have been extracted from the previous figures and shown in Table 3.1 for machining 42CrMo4 steel with coated carbide insert. For the convenience of comparison, the ranges and averages of percentage savings in θ have been separately shown in Table 3.2, which visualizes how the beneficial role of MQL varied with different cutting fluids.

Table 3.1 and Table 3.2 shows that the reduction in cutting temperature among all V-f combinations is more for the set V =175m/min and f = 0.10 mm/rev. In this V-f combination temperature reduction under MQL by cutting oil, vegetable oil and soluble oil varies from 8.60~12.53%, 6.67~8.98% and 3.36~5.44% respectively. It can be noticed that with the increase in speed and feed MQL becomes less effective. This may be due to the increase in chip load and increase in plastic contact length during cutting prevents the MQL to enter into the chip-tool interface. More over, it shows the best reduction at higher cutting speed for lower feed rate. Again Table 3.2 presents that the average percentage reduction in chip-tool interface temperature under MQL by cutting oil, vegetable oil and soluble oil are 10.58%, 7.60% and 4.29% respectively. Therefore, in all the tests through out the entire experiment, MQL with cutting oil (VG 68) shows the best performance due to its better cooling and lubrication irrespective of speed feed and depth of cut.

Table 3.1 Percentage reduction in θ due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM TN-2000 inserts

Feed rate, f, mm/rev	Cutting speed, V, m/min	Percentage reduction in θ under different MQL environments		
		MQL (Cutting fluid)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.10	175	5.44	8.98	12.53
	246	4.60	7.93	10.92
	352	4.58	7.37	10.71
0.12	175	4.42	8.72	12.09
	246	4.09	7.49	10.10
	352	4.62	7.14	9.34
0.14	175	3.76	7.18	11.73
	246	3.36	6.95	9.19
	352	3.76	6.67	8.60

Table 3.2 Average percentage reduction in θ due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM TN-2000 inserts

Savings	Average percentage reduction in θ		
	MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
Range	3.36 - 5.44	6.67 - 8.98	8.60 - 12.53
Average	4.29	7.60	10.58

3.2 Machining Chips

During machining ductile materials the form and shape of chips are found to depend upon the mechanical properties of the work material, tool geometry particularly rake angle, levels of process parameters particularly V and f and cutting environment. In absence of chip breaker, the length and uniformity of chips increase with the increase in ductility and softness of the work material, tool rake angle and cutting speed unless the chip-tool interaction is adverse inducing intensive friction and built-up edge formation.

Table 2.2 and Table 2.3 represent the shape and colour of the chips produced during machining 42CrMo4 steel with coated SNMM carbide insert under dry and different MQL conditions. Table 2.2 and Table 2.3 show that the chips having unfavourable shape (snarled ribbon or long tubular) is under dry and MQL with soluble oil condition and more favourable chips (Short ribbon) are produced under MQL with vegetable oil and MQL with cutting oil conditions. Depending upon the cutting temperature (level of process parameter) the chips become metallic, golden or blue. From Table 2.3 it is clear that when V and f increase, the chip becomes much deeper (from metallic to blue) for increase in chip-tool interface temperature. Again the colour of the chips also becomes lighter depending upon reduction in cutting temperature by the application of MQL. Under dry condition the colour of the chips produced are deep blue due to high cutting temperature. The colour of the chips significantly changes from dark blue to golden or metallic with the application of minimum quantity lubrication comparing to dry condition. But among the three types of cutting fluids the VG 68 cutting oil shows the favourable results in this regard.

The chip-thickness ratio (r_c) is an important index of chip formation and specific energy consumption for a given tool-work combination. Chip thickness depends on almost all the parameters involved in machining. The degree of chip thickening which is measured by chip thickness ratio, plays an important role on cutting forces and hence on cutting energy requirements as well as cutting temperature. It is evaluated from the ratio,

$$r_c = \frac{a_1}{a_2} = \frac{f \sin \varphi}{a_2} \qquad (3.1)$$

Where,

r_c = Chip thickness ratio

a_1 = Chip thickness before cut = $f \sin\varphi$

a_2 = Chip thickness

f = Feed rate

φ = Principal cutting edge angle

During the machining of the ductile metals and alloys, continuous chips are produced and the value of r_c is generally less than 1.0 because chip thickness after cut (a_2) becomes greater than chip thickness before cut (a_1) due to almost all sided compression and friction at the chip-tool interface. Smaller value of r_c means larger cutting forces and friction and hence is undesirable.

The effect of increase in V and f and the change in environment on the value of chip-thickness ratio (r_c) obtained during turning 42CrMo4 steel are shown in Fig.2.8, Fig.2.9, Fig.2.10 and Fig.2.11 which depict some significant facts: (i) values of r_c has all along been less than 1.0, (ii) the value of r_c has increased by the application of minimum quantity of lubricant and (iii) the value of r_c increases with increase in V and f. The value of r_c usually increases with the increase in V particularly at its lower range due to plasticization and shrinkage of the shear zone for reduction in friction and built-up edge formation at the chip-tool interface due to increase in temperature and sliding velocity. In machining steels by tools like carbide, usually the possibility of built-up edge formation and size and strength of the built-up edge, if formed gradually increase with the increase in temperature due to increase in V and also f and then decrease with the further increase in V due to too much softening of the chip material and its removal by high sliding speed.

Table 3.3 Percentage increment in r_c due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM TN-2000 inserts

Feed rate, f, mm/rev	**Cutting speed, V, m/min**	**Percentage increment in r_c under different MQL environments**		
		MQL (Soluble oil)	**MQL (Vegetable oil)**	**MQL (VG 68 cutting oil)**
0.10	175	5	12	16
	246	3	11	15
	352	5	10.6	14
0.12	175	3	11.29	14.51
	246	3	11	14
	352	6	13	17.39
0.14	175	5	11	15.38
	246	4	12	17.39
	352	5.4	11	15

Table 3.4 Average percentage increment in r_c due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM TN-2000 inserts

Savings	**Average Percentage increment in r_c**		
	MQL (Soluble oil)	**MQL (Vegetable oil)**	**MQL (VG 68 cutting oil)**
Range	3-6	10-13	14-17
Average	4.38	11.36	15.23

Fig. 2.8, Fig. 2.9, Fig. 2.10 and Fig. 2.11 show that MQL has increased the value of chip thickness ratio for all V-f combinations due to reduction in friction at the chip-tool interface, reduction in built-up-edge formation and wear at the cutting edges. In all V-f combinations MQL by cutting oil and vegetable oil show more effectiveness than soluble oil. The figures clearly show that throughout the present experimental domain the value of r_c gradually increased with the increase in V and f in different degree under both dry and MQL conditions. Among three MQL conditions, cutting oil (VG 68) has shown the best performance, because the value of r_c has increased more than the other two fluids, i.e. vegetable oil and soluble oil.

The percentage increment in chip-thickness ratio, r_c attained by MQL for different cutting speed and feed have been calculated from the previous figures and shown in Table 3.3. For ease of comparison, the ranges and averages of percentage increment in r_c has been separately shown in Table 3.4 which visualizes the variation of beneficial role of MQL with different cutting fluids. From Table 3.4 the range of percentage increment of chip thickness ratio for the above mentioned V-f combinations for MQL by cutting oil, vegetable oil and soluble oil over dry condition are 14~17%, 10~13% and 3~6% respectively. Again Table 3.4 presents the average value of percentage increment in chip-thickness ratio for MQL by cutting oil, vegetable oil and soluble oil are 15.23%, 11.36% and 4.38% respectively. These indicate that cutting oil (VG 68) gives best performance than other two fluids.

3.3 Cutting Forces

It has already been mentioned in the previous chapter that the magnitude of the cutting force is a major index of machinability which governs productivity, product quality and overall economy in machining. The cutting forces increase almost proportionally with the increase in chip load and shear strength of work material.

During machining 42CrMo4 steel by coated carbide insert (SNMM-TN2000) main cutting force (F_C) and feed force (F_f) were recorded under dry, MQL (soluble oil), MQL (vegetable oil) and MQL (cutting oil) conditions. The variation in main cutting forces (F_C) and feed force (F_f) at different cutting speed, feed and environment combinations have been shown in Fig. 2.13, Fig. 2.14, Fig. 2.15, Fig. 2.16, Fig. 2.17, Fig. 2.18. Fig. 2.19 and Fig. 2.20. The figures clearly indicate the influence of feed and cutting speed on main cutting force (F_C) and feed force (F_f). The main cutting force and feed force are increased though in different degree by increasing feed due to increased energy input and chip load and decreased by increasing cutting speed due to much softening of the work material ahead of the advancing tool. It could be expected that MQL would be more effective at higher values of cutting speed, V and lower values of feed, f. Fig. 2.13, Fig. 2.14, Fig. 2.15, Fig. 2.16, Fig. 2.17, Fig. 2.18, Fig. 2.19 and Fig. 2.20 show that MQL is better than dry machining for all the V-f combinations but among three MQL conditions cutting oil shows better results than other two.

It is evident from the figures Fig. 2.13, Fig. 2.14, Fig. 2.15, Fig. 2.16, Fig. 2.17, Fig. 2.18, Fig. 2.19 and Fig. 2.20 that as the cutting speed increases, the percentage reduction in main cutting force and feed force decrease. The cause behind the percentage reduction in main cutting force and feed force is that the MQL jet becomes less effective with the increase in V and f due to increase in contact length of the chips with the tool which do not allow significant entry of coolant jet

The percentage saving in main cutting force and feed force attained by different MQL for a set of V-f combinations have been extracted from the previous figures and shown in Table 3.5. For the convenience of comparison, the ranges and averages of percentage savings in F_C and F_f have been separately shown in Table 3.6, which visualizes the variation of the beneficial role of MQL using different cutting fluids.

Table 3.5 Percentage reduction of cutting forces (F_c and F_f) due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM TN-2000 inserts

Feed rate, f, mm/rev	Cutting speed, V, m/min	Cutting forces					
		Main cutting force (F_c)			Feed force (F_f)		
		MQL (Cutting fluid)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)	MQL (Cutting fluid)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.10	175	9.52	11.90	14.29	7.99	10.41	12.11
	246	6.89	9.44	11.99	5.31	7.90	9.75
	352	5.33	8.00	10.67	3.73	6.44	8.40
0.12	175	8.30	10.48	13.76	6.74	8.96	11.56
	246	6.78	9.11	11.68	5.20	7.57	9.44
	352	7.00	9.50	12.00	5.42	7.97	9.76
0.14	175	6.93	8.91	12.48	5.35	7.37	10.25
	246	6.12	8.23	10.55	4.53	6.67	8.27
	352	4.02	6.25	8.48	2.39	4.66	6.16

Table 3.6 Average percentage reduction in cutting forces due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM inserts

Savings	Average Percentage reduction in cutting forces					
	Main cutting force (F_c)			Feed force (F_f)		
	MQL (Cutting fluid)	**MQL (Vegetable oil)**	**MQL (VG 68 cutting oil)**	**MQL (Cutting fluid)**	**MQL (Vegetable oil)**	**MQL (VG 68 cutting oil)**
Range	4.02-9.52	6.25-11.9	8.48-14.29	2.39-7.99	4.66-10.41	6.16-12.11
Average	7.09	9.4	12.07	5.18	7.55	9.52

Table 3.6 shows that the percentage reduction of main cutting force for the stated V-f combinations under MQL using cutting oil, vegetable oil and soluble oil over dry condition are 8~14%, 6~11% and 4~9% respectively with an average of 12%, 9% and 7% respectively. Percentage reduction of feed force for the stated V-f combinations for MQL using cutting oil, vegetable oil and soluble oil over dry condition are 6~12%, 4~10% and 2~7% respectively with an average of 9%, 7% and 5% respectively. Among the environments MQL cutting oil (VG 68) gives the best performance.

3.4 Cutting Tool Wear

It has already mentioned that cutting tool wear are generally quantitatively measured by the magnitudes of VB, VS, VM, VSM etc. shown in Fig. 2.21, out of which VB is considered to be the most significant parameter in R&D work. Among the different tool wears, the principal flank wear is the most important because it raises the cutting forces and the related problems. The life of carbide tools, which mostly fail by wearing, is assessed by the actual machining time after which the average value of its principal flank wear (VB) reaches a limiting value, like 300μm Therefore attempts should be made to reduce the rate of growth of flank wear in all possible ways without sacrificing MRR.

The gradual growth of VB, the predominant parameter to determine the end of tool life, has been observed during turning of 42CrMo4 steel by coated carbide (SNMM-TN 2000) inserts at a cutting speed 175 m/min, feed rate 0.12mm/rev and depth of cut 1.0 mm under dry and MQL have been shown in Fig. 2.22. MQL by cutting oil and vegetable oil at feed 0.12 mm/rev, cutting speed 175 m/min and depth of cut 1.0 mm is more effective, for this, the above process parameters are selected to assess the wearing of insert. It is clearly observed from the Fig. 2.22 that the principal flank wear (VB) decreases significantly under MQL condition due to cooling and lubrication even under adverse conditions. Such improvement by MQL jet can be attributed mainly to retention of hardness and sharpness of the cutting edge for their steady and intensive cooling, protection from oxidation and corrosion and absence of built-up edge formation, which accelerates both crater and flank wear by flaking and chipping. Fig. 2.22 also shows that growth rate of VB slowdown in case of applying cutting oil as MQL than vegetable oil.

Another important tool wear criteria is average auxiliary flank wear 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 auxiliary flank wear, which occurs due to rubbing of the tool tip against the finished surface. Gradual decrease in depth of cut which is proportional to the magnitude of auxiliary flank wear (VS) increases the diameter of the job in straight turning with the progress of machining. And the irregularity developed in the auxiliary cutting edge due to wear impairs the surface finish of the product.

The growth of VS has been depicted in Fig. 2.23 for different environments. MQL jet cooling provides remarkable reduction in VS with the progress of machining. So, it is clearly appears from figures that the rate of growth of flank wears (VB and VS) decreases substantially by MQL when turning steel by SNMM inserts. Pressurized jet of MQL has easily been dragged into the plastic contact by its high energy jet, cools the interface and lubricate properly. It not only cools the interface but also reduces frictional heat generation by lubricating the friction zones.

Application of MQL has provided substantial improvement and much uniform flank wears those have been much smaller in magnitude and there was no sign of notch wear. In the process of machining, the cutting tools usually undergo rapid wear called break-in wear at the beginning of machining due to attrition and micro-chipping and then uniformly and relatively slow mechanical wear followed by faster wear at the end. The mechanism and rate of growth of cutting tool wear depend much on the mechanical and chemical properties of tool and the work materials and their behaviour under the cutting condition. While machining this steel, no notching has been found to develop in any of the inserts even under dry machining condition possibly for less hardenability and more chemical stability of this steel.

The SEM views of the worn out inserts after turning 42CrMo4 steel at a particular V-f-d combination under different environments after 33 min of machining, shown in Fig. 2.24 and Fig. 2.25, qualitatively indicate that MQL has provided sizeable reduction in overall wear of the insert. Fig. 2.24 also shows that principle flank wear occurred non-uniformly along the main cutting edge of SNMM tool under dry and MQL with vegetable oil condition. During dry cutting the cutting insert suffered a lot due to intensive high temperature. Though MQL with vegetable oil reduces the cutting temperature the cutting insert suffers drastically at its nose and surrounding due to more abrasion. MQL with cutting oil provided more or less uniform principal flank wear in machining the 42CrMo4 steel. Substantial reduction in average auxiliary flank wear (VS) of SNMM inserts enabled by present MQL in machining 42CrMo4 steel has been revealed in Fig. 2.25. So it is found that cutting oil increased tool life by decreasing tool wear.

3.5 Surface Roughness

Surface roughness is an important measuring criterion of machinability because performance and service life of the machined component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface micro-cracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part. Surface roughness is an important design consideration as it impacts many parts characteristics such as fatigue strength, cleanability, assembly tolerances, coefficient of friction, wear rate, corrosion resistance and aesthetics [74]. Tsai et al [75] stated that the possible factors affecting surface finish were feed rate, cutting speed, depth of cut, cutter geometry, cutter runout, tool wear, cutter force and vibration under dynamic cutting conditions. The major causes behind development of surface roughness in continuous machining processes are:

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

iv. built-up edge formation, if any

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

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

Where,

h_m = Peak value of roughness caused due to feed marks
r = Nose radius of the turning inserts
f = Feed rate

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

For the present study, only surface finish has been considered for assessment of product quality under dry and MQL machining conditions. It is evident that MQL improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation. Feed force as well as chip thickness ratio is responsible for surface roughness along the longitudinal direction of the turned job. Usually surface roughness increases with the increase in feed (f) and decreases with the increase in cutting speed (V). Reduction in R_a with the increase in V may be attributed to smoother chip-tool interface with lesser chance of built-up edge formation in addition to possible truncation of the feed marks and slight flattening of the tool-tip as cutting force decreases and chip thickness ratio increases with the increase in cutting speed. Increase in cutting speed may also cause slight smoothing of the abraded auxiliary cutting edge by adhesion and diffusion type wear and thus reduces surface roughness. So, cutting speed (V) influences on surface roughness under dry and MQL machining.

Fig. 2.26, Fig. 2.27, Fig. 2.28 and Fig. 2.29 show the variation of surface roughness, R_a attained during turning 42CrMo4 steel by coated carbide insert (SNMM-TN 2000) at various V-f combinations under dry and MQL (soluble oil, vegetable oil and cutting oil) conditions. It is clear that the surface roughness decreases with the increase in cutting speed and increases with the increase in feed but during all the treatments under dry and MQL machining conditions MQL provides lesser surface roughness than corresponding dry condition. This is mainly because of frequent formation or chance of formation of built-up edge, quick separation of built-up edge and behaviour of materials to be machined under dry machining condition than that of MQL condition. Cutting oil gives the smoother surface among the three MQL conditions.

Table 3.7 Percentage reduction in R_a due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM TN-2000 inserts

Feed rate, f, mm/rev	Cutting speed, V, m/min	Percentage reduction in R_a under different MQL environments		
		MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
0.10	175	14	18	21
	246	8	12	17
	352	6	10	14
0.12	175	15	19	25
	246	11	16	22
	352	17	21	25
0.14	175	12	16	22
	246	12	16	25
	352	11	15	22

The percentage reduction in average surface roughness (R_a) attained by MQL for different V-f combinations have been extracted from the previous figures and shown in Table 3.7. For convenience of comparison, the ranges and averages of percentage savings in R_a have been separately shown in Table 3.8 which visualizes how the beneficial role of MQL varied with different cutting fluids. From the Table 3.8 it is shown that in respect of surface roughness MQL is better for f=0.12 mm/rev and V=352 m/min. The value of percentage reduction for cutting oil, vegetable oil and soluble oil are 17~25%, 12~21% and 6~17%respectively. Again the average percentage reductions are 21.4%, 15.75% and11.5% for cutting oil, vegetable oil and soluble oil respectively.

Table 3.8 Average percentage reduction in R_a due to minimum quantity lubrication (MQL) in turning 42CrMo4 steel by coated carbide SNMM TN-2000 inserts

Savings	Average percentage reduction in R_a		
	MQL (Soluble oil)	MQL (Vegetable oil)	MQL (VG 68 cutting oil)
Range	6-17	12-21	17-25
Average	11.5	15.75	21.4

Surface roughness has also been measured at regular intervals while carrying out turning for study of tool wear. It has been found that surface roughness developed with the progress of machining, though in different degree under different tool-work-environment combinations. Fig. 2.30 shows the growth in surface roughness observed with progress of machining of 42CrMo4 steel by the SNMM insert at predefined speed-feed-depth of cut (V =175 m/min, f=0.12 mm/rev and d=1.0 mm) combination under dry and MQL conditions up to 35 minutes of machining. Fig. 2.25 reveals the pattern of growth of surface roughness. Such observations indicate distinct correlation between auxiliary flank wear and surface roughness. From Fig. 2.30, it is clear that surface roughness gradually increases with the machining time due to gradual increases in auxiliary flank wear (VS). MQL has appeared to be more effective in reducing surface roughness as it did for auxiliary flank wear. The rate of increase in surface roughness decreases to significant extent when machining has been done under minimum quantity lubrication. MQL jet not only reduce the VS but also possibly of built-up edge formation due to reduction in temperature. However, it is apparent that MQL jet substantially improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.

Chapter 4

Conclusions and Recommendations

4.1 Conclusions

During machining the use of cutting fluids change the performance of machining operations because of their lubrication, cooling and chip flushing functions. Minimum quantity lubrication (MQL) presents as a feasible alternative for machining steels with respect to cutting temperature, chip formation, cutting forces, tool wear and surface roughness. The results clearly indicate the advantages of using VG 68 cutting oil as MQL coolant over dry as well as other coolants like vegetable oil and water soluble cutting fluid when applied as MQL. The following conclusions can be made based on the observations and the experimental results obtained,

(i) Application of minimum quantity lubrication (MQL) not only reduced the demand for cutting fluid but also made significant technological benefits which has been observed during machining 42CrMo4 steel by coated carbide insert (SNMM-TN 2000).

(ii) MQL assisted jet enabled reduction in average chip-tool interface temperature from 3 to 12.5% depending upon the types of cutting fluids.

Even such apparently small reduction, enabled significant improvement in the major machinability indices. MQL by VG 68 cutting oil reduced cutting temperature by about 8.6%-12.5% that indicates the effectiveness of cutting oil over other two MQL coolants.

(iii) Application of minimum quantity lubrication (MQL) provides an effective and efficient cooling and improved chip-tool interaction in turning 42CrMo4 steel, which changes the mode of chip formation and ascertain favourable chip shape and colour. Chip thickness ratio (r_c) increases more predominantly by the use of MQL than dry condition because MQL reduces the friction between the contact surfaces of the chip-tool and work-tool. Among the three MQL coolants VG 68 cutting oil exhibits the best results in respect of chip thickness ratio when 42CrMo4 steel is machined using coated SNMM carbide insert. MQL by VG 68 cutting oil has increased the chip thickness ration (r_c) by 14 to 17%.

(iv) The magnitude of cutting forces was reduced sizably by the application of MQL as the chip formation modes become favorable. Main cutting force reduced more predominantly than feed force. Favorable changes in the chip-tool interaction and retention of the cutting edge sharpness for a prolong time of machining due to the reduction of cutting zone temperature seemed to be the main reason behind the reduction of cutting forces by MQL. Cutting oil more prominently reduced main cutting force and feed force as well as energy consumption than vegetable oil and water soluble cutting fluid.

(v) The most incredible contribution of MQL jet in turning 42CrMo4 steel by coated SNMM carbide insert undertaken was the high reduction rate in flank wear as well as large increment in tool life that improve the dimensional accuracy of the job even under high speed feed condition. Cutting tool wear, flank wear in particular have decreased substantially due to the retardation of the temperature sensitive wear, like diffusion and adhesion when turning 42CrMo4 steel under minimum quantity lubrication by VG 68 cutting oil in comparison to other environments.

(vi) Surface quality depends upon the pattern and magnitude of auxiliary flank wear. MQL significantly reduced auxiliary flank wear by reducing the cutting temperature, accordingly surface roughness was reduced to a large extent when VG 68 cutting oil was employed as MQL. VG 68 reduced or eliminated the formation or possibility of formation of built-up edge due to more drastic reduction in flank temperature that also helped to produce smoother surface.

4.2 Recommendations

(i) MQL jet can be applied along principal cutting edge or along the flanks or in combination of cutting edges and flanks in lieu of only along auxiliary cutting edge. The best solution of application methods to control tool wear and air quality can be offered through studying those configurations.

(ii) Tool geometry plays significant role on chip formation mode, cutting temperature, tool wear and failure, surface finish, residual stresses, and white layer generation. SNMM tool configuration was used for these treatments. Other tools can be used for machining this steel to find out the suitability of tool geometry.

(iii) To achieve a better understanding of the machining process planning with environmental concerns as a factor of consideration, the cutting fluid atomization behavior in near dry turning process in order to estimate the resulting air quality can be further investigated in the future.

(iv) In this work, the pattern of flow is not considered. So for future investigations the pattern of flow of jet can be measured, i.e., whether it is laminar or turbulent. Though turbulent flow is able to transport more heat in comparison to laminar jet, but for more thinning of jet laminar flow jet is preferable. With increase in air pressure and nozzle tip diameter, the effective laminar flow pattern for more effective and efficient cooling can be easily maintained.

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