DESIGN AND DEVELOPMENT OF PULSE JET MINIMUM QUANTITY LUBRICANT (MQL) APPLICATOR AND ITS EFFECT ON SURFACE MILLING OF HARDENED AISI 4140 STEEL

By

Mahmood Al Bashir

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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.

Mahmood Al Bashir

This work is dedicated to my
Loving Parents

Dr. Md. Bashir Uddin
and
Mrs. MahbubaShirin

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ABSTRACT

Modern manufacturing industries are seeking different alternatives to attain the need of higher machining speeds, lower wastage and a better product quality as well as reducing the cost of the manufacturing process.An approach to this problem is considering high speed machining but high speed machining at high speeds and feeds generates large heat and high cutting temperature, which shortens the tool life and deteriorates the job quality. To reduce this high temperature machining of hardened medium carbon steelneeds large quantities of cutting fluid to be applied which not only incur expenses but also can cause grave environmental and health hazards. Dry machining might be an alternative in this context and is totally free from the problems associated with cutting fluid but is difficult to implement on the existing shop floor as it needs ultra-hard cutting tools and extremely rigid machine tools. The manufacturing industries hence are looking to mitigate these problems by experimental investigations and by adoption of advanced techniques such as cryogenic cooling, high-pressure coolant, and minimum quantity lubricant (MQL) application. Among these, Minimal Quantity Lubrication machining is found to be quite effective in improving tool life and surface finish.

In this research work surface milling of AISI 4140 steel (40 HRC)was investigated with pulsed jet Minimum Quantity Lubricant (MQL) applicator using straight oil as the cutting fluid. The investigation was carried upon comparing the performance of MQL applicator on the basis of tool wear, cutting force, and surface finish. The effects of different cutting parameters were compared at different combinations of feed, depth of cut and cutting conditions. A pulsed jet MQL applicator was designed and developed with the help of full factorial analysis (Design of Experiment) and it was ensured that the cutting fluid can be applied in different timed pulses and quantities at critical zones during surface milling.An investigative comparison with dry milling under same conditions has been done to evaluate the relative performance of hard milling with MQL applicator. It was observed that the MQL applicator system for surface milling on hardened steel can bring forth better performance when compared to dry milling.

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Introduction

1.1 Introduction

Machining is a process in which a cutting tool is used to remove small chips of material from the workpiece. To perform the operation, relative motion is required between the tool and the work. This relative motion is achieved in most machining operation by means of a primary motion, called "cutting speed" and a secondary motion called "feed". The shape of the tool and its penetration into the work surface, combined with these motions, produce the desired shape of the resulting work surface.Machining plays important role in producing product from different types of material ranging from soft to hard. Hard materials (45 HRC and harder) include tool steels, mold steels, chilled and chrome irons, weld overlays and some nickel and cobalt-base superalloys. Manufacturers use hard materials to extend tool wear life and maintain precision in molds, gears, tools and dies, aerospace components and processing equipment. Unfortunately, the characteristics that make hard-material parts perform so effectively that it also make the materials more difficult to machine. Bringing a hardened part to machine traditionally has been slow and tool consuming.The traditional approach is to rough and semi finish parts before hardening via heat treatment if possible, then tediously finish them with round tools, inserts, grinding or EDM Machining. Parts that begin as hard materials or those where hardening would affect final precision, require slow processing right from the start. This process has long been in the common play of the manufacturing industries as no other alternate and viable solutions were found. Long cycle times, multiple operations and part setups and excessive work-in-process, all adhered up to increase the manufacturing costs.The manufacturing industries always seek for alternate solutions that will decrease the cost of the manufacturing without compromising the quality of the product as well as the dimensional accuracy. One way to reduce those costs is milling parts in the hardened state. The moldmaking industry has been a pioneer in hard milling, applying hard yet tough micro grain carbide cutting tools usually with coatings that increase heat resistance and boost lubricity, CBN, PCBN, Ceramic and diamond tools. Hard milling with carbide tools typically involves small depth of cut, generating relatively low cutting forces andusually with coatings that increase heat resistance and boost lubricity. Following these modern trends in manufacturing are steering the machining processes towards higher speeds, lower waste and improved product quality. The quality of machined components is evaluated in respect of how closely they adhere to set product finish and reflective properties. Dimensional accuracy, tool wear and quality of surface finish are three factors that manufacturers must be able to control at the machining operations to ensure better performances and service life of engineering component. In the leading edge of manufacturing, manufacturers are facing the challenge of higher productivity, quality and overall economy in the field of manufacturing by machining. To meet the above challenges in a global environment there is an increasing demand for high material removal rate (MRR) and also longer life and stability of the cutting tool. Material removal rates between 150−1500 cm^3/min can now be achieved for most materials.Tools and coatings with hardness up to 9000 HV commercially exist, and the use of Computer Numerical Control (CNC) machines allows for accuracies down to 10 μm**[Byrne et al. 2003]**.But additional cooling and lubrication of high speed cutting processes is necessarydue to the high thermal and physical stresses generated during these machining processeswhich have an impact on the tool life, the quality of the finished workpiece and the power consumption. In addition, as material is cut a fresh high energy surface is generated and quickly reacts with the surroundings like oxygen and water in humid air. The use of cutting fluids provides protection from these reactions, which may negatively affect the quality of the finished surface.Use of cutting fluid has been a common practice in manufacturing industries to reduce the heat, facilitate chip removal and lubrication process. But use of coolants also require additional cost that eventually boosts up the total manufacturing cost due to cutting fluid’s purchase, usage, storage and disposal. The increased use of cutting fluids in the traditional machining industries also creates health hazards for the operators as well as the environment. A number of studies have shown that the mist that is generated from the use of cutting fluid on the heated surface of the machined material creates a number of health problems for the operator and people working in the proximity [**Ding and Hong 1998, Thornburg and Leith 2000, Bennett and Bennett 1987**]. Based on these facts an alternate approach to reduce the usage of cutting fluid has been long in the focus of the industries. A review of the literature connected with the work is presented in this sectionwhich also highlights the latest developments in the areas related to the present work. The features of hard machining including cutting fluids in metal machining and machining with Minimum Quantity Lubricant (MQL) applicator are also presented here.

1.2 Literature Review

Cutting forces, cutting temperature, chip tool interaction, dimensional accuracy, surface integrity and quality, chip morphology, wear and life of the cutting tool in different cutting conditions are the main concerns in the research and investigation done so far on different types of machining operations.While lubrication is necessary in controlling friction and by consequence the heat generation, more cooling is required in cases where heat generation considerably affects the machining quality, and where more temperature control is needed. These high temperatures are due to the fact that nearly all work done in a machining process is transformed into heat. In a metal cutting operation, the primary heat source is the result of the plastic deformation work at the shear plane, the boundary between deformed and undeformed material. The secondary heat source is located at the tool-chip interface, as a result of the secondary plastic deformation work, as well as friction. A tertiary heat source could result from friction at the tool flank-workpiece interface, such as the case of a worn tool edge **[Abukhshim et al.2006]**.In machining process, the tool removes material from the surface of a less resistant body, through relative movement and application of force. The material removed called chip slides on the face of tool submitting it to high normal and shear stresses and moreover to a high coefficient of friction during chip formation. Most of the mechanical energy used to form the chip becomes heat, which generates high temperatures in the cutting region. A major portion of the energy is consumed in the formation and removal of chips. The greater the energy consumption, the greater the temperature and the frictional force at the tool-chip interface and consequently the higher is the tool wear. For this reason, conventional coolant is often used on the cutting tool to prevent overheating. However, the main problem with conventional coolant is that it does not reach the real cutting area **[Werthem1992]**. Moreover because of having high temperature conventional cutting fluids evaporates before reaching the cutting zone [**Dhar and Kamruzzaman 2009**]. Hence, heat generated during machining is not removed and is one of the main causes of the reduction in tool life **[Kumar 2002]**.

1.2.1 Cutting Fluid Used in Machining Operation

High temperature in cutting zone has been traditionally tried to be controlled by using cutting fluids. The coolant effect reduces temperature in cutting zone and the lubrication action decreases cutting forces. Thus the friction coefficient between tool and chip becomes lower in comparison to dry machining **[Çakıret al. 2004, El Baradie 2007]**. The aims of cutting fluid applications were determined as cooling and lubrication in metal cutting. In addition, cutting fluids can help to disposal of the chips from hole and control chip formation. Because they decrease contact length between chip and tool, and this situation has a positive effect on chip breaking. Thus, they can help to achieve better tool life **[Yildizet al. 2007, Stanford et al. 2007]**. As cutting fluid is applied during machining operation, it removes heat by carrying it away from the cutting tool/work-piece interface **[Silliman and Perich 1992]**. This cooling effect prevents the tool from exceeding its critical temperature range beyond which the tool softens and wears rapidly [**Bienkowski 1993**]. Cutting fluids are used throughout industry in many metal cutting operations and they are usually classified into three main categories: neat cutting oils, water-soluble fluids and gases [**Diniz and Oliveira 2004**]. The three categories of the cutting fluids all have the generic characteristics required to enhance the cutting process. Yet they possess some different attributes that are related to their physical estate conditions too. The major needs in machining are high material removal rate, good work surface finish and low tool wear. These objectives can be achieved by reducing tool wear using proper cooling system of the tool during machining. The main objective of using cutting fluids in machining operations is the reduction of temperature in the cutting region to increase tool life. The cutting fluids are used in machining operations in order to

- reduce friction at the tool-chip and tool work-piece interfaces,
- cool both chip and tool, and
- remove chip

Furthermore, they have a strong effect on the shearing mechanisms and, consequently, on the work-part surface finish and tool wear [**Diniz et al. 2003, Vikram and Ramamoorthy 2007**]. The positive effect of the use of fluids in metal cutting was first reported in 1894 by F. Taylor [**1906**], who noticed that by applying large amounts of water in the cutting area, the cutting speed could be increased up to 33% without reducing tool life. Since then, cutting fluids have been developed resulting in an extensive range of products covering most work-piece materials and operations. According to Kress [**1997**], the costs associated with the use of cutting fluids represent approximately 17% of the finished work-piece cost against 4% spent with tooling. Kwon [**2000**] studied flank wear by incorporating cutter temperature and physical properties of coating and work materials and stated use of cutting fluid has a positive impact on flank wear but the flood cooling method also reduces the effectiveness of the cutting fluid as too little amount of the cutting fluid reaches the tool workpiece interface.Thus it is recommended that proper amount of cutting fluid as well as certain attributes of the cutting fluids is also necessary to provide the required cooling during the machining process.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained by such cutting fluid[**Satoshi et al. 1997]** althoughit was observed that the surface finish did not improve significantly. It has been seen previously that copious amount of cutting fluid in machining leads to environmental pollution mainly because during machining operations, workers could be exposed to cutting fluids by skin contact and inhalation because of the mist created when the cutting fluid comes in contact with the heated surface during the machining operation[**Ding and Hong 1998, Thornburg and Leith 2000, Bennett and Bennett 1987**].Along with that several types of additives and chemical compounds are used with conventional cutting fluids to increase its cooling and lubrication properties. Chemical agents such as amines and nitrites are used for corrosion inhibitors, phosphates and borates for water softening, soaps and wetting agents for lubrication, phosphorus, chlorine and sulfur compounds for chemical lubrication. Bactericides are added to control the growth of micro-organisms such as bacteria, algae and fungi [**Baradie1996**]. These chemical compounds and the additives which are used cause the techno-environmental problems [**Paul et al. 2001**]such as:

- Required extra floor space and additional systems for pumping, storage, filtration, recycling, chilling etc.
- Neat oils which are used cause skin disorder and irritation of the hair roots
- Dermatitis are caused by bacteria and the biocides which are used to control the growth of bacteria

- Asthma, bronchitis, irritation of the respiratory tract, breathing difficulties, hypersensitivity pneumonitis and lung cancer are caused metalworking fluid mist and vapor
- Irritations of the respiratory tract or flu-like symptoms are caused by inhalation of bacteria and fungi
- The use of unrefined mineral oils is responsible to skin cancer
- Water pollution and soil contamination during disposal of cutting fluids

Environmental problems are occurred during dissociation of chemical compounds at high cutting temperature.

Furthermore, the cost of treating the waste liquid is high and the treatment itself is a source of air pollution. Skin exposure to cutting fluid can cause various skin diseases [**NIOSH 1998**]. In general, skin contact with straight cutting oils cause folliculitis, oil acne, and keratoses while skin exposure to soluble, semi-synthetic and synthetic cutting fluid would result in irritant contact dermatitis and allergic contact dermatitis. Another source of exposure to cutting fluids is by inhalation of mists or aerosols. Airborne inhalation diseases have been occurring with cutting fluid aerosols exposed workers for many years. These diseases include lipid pneumonia, hypersensitivity pneumonitis, asthma, acute airways irritation, chronic bronchitis, and impaired lung function [**NIOSH 1998**]. In response to these health effects through skin contact or inhalation, the National Institute for Occupational Safety and Health (NIOSH) has recommended that the permissible exposure level (PEL) is 0.5 mg/m3 as the metalworking fluid concentration on the shop floor.Albeit the PEL, in a number of places it has been found that maintaining a PEL value was not always possible based on a few facts. Hardened materials, for example, requires a greater amount of cutting fluid, increasing the PEL value and causing detrimental effect on the environment as well as the humans around the machining operation. Thus, based on these facts, the manufacturing industries are looking for alternative solutions. Decreasing the usage of the cutting fluid, usage of cutting fluid with which the exposure limit of the cutting can be kept under limit, machining without cutting fluid are few of the solutions that the manufacturing industries are currently seeking for without affecting the quality and surface integrity of the material to be machined.

1.2.2 Hard Machining

Hard machining is a relatively recent technology that can be defined as a machining operation, using tools with geometrically defined cutting edges, of a work piece that has hardness values typically in the 45-70HRc range. Hard machining always presents the challenge of selecting a cutting tool insert that facilitates high-precision machining of the component, but it presents several advantages when compared with the traditional methodology based in finish grinding operations after heat treatment of work pieces. Completely dry cutting has been a common industry practice for the machining of hardened steel parts. These parts typically exhibit a very high specific cutting energy. Traditional beliefs indicate that completely dry cutting of them, as compared to flood cutting, lowers the required cutting force and power on the part of the machine tool as a result of increased cutting temperature. However, achievable tool life and part finish often suffer under completely dry condition because of the increase in temperature. Therefore, the permissible feed and depth of cut have to be restricted. Under these considerations, the concept of minimum quantity lubrication presents itself as a possible solution for hard turning in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, provided that the minimum quantity lubrication parameters can be strategically tuned.

In the hard turning processes, the high hardness of materials creates large cutting forces when turned with carbide inserts. For this reason, rigid and precise machine tools are required to expel any vibration and chatter. Tonshoff et al. [**1986**] found that the large negative rake angles (from the edge chamfer) on tools used for hard machining yield large dynamic thrust forces that require adequate machine rigidity, spindle power, damping characteristics, and accuracy of motion along the axes of the machine. Bosssom [**1990**] found that tools with chamfered edges produced cutting forces twice as large as non-chamfered tools. Chryssolouris[**1982**] showed that when machining in a poor stiffness setup, tools failed quickly due to edge fracture. These needs have led to recent machine tool designs that improve stiffness and damping by several methods. New machines have incorporated polymer composite materials in the machine base, reduced the number of joints in the machine, and developed improved slide ways such as hydrostatic designs [**Sheehy 1997, Devitt 1998**]. Advances in the control capabilities have also improved the accuracy of the machines.

Hard turning and grinding both operations are time consuming as well as not very efficient. So, the ideal case is elimination of all machining operations. But as the market competition demands for producing parts with certain dimensional accuracy, which was previously done using grinding processes are now gradually replaced by hard turning if and only if the hard turning can produce parts with similar dimensional characteristics, geometric precision, and quality surface. Several studies have investigated the capability of the process to compete with grinding, and most have concluded that at proper conditions with a good machine, hard turning can produce dimensional accuracy and surface finishes acceptable for most applications. Matsumoto et al. [**1986**] were able to hard turn parts with surface finish ranging from 0.045-0.197 μm, and surface waviness from 0.775-1.26 μm. They had determined that requirements for a ball bearing surface were less than 0.2 μm for R_a surface finish and less than 1.5 μm for waviness. Similar results were found by Jochmann and Wirtz [**1999**], who produced consistent peak-to-valley finishes below 1.0 μm, roundness below 0.2 μm, and cylindricity below 1.0 μm. Abrao and Aspinwall [**1996**]were able to produce a surface finish with roughness value R_a as low as 0.14 μm.

If hard turning is to replace any grinding operation, it must be capable of producing surfaces of acceptable quality. This includes both the surface topography (surface finish) and surface integrity, which is achieved when "the surface of a component meets the demands of a specific stress system and environment" [**Field et al. 1972**]. Ramesh et al. [**1999**] defined an "extended surface integrity data set" which includes: surface finish, microstructure, microhardness, fatigue resistance, residual stress state, and frictional characteristics.

To discuss the effects of hard turning on residual stresses, the surface influences of hard turning compared to grinding should be mentioned. Compared to grinding, the force components are large, particularly the thrust force, which is generally larger than the cutting force in hard turning. If the tool loading is thought of as a Hertzian contact, the maximum compressive stress induced in the workpiece occurs at a depth approximately 0.7 times the contact area of the tool. Because the contact area is larger than grinding (a single grit) and load is increased, larger residual compressive stresses that penetrate deeper below the workpiece surface result in hard turned components. This was verified by Brinksmeier et al. [**1982**] and Konig et al. [**1993**]. As expected, the magnitude and depth of residual stresses are a function of tool geometry and process conditions [**Matsumoto et al. 1986, Tonshoff et al. 1995, Brinksmeier et al. 1982 and Thiele 1998**].

Unlike residual tensile stress, reasonable levels of compressive stress are desirable. Based on the residual stress caused by mechanical loading only, hard turned surfaces should exhibit increased fatigue life compared to ground surfaces. However, the undesirable tensile stresses generated by heat are superimposed on the compressive stress [**Tonshoff et al. 1996, Konig 1993**]. As tool flank wear increases, so does the frictional energy between the tool flank and workpiece, as well as the depth of the compressive stress induced by mechanical loading. Thus, increasing tool wear results in larger tensile stresses near the surface, which is then followed by steep stress gradients with a larger compressive stress further below the surface. The stress pattern with less overall change was generated by a tool with very little flank wear compared to the other stress pattern, which was generated with a significantly worn tool.

Dhar and Kamruzzaman**[2009]** conducted an experiment by turning $17CrNiMo_6$ and $42CrMo_4$ under dry and high pressure cooling conditions. It was reported that high pressure cooling enable to reduce cutting temperature up to 25% depending upon process parameters. High pressure coolant reduced friction, built-up-edge formation, thermal distortion of the tool and work. It was observed that high pressure coolant reduced the flank wear, thus the tool life was improved. Better surface finish was obtained under high pressure cooling condition due to reduction of wear and damage at the tool tip. **[Kovacevic et al.1995**] investigated the effect of high pressure coolant/lubricant in improving the thermal/frictional conditions in milling operations. A high pressure water jet was used during the investigation. Application ofcutting fluid at high pressure enhanced the effectiveness of cutting performance and led tothe reduction in the quantity of cutting fluid and reduction in the amount of disposal whichis a primary concern of Environmental Protection Authorities (EPA). From this investigation, itwas also evident that applying cutting fluid in the form of a jet at higher pressures into thecutting zone is more beneficial than conventional fluid application techniques such asflood cooling.If the coolant is applied at the cutting zone through a high speed nozzle, it could reduce the contact length and co-efficient of friction at chip-tool interface and then cutting force and temperature may be reduced and tool life can be increased [**Mazurkiewicz et al. 1998**, **Kumar et al. 2002**]. High-pressure is often the solution to get the coolant to the target so it can cool, lubricate, and sometimes perform its third function, breaking chips that do not break neatly with ordinary machining processes [**Lacalle et al. 2000**]. Concern for the environment, health and safety of the operators, as well as the requirements to enforce the environmental protection laws and occupational safety and health regulations are compelling the industry to consider a high-pressure coolant (HPC) machining process as one of the viable alternative instead of using conventional cutting fluids.

The conventional coolant method as based on a floodingsystem is not always effective as the coolant often fails topenetrate into the tool chip interface during the machiningprocess **[Paul et al. 2000].**Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. Typically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Minimum quantity lubrication (MQL) presents itself as a viable alternative for hard machining with respect to tool wear, heat dissertation, and machined surface quality. MQL, also known as "Microlubrication", **[MaClure et al. 2007]** and "Near-Dry Machining" **[Klocke and Eisenblatter, 1997]**, is the latest technique of delivering metal cutting fluid to thetool/work interface. Using this technology, a little fluid, when properly selected and applied, can make asubstantial difference in how effectively a tool performs. In conventional operations utilizing flood coolant, cutting fluids are selected mainly on the basis of their contributions to cutting performance. In MQL however, secondary characteristics are important. These include their safety properties,biodegradability, oxidation and storage stability.This is important because the lubricant must be compatible with the environment and resistant to long term usage caused by low consumption **[Wakabayashi et al. 2006]**. In MQL, lubrication is obtained via the lubricant, while a minimum cooling action is achieved by the pressurized air that reaches the tool/work interface. Further, MQLreduces induced thermal shock andhelps to increase the workpiece surface integrity in situations of high tool pressure **[Attanasio et al. 2006]**.Ronan et al. **[2003]**compared the mechanical performance of minimum quantity lubrication to completely dry lubrication for the turning of hardened bearing-grade steel materials based on experimental measurement of cutting forces, tool temperature, white layer depth, and part finish. The results indicate that the use of minimum quantity lubrication leads to reduced surface roughness, delayed tool flank wear, and lower cutting temperature, while also having a minimal effect on the cutting forces.

1.2.3 Application of MQL in Hard Machining

The following sections review the recent studies on the application of MQL machining in drilling, milling, turning, and grinding, comparing the MQL machining performance with conventional flood lubrication and dry machining. The performance is evaluated by comparing cutting temperatures, cutting forces, tool wear, and machining quality under the different machining conditions. Unless otherwise specified, external MQL with pure oil is applied in all of the reviewed experiments.

Vadarajan et al.**[2002]** have introduced a new MQL application technique which overcomes the problems caused by mist. In this method, small quantities of cutting fluid were applied in form of high velocity, narrow, pulsed jet. The amount of cutting fluid used was only 2 ml/min. The performance in hard turning of hardened tool steel during minimal cutting fluid application was superior to that during dry turning and conventional flood turning on the basis of cutting force, tool life, surface finish, cutting ratio, cutting temperature and tool-chip contact length. Anyway, focusing a pulsed jet to the cutting zone poses no problem in turning because the cutting tool is stationary [**Varadarajan et al. 2002**]. This process also can be done on high speed milling as proven by ThanongsakThepsonthi in May 2005 with his paper “Investigation into minimal cutting fluid application in high speed milling of hardened steel using carbide mills”. From all investigations, the minimal cutting fluids application in pulse jet form has shown to be a viable alternative to the current, flood and dry cutting method that being used widely in industries.

Zeilmann et al. **[2006]** compared the effects of internal and external application of MQL in the drilling of a titanium alloy (Ti-6Al-4V), at speeds between 10 and 50 m/min, feeds between 0.1 and 0.2 mm/rev, with coated and uncoated carbide tools. The most stable behavior of cutting temperatures was observed when applying conventional cooling internally, followed by internal MQL and dry cutting. The higher temperatures obtained when applying internal MQL had a positive effect in reducing the feed forces when compared with internally supplied flood cooling, but adverse effects were obtained with dry cutting due to excessive chip entanglement at high temperatures. However, the maximum temperatures obtained when applying internal MQL were 50% lower than those with external MQL.

Khan et al. **[2009]** applied external vegetable oil MQL in turning of steel (AISI 9130) using an uncoated carbide inserts. Tests were conducted with a 1 mm depth of cut at cutting speeds between 223 and 483 m/min and feed rates in the range of 0.1 to 0.18 mm/rev. The pure oil MQL flow rate was 100 ml/h with an air pressure of 6 bar. The performance of MQL was compared with that of dry machining and flood cooling at a rate of 360 l/h. It was found that MQL provided a 10% reduction of temperatures compared to flood cooling. This effect was more prominent at higher speeds, producing smoother and brighter chips and preventing any BUE formation.

Sadeghi et al. **[2009]** used MQL at rates between 20 and 140 ml/h, and 4 bar air pressure, to compare the effects of the tribological conditions when grinding titanium (Ti-6Al-4V). Aluminum oxide (Al2O3) wheels were used at a wheel speed of 15 m/s, work speed of 40 m/s, and depth of cut of 0.007 mm. Considerable reduction in cutting forces was obtained when applying MQL, as compared to cutting with flood cooling. In addition, better performance was obtained when the MQL fluid was synthetic oil, than a vegetable oil. In terms of surface roughness, MQL grinding can achieve similar results as flood cooling. Flood cooling slightly outperformed MQL, however. The comparison of different MQL oil flow rates showed that an optimal flow rate exists; 60 ml/h, with the existing setup combination and materials.

Lathkar and Basu[**2001**] investigated the effect of application of graphite based grease on cutting performance during turning of medium alloy steels with minimumquantity lubrication using tungsten carbide tools and compared the results with dryturning. Results indicated that there was improvement in cutting performance in the form of reduction in tool wear and improvement in surface finish. Deshmukh and Basu [**2006**] investigated the influence of solid lubricants like MoS_2, MoS_2-based grease, graphitebased grease and silicon compound mixed with SAE 20 oil and found that the applicationof such semisolid lubricant improved the cutting performance. On a similar line in the present investigation, it is planned to explore whether silicon grease can act as a cutting performance enhancer during surface milling of hardened AISI4340 steel with minimal fluid application using a high velocity narrowpulsed jet of cutting fluid. Heinemann et al. **[2006]** stated that continuous MQL supply is beneficial in terms of tool life, whereas interrupting the MQL supplyleads to a substantial drop in tool life, especially in the case of heat-sensitive drills. With respect to the type ofMQL lubricant, a low viscous type with high cooling capability gives rise to a notably prolonged tool life.

Minimum quantity lubrication technique reduces the amount of consumption of cutting fluid at a considerable amount. Along with that, the MQL system facilitates drastic reduction in the tool chip interaction. This leads to reduction in cutting force which decreases the tool wear. Reduced tool-chip and tool-work interactions also leads to lower thermal distortion and tool wear. This leads to improvement in surface finish and dimensional accuracy **[Dhar et al. 2007].**

Kamata et al. **[2007]** studied the effect of the MQL air pressure on high speed finish-turning of Inconel 718, using a biodegradable synthetic ester. It was found that when using external MQL with an oil flow rate of 16.8 ml/h and an air pressure of 4 bar, the tool wear obtained was consistently lower than with flood cooling (3.7 L/min) or dry machining. An increase in air pressure from 4 bar to 6 bar yielded higher tool wear, similar to dry cutting. It was suggested that increased oxidation, due to the more abundant oxygen, was the reason. The possibility that the excess air resulted in excessive atomization of the MQL fluid, thus not reaching the cutting zone, was not considered. When applying argon as the carrier gas, at a pressure of 4 bar, the tool life was in fact shorter than that with air or under dry conditions. This is likely due to the lower specific heat and thermal conductivity of argon, compared to air. An increase in lubricant supply from 16.8 ml/h to 31.8 ml/h caused an increase in tool life, without a significant improvement in the machined surface finish.

In a similar study, Obikawa**[2006]**et al. examined the effects of MQL flow parameters on the cutting temperature and tool wear. Internal application of MQL (7 ml/h with vegetable oil; 3 bar and 7 bar air pressures) was used in grooving experiments on 0.45% carbon steel, using uncoated and triple coated tools (TiN/TiCN/TiC). Tests were conducted at high speeds of up to 300 m/min, and a constant feed of 0.12 mm/rev. The internal MQL supply (through the tool) proved to be more effective in reducing tool wear, when compared with the external MQL, as it enhanced the concentration of the oil supply in the cutting zone. A decrease in maximum temperature and tool wear were observed when the MQL air pressure was increased, for a fixed oil flow rate. This indicated a potential effect of the injection parameters on the atomization of the lubricant, and consequently its effect on machining. The observed temperature reduction using MQL was also strongly dependent on the tool wear.

Bhowmick et al. **[2008]** used diamond-like-carbon-coated (DLC) drill bits in the drillingof an aluminum-silicon alloy, at a speed of 50 m/min and feed of 0.25 mm/rev. They compared thrust force and torque values when machining dry, with distilled water as the MQL fluid (30 ml/h), and with emulsion flood cooling (30,000 ml/h). The results obtained showed comparable thrust force and torque values for flood cooling and MQL. Applying MQL in drilling resulted in considerably lower adhesion levels as well as more stable cutting forces, when compared with dry drilling. The results also highlighted the better performance of non-hydrogenated DLC coated drills, compared to hydrogenated DLC coated drills, in terms of thrust force, torque, and Buit-UpEdge (BUE) formation, when water MQL is used.

The main drawbacks of the MQL method is the application of cutting fluid in the form of mist which increases the exposure of hazardous aerosols in the shop floor **[Anshuet al. 2007]**. The vapor, mist and smoke generated during the use of MQL in machining can be considered as undesirable byproducts, since they contribute to increase the index of airborne pollutants. This has become a factor for concern, requiring an adequate exhaustion system in the machine tool. Special techniques for transporting chips may be necessary and productivity may decrease due to the thermal impact on the machined components. The compressed air lines generate noise that usually exceed the legally established limits **[Machado and Diniz 2000]**. The limitations of MQL system are being taken into attention and a number of measures are taken to decrease those. For example, the use of compressed air can be replaced using fuel pumps working as pressure developer and hence reducing the amount of noise the MQL system develops.

Rahman et al. **[2002]** investigated MQL technique on milling of ASSAB 718 HH steel of 35 HRc with uncoated carbide inserts. The rate of flow of cutting fluid was 8.5 ml/h during MQL and 42,000 ml/min during flood application. The comparison of cutting performance indicated that MQL can definitely be regarded as a replacement for dry cutting and conventional flood cooling owing to the drastic reduction in lubricant consumption. They also found that there was a considerable reduction in cutting force components for the MQL technique as compared to dry milling and milling with flood cooling. Fracture or chipping was not common for the MQL aided inserts and surface finish obtained during MQL application was comparable to that during flood cooling.

There are two basic types of MQL delivery systems: external spray and through-tool. The external spray system consists of a coolant tank or reservoir which is connected with tubes fitted with one or more nozzles. The system can be assembled near or on the machine and has independently adjustable air and coolant flow for balancing coolant delivery. It is inexpensive, portable, and suited for almost all machining operations. Through-tool MQL systems are available in two configurations; based on the method of creating the air-oil mist. The first is the external mixing or one-channel system. Here, the oil and air are mixed externally, and piped through the spindle and tool to the cutting zone. The advantages of such systems are simplicity and low cost; they are suited to be retrofitted to existing machines with high-pressure, through the tool coolant capability. They are easy to service as there are no critical parts located inside the spindle. Also this system provides the flexibility of fine tuning the placement of the nozzle to facilitate better effect on the machining. The disadvantage is that the oil-mist is subjected to dispersion and separation during its travel from the nozzle. To minimize oil drop outs, a mist of relatively fine particles is used, and in certain cases this often limits the amount of lubrication that can be supplied to the cutting zone and consequently affects the performance of the cutting process. The second configuration is the internal mixing or two channel systems. Most commonly in a two channel system, two parallel tubes are routed through the spindle to bring oil and air to an external mixing device near the tool holder where the mist is created. This approach requires a specially designed spindle. Such systems have less dispersion and dropouts and can deliver mist with larger droplet sizes than external mixing devices. They also have less lag time when changing tools between cuts or oil delivery rate during a cut. However, the systems are more difficult to maintain; critical parts are located inside the spindle [**Filipovicand 2006**].

In the case of typical MQL, cooling ability depends only on the rate of flow of air. MQL with water droplets which are also known as oil film on water droplet (OoW) is a new technique, has a large cooling ability because the water droplets will not only act as the oil carrier but will also evaporate fast on the tool and work surface to their size, eventually cooling the surface by absorbing the latent heat by evaporative heat transfer. According to Itigawa et al. **[2006]**, this cooling ability is important not only for dimensional accuracy but also for tribological phenomena between the tool and work surface such as adhesion. In addition the water droplets ensure that their lubricant coating gets deposited and spreads over the work and tool surface due to the droplets' inertia.

Lubricant concentration in MQL varies between 0.2 and 500 ml/hr., and does not recirculate through the coolant delivery system. Since very good lubrication properties are required in MQL, vegetable oil or synthetic ester oil are used instead of mineral oil. Air pressure is roughly 5 bars **[Filipovicand 2006]**. MQL is consumption lubrication as the bulk of the lubrication applied is evaporated at the point of application. This evaporation, in concert with the compressed air stream, cools the workpiece. The remaining heat is dissipated through the tool and the chips. The chips, workpiece and tool remain nearly dry in an ideally adjusted MQL system. Wakabayashi et al.**[2003]** introduced synthetic polyol esters and described their capabilities as MQL fluids. These represent a potential replacement for vegetable-based MQL oils, particularly with regard to their optimal secondary performance characteristics. All vegetable oils display high biodegradability. Synthetic esters, however, provide a wide range of biodegradability depending on their combined molecular structures of acids and alcohols. This characteristic, in conjunction with their suitable viscosities, prompted Wakabayashi, et al.**[2006]**, to identify these lubricants for further examination.

Physical properties and biodegradability of polycol esters were compared with a vegetable oil. The viscosity, total acid number, pour point and biodegradability for polycol ester oil were 19.1mm^2/s, 0.02mgKOH/g, 45^{o}C and 100% respectively. These characteristics for vegetable oil were 35.6 mm^2/s, 0.04 mgKOH/g, 20° C and 98% respectively. The molecular weights of polycol ester oil and vegetable oil were also compared. The molecular weight of the oil film increased by more than 10%.The molecular weight of vegetable oil increased by 65%. In contrast, there was no significant change in the molecular weights of polyol esters. Most vegetable oils consist of a number of ester compounds mainly derived from a combination of glycerin and fatty acids.

Vegetable oils are usually liquids at room temperature, due to their unsaturated bonds. Unfortunately, unsaturated bonds are chemically unstable and may cause vegetable oils' molecular weight to increase. A detailed investigation of this behavior was carried out using GPC analysis. The results indicated that some of the molecules in vegetable oil had changed into compounds having higher molecular weights. Results of the UV analysis, which can selectively detect changes in unsaturated double bonds, indicate the unsaturated structure decreased significantly. This result supports the hypothesis that the unsaturated bond structure of vegetable oil molecules is the main cause of their easy degradation by oxidation polymerization. The polyol esters chosen as preferable biodegradable lubricants in this investigation are synthesized from a specific polyhydric alcohol rather than glycerin. Their molecules can greatly improve oxidation stability; they are free from unsaturated bonds.Regardless, they can be liquid at room temperature. Compared with vegetable oils, the synthetic polyol esters studied were optimal lubricants for MQL machining from the standpoint of maintaining a clean working environment.

Another secondary characteristic studied concerned the long-term storage potential of polyol esters and vegetable oils. Lubricant containers are often stored outside, and the temperature in the containers can rise as high as 70˚C. Since an MQL system consumes very little lubricant, the lubricant must remain stable under such conditions. In order to simulate this storage situation, an oxidation test was conducted at 70˚C for 4 weeks. Changes in viscosity and Total Acid Number (TAN) were measured. The change in viscosity for polyol ester oil and vegetable oil after the storage stability test were 0.01% and 1.5% and the change in total acid number (TAN) were 0.01% and 0.18% respectively. While the viscosity and TAN of polyol ester were almost constant, the values for vegetable oil increased considerably. These results confirm the stability of the molecular structure of the synthetic esters regarding oxidative degradation, thus promoting their stability in storage**[Wakabayashi et al. 2006]**.

From a practical point of view, the cutting fluids used in MQL need to be storable for long periods of time, as they are only used in minimal quantities. In the storage containers, the temperatures can rise up to 70^{0} C and therefore the fluids need to withstand this environment for long periods, without degradation. They also need to have a good oxidation resistance, so as to avoid the formation of an adhesive layer, in case they are left on the equipment.

It is clear that the applicability of near-dry machining will depend on the process, the cutting conditions (cutting speed, chip thickness), the tool material and geometry (insert, coating), the workpiece material, and the MQL supply parameters (internal, external, flow rates, type of fluid). In high speed machining, wear regimes are either mechanically activated such as adhesion, abrasion, and fatigue, or thermally activated such as diffusion, all contributing to tool life reduction. Other forms of wear exist, such as erosion (chemical wear) and micro chipping**[Kishawy et al., 2005]**. Although they are often present in combinations, the dominant wear regime varies with the aforementioned machining conditions.

Milling is a material removal process that applies to various operations such as planning, slotting, routing, and orbital drilling. In end-milling, the cutting is performed at the tip as well as the sides of the end-mill, thus the lubrication system must supply all these areas if adequate lubrication is necessary. Yan et al.[**2012**] investigated the significance of the MQL injection parameters on the milling of 50CrMnMo steel. Tests were conducted at a cutting speed of 220 m/min and a feed of 0.14 mm/tooth. The axial depth of cut used was 0.5 mm, and the radial depth of cut was 8 mm. The oil flow rate was varied between 13.9 and 58.4 ml/h, and the air pressure was varied between 2 and 6 bar. Within this range, the change in oil flow rate had negligible effects on flank wear, except at the lower levels. The increase in air flow rate led to a reduction in tool wear, reportedly due to better chip removal and the improved penetration of the flow to the cutting zone. Comparison of MQL with dry and flood cooling conditions showed that MQL produced the lowest tool flank wear and average roughness of the machined surface.

Rahman et al.**[2001]** applied MQL in low speed milling of steel (ASSAB 718 HH). In these tests, MQL was applied using a mineral oil with anti-wear and extreme pressure additives, at flow rate of 8.5 ml/h and air pressure of 5.2 bar. Tests were performed at a constant depth of cut (0.35 mm), with speeds in the range of 75 and 125 m/min, and feeds between 0.01 and 0.03 mm/tooth. Considerable reduction in cutting forces and thermal stresses in the case of MQL, compared to flood and dry cutting, was observed. No catastrophic tool failure occurred in the case of MQL, in contrast with flood cooled and dry cutting. In addition, the lowest amount of burr formation was obtained using MQL. In a similar study, but at higher speeds, **Liao et al. [2007]** used an oil flow rate of 10 ml/h and air pressure of 4.5 bar, as MQL flow parameters in the milling of hardened steel (NAK80). Tests with TiAlN and TiN coated carbide tools were conducted at speeds between 150 and 250 m/min, and feeds between 0.1 and 0.2 mm/tooth. The axial depth of cut and the radial depth of cut were 0.6 mm and 5 mm, respectively. The same conditions were used in tests with dry and flood coolant (20 l/min), in order to study the feasibility of MQL using biodegradable esters. The results showed that the lowest cutting forces were in the case of flood coolant, followed by MQL and dry cutting. The lowest tool wear values, however, were obtained under MQL, while flood cooling resulted in thermal cracking in the tool. The higher thermal wear in cutting tools at high speeds resulted in higher surface roughness values in the workpiece, when flood cooling was used. This trend was reversed at lower speeds, where flood cooling proved superior to MQL, making MQL a more suitable cooling method for high speed machining.

Kishawy et al.[**2005**] applied MQL (synthetic ester with EP additives) in milling of cast aluminum-silicon alloy (A356). Tests were conducted at speeds up to 5,225 m/min, using diamond coated and uncoated carbide inserts. The study was aimed at comparing MQL with flood and dry machining, in terms of tool life, cutting forces, and machined surface quality. The results showed that the cutting forces in the case of MQL and flood cooling were similar up to a speed of 2,000 m/min, beyond which flood cooling becomes superior in reducing cutting forces. As expected, dry machining exhibited the highest cutting forces. MQL cutting minimized the difference in the chip thickness ratio between sharp and worn tools. Also the lowest volume of adhered aluminum was obtained in the case of the MQL environment.

Hwang et al.**[2009]**evaluated the machinability of aluminum (Al6061) in milling tests using MQL (vegetable oil) and flood as the mode of lubrication. Analysis of Variance (ANOVA) was used to evaluate the importance of the different parameters on the surface roughness and cutting forces. The results showed that the cutting forces were largely dependent on the cutting parameters, as opposed to the mode of lubrication. The surface roughness values, however, were dependent on all the cutting conditions. Little difference in cutting forces was found, but the roughness values were lower in the case of MQL, consistent with previous studies.Hwang et al.[**2009**] compared tribological environments using titanium (Ti-6Al-4V) as the workpiece material. Tests were conducted using dry, flood, and vegetable oil MQL with flow rates between 2 and 10 ml/h and air pressure of 5.2 bar. All tests were carried out at speeds between 40 and 140 m/min, feeds of 0.05 to 0.2 mm/rev, axial depth of cut of 0.5 mm, and radial depths of cut between 2 and 8 mm. The MQL supply was efficient in reducing the tool adhesion levels, which was the main wear mechanism, and was strongly dependent on the coolant supply method. MQL led to significantly longer tool life, particularly at higher speeds, while flood cooling was ineffective even when compared to dry cutting. The use of MQL also resulted in lower levels of thermal cracking in the tool, compared to flood and dry machining, due to the lower temperature gradients which were significant in the case of flood cooling. The lower tool wear rate in the case of MQL also had a strong impact on reducing the cutting forces.

Thepsonthi, et al.**[2009]** and Marzurkiewicz, et al. **[1989]** indicated that the method of coolant application with high pressure jet could give better machining performance in terms of cutting force, tool life, surface finish, cutting temperature and tool-chip contact length. Machado and Wallbank**[1997]**conducted machining experiments using aventuri to mix compressed air with an air pressure of 2.3 bar with small quantities of liquid lubricant, water or soluble oil where the mean flow rate was between 3 to 5 ml/min. The literature also indicates that the MQL has many advantages in terms of environmental, economic and better machining quality. When dealing with steel materials, most of the research and applications of MQL are mainly focused on the milling and turning operations [**Abou-El-Hossein 2008**]. In addition, the investigations on high speed milling by using MQL technique are required further study especially on machining hardened steel and stainless steel **[Sun et al 2006]**.

Investigating the effect of application of graphite based grease mixed with base oil on cutting performance during turning of medium alloy steels using tungsten carbide tools, Lathkharet al.**[2001]** found that there was improvement in cutting performance. The influence of solid lubricants like MoS_2, MoS_2-based grease, graphite based grease and silicon compound mixed with SAE 20 oil was investigated by Deshmukh and Basu**[2001]** found that the presence of grease with cutting fluid has enhanced the cutting performance to some extent. A high velocity narrow jet of cutting fluid was applied during surface milling of hardened AISI 4340 steel with silicon grease to investigate whether the cutting performance is enhanced with the same line of investigation.

1.3 Design of Experiment (DOE)

Experimental design is a critically important tool in engineering for continuous improvement of the performance of manufacturing process. Statistical experiments are generally carried out to explore, estimate or confirm **[Jiju 2003]**. Exploration consists of gathering and understanding data to learn more about the process or product characteristics. Estimation refers to determining the effects of process variables or factors on the output performance characteristic. This information is used to estimate the settings of factors to achieve maximum output. Confirmation implies verifying the predicted results obtained from the experiment. The application of experimental design is useful in all the above phases. A well designed experiment can ensure improved process outputs, reduced development time and reduction in overall cost. Traditional approach of experimental design is empirical in nature. In this approach one factor is varied at a time keeping all other variables in the experiment fixed. This approach depends upon guesswork, luck, experience and intuition for its success. Moreover, this type of experimentation required large resources to obtain a limited amount of information about the process. One Variable-At-a-Time experiments often are unreliable, inefficient, time consuming and may yield false optimum condition for the process. Statistical thinking and statistical methods play an important role in planning, conducting, analysis and interpreting data from engineering experiments. When several variables influence a certain characteristic of a product, the best strategy is then to Statistical design of experiment which can give valid, reliable and sound conclusions that can be drawn effectively, efficiently and economically **[Jiju 2003]**.

1.4 Summary of the Review

A review of the study presents that the modern manufacturing industries are seeking manufacturing processes to increase the production rate without sacrificing quality. Although hard machining is a process that is used for a long time but due to the longer machining time required for the operations, various alternatives as cryogenic cooling, minimum quantity lubricant, pulsed jet machining MQL are being used frequently. These alternatives processes have shown significant improvement in terms of tool wear, temperature and cutting force under different cutting speed, depth of cut and feed rate.

Minimum Quantity Lubrication provides a better result than not only conventional flood cooling, but also other cooling processes. Pulsing the MQL provides a better cooling along with good surface finish and low cutting force. Although different combinations of cutting velocity, feed and depth of cut exhibits different qualities during surface milling, MQL has shown significant improvement over other processes.

1.5 Objectives of the Present Work

The objectives of the present work are:

(a) Design and development of a pulsed jet Minimum Quantity Lubricant (MQL) applicator

(b) Experimental investigation on the roles of Minimum Quantity Lubricant (MQL) by pulsed jet in respects of

- (i) Cutting forces and cutting temperature
- (ii) Pattern and mechanism of deformation of the cutting tools
- (iii) Extent of tool damage and tool life
- (iv) Surface roughness

in machining hardened AISI4140 steel at different speed, feed combinations.

(c) The scopes of the present work are design, development and fabrication ofa pulsed jet MQL applicator that can deliver cutting fluid at different volume at critical zones during surface milling.

1.6 Scope of the Thesis

To stay ahead in the ever growing competition of the global world, all the manufacturing industries are seeking for better alternatives of the traditional machining process that can reduce the cost and have little impact on the environment. Increasing usage of the hard materials has also caused the increase of temperature during the machining process. The cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy, can be controlled by the application of conventional cooling, precision cutting tools during dry machining or by application of straight oil as coolant in MQL. Keeping this in view, the present research work has been taken up to design and develop a Pulsed Jet Minimum Quantity Lubricant Applicator and explore the role of MQL applicatoron the major machinability characteristics in machining (surface milling) hardened steels by carbide end mill cutter under different machining conditions as well as to predict tool wear, surface roughness and cutting force in machining when machining under different environmental condition.

Chapter 1 presents the survey of previous work regarding general requirements in machining industries, technological-economical-environmental problems associated with the conventional cooling practices as well as dry machining practice and expected role of MQL on machining hardened steel. It presents specific objectives of this thesis work and also outlines the methods which have been followed to draw effective results that commensurate with the goals of the thesis.

Chapter 2presents the design and development of the pulsed jet Minimum Quantity Lubricant applicator for delivering cutting fluid to the effective cutting zone. Commonly used DOE methods, steps to follow DOE method and Full factorial analysis, one of the powerful and popular DOE methods has been adopted to optimize the important parameters of the applicator are described in this chapter.

Chapter 3 presents the material preparation steps and detail processes involved for bulk hardening of the sample workpiece for the experimental investigations. The deliveryprocesses of the cutting fluid from the reservoir to the cutting zone through the applicator are described in length. Complete experimental set up with experimental conditions are briefly described in this chapter. Finally the experimental results in terms of surface roughness, cutting forces and tool wear are represented by different graphs. Machine responses under different environmental conditions are graphically presented to observe the behavior of the workpiece, cutting tool on different environment. Effects of MQL, relative to dry condition on surface roughness, tool wear and cutting forces in milling hardened steel of hardness about 40 HRC by carbide end mill cutter under different cutting conditions are also discussed.

Chapter 4 contains the detailed discussions on the experimental results, possible interpretations on the results obtained.

Finally,**Chapter 5** contains a summary of major contributions, recommendation for the future work and references are provided at the end.

Chapter-2

Design and Development of Pulsed Jet Minimum Quantity Lubricant Applicator

2.1 Introduction

A major importance is given on the experimental design. The performance of the manufacturing process as well as its development depends on the experimental design in a large scale. Experimental design consists of planning, designing, conducting and analyzing and drawing reliable valid conclusions that can be later used in an effective manner. A number of statistical tools are used to explore, estimate or confirm the data acquired through the use of experimental design [**Antony 2003**]. Experimentaldesign has proved to be very effective for improving the process performance and process capability. A structured approach is used to achieve the most reliable results possible with the minimum amount of wastage of time and money. This enables to have an overall view of the manufacturing process with a limited number of experiments. The information gained can be used to optimize aprocess and define which parameters need to be placed under the most influencing in orderto maintain the repeatability of a process.The traditional approach of experimental design is empirical in nature. In this approach one factor is varied at a time keeping all other variables in the experiment fixed. This approach depends upon guesswork, luck, experience and intuition for its success. Moreover, this type of experimentation requires large resources to obtain a limited amountof information about the process. One variable-at-a-time experiments often are unreliable, inefficient, time consuming and may yield false optimum condition for the process. Statistical thinking and statistical methods play an important role in planning, conducting, analyzing and interpreting data from engineering experiments. When several variables influence a certain characteristic of a product, the best strategy is then the statistical design of experiment (DOE) which can give valid, reliable and sound conclusions that can be drawn effectively, efficiently and economically [**Antony 2003**].

Any experimental design has randomization as the first and basic principle. Randomization is a process of assigning specific treatments to the experimental units. This randomization attributes to equal possibilities of each allotment of the treatments. An experimental unit is the smallest division of the experimental material and a treatment means an experimental condition whose effect is to be measured and compared. The randomization is used to remove bias and other sources of extraneous variation which are not controllable. Moreover, randomization forms the basis of any valid statistical test. Hence the treatments must be assigned at random to the experimental units. Randomization can be done in a number of ways. It can be done by drawing numbered cards from a well-shuffled pack of cards, drawing numbered balls from a well-shaken container or even taking numbers from a table of random numbers.

Replication is the second principle of any experimental design. This states a repetition ofthe basic experiment. In other words, it is a complete run for all the treatments to be tested in the experiment. In all experiments, some variations are introduced. This type ofvariations can be removed by replication. The experiments are to be performed more thanonce. An individual repetition is called a replicate. The number of replicates depends upon the nature of the experimental material. The increase in the number of replications tends to remove the errors caused by the variations.

However, although randomization and replications are used to remove the extraneous sources of variation, it is not always possible to remove all the sources. Hence, a refinement in the experimental technique is required. In other words, a design is to be selected in such a manner that all extraneous sources of variation are brought under control. For this purpose, one has to make use of local control, a term referring to the amount of balancing, blocking and grouping of the experimental units. Balancing means that the treatments should be assigned to the experimental units in such a way that the result is a balanced arrangement of the treatments. Blocking means that similar experimental units should be collected together toform a relatively homogeneous group. Blocking reduces known but irrelevant sources of variation between units and thus allows greater precision in the estimation of the source ofvariation under study. The main purpose of the principle of local control is to increase theefficiency of an experimental design by decreasing the experimental error. Control in experimental design is used to find out the effectiveness of other treatments through comparison.

Orthogonality concerns the forms of comparison (contrasts) that can be legitimately and efficiently carried out. Contrasts that can be represented by vectors and sets of orthogonal contrasts are uncorrelated and independently distributed if the data are normal. Because of this independence, each orthogonal treatment provides different information to the others.

In many fields of study it is hard to reproduce measured results exactly. Comparisons between treatments are much more reproducible and are usually preferable.Often one compares against a standard or traditional treatment that acts as baseline.The following steps are involved in the design of experiment:

- Defining the objective of the experiment
- Selection of the response or output
- Selection of the process variables or design parameters (control factors)
- Determination of factor levels and range of factor settings
- Choice of appropriate experimental design
- Experimental planning
- Experimental execution
- Experimental data analysis and interpretation

2.2 Design of Experiment (DOE)for MQL Applicator

Design of Experiments (DOE) is a methodology that can be effective for general problem-solving, as well as for improving or optimizing product design and manufacturing processes. Specific applications of DOE include identifying proper design dimensions and tolerances, achieving robust designs, generating predictive math models that describe physical system behavior, and determining ideal manufacturing settings. Much of the knowledge about products and processes in the engineering and scientific disciplines is derived from experimentation. An experiment is a series of tests conducted in a systematic manner to increase the understanding of an existing process or to explore a new product or process. Design of Experiments, or DOE, is a tool to develop an experimentation strategy that maximizes learning using a minimum of resources. Design of Experiments is widely used in many fields with broad application across all the natural and social sciences. It is extensively used by engineers and scientists involved in the improvement of manufacturing processes to maximize yield and decrease variability. Often times, engineers also work on products or processes where no scientific theory or principles are directly applicable. Experimental design techniques become extremely important in such situations to develop new products and processes in a cost-effective and confident manner.

With modern technological advances, products and processes are becoming exceedingly complicated. As the cost of experimentation rises rapidly, it is becoming impossible for the analyst, who is already constrained by resources and time, to investigate the numerous factors that affect these complex processes using trial and error methods. Instead, a technique is needed that identifies the "vital few" factors in the most efficient manner and then directs the process to its best setting to meet the ever-increasing demand for improved quality and increased productivity. The techniques of DOE provide powerful and efficient methods to achieve these objectives. Designed experiments are much more efficient than one-factor-at-a-time experiments, which involve changing a single factor at a time to study the effect of the factor on the product or process. While the one-factor-at-a-time experiments are easy to understand, they do not allow the investigation of how a factor affects a product or process in the presence of other factors. When the effect that a factor has on the product or process is altered due to the presence of one or more other factors, that relationship is called an interaction. Many times the interaction effects are more important than the effects of individual factors. This is because the application environment of the product or process includes the presence of many of the factors together instead of isolated occurrences of single factors at different times. Consider an example of interaction between two factors in a chemical process where increasing the temperature alone increases the yield slightly while increasing pressure alone has no effect on the yield. However, in the presence of both higher temperature and higher pressure, the yield increases rapidly. Thus, an interaction is said to exist between the two factors affecting the chemical reaction.

The methodology of DOE ensures that all factors and their interactions are systematically investigated; thus, information obtained from a DOE analysis is much more reliable and complete than results from one-factor-at-a-time experiments that ignore interactions and may lead to misleading conclusions.Designed experiments are usually carried out in five stages planning, screening, optimization, robustness testing and verification.

It is important to carefully plan for the course of experimentation before embarking upon the process of testing and data collection. A few of the considerations to keep in mind at this stage are a thorough and precise objective identifying the need to conduct the investigation, assessment of time and resources available to achieve the objective and integration of prior knowledge to the experimentation procedure. A team composed of individuals from different disciplines related to the product or process should be used to identify possible factors to investigate and the most appropriate response(s) to measure. A team approach promotes synergy that gives a richer set of factors to study and thus a more complete experiment. Carefully planned experiments always lead to increased understanding of the product or process. Well planned experiments are easy to execute and analyze. Botched experiments, on the other hand, may result in data sets that are inconclusive and may be impossible to analyze even when the best statistical tools are available.

Screening experiments are used to identify the important factors that affect the process under investigation out of the large pool of potential factors. These experiments are carried out in conjunction with prior knowledge of the process to eliminate unimportant factors and focus attention on the key factors that require further detailed analyses. Screening experiments are usually efficient designs requiring few executions, where the focus is not on interactions but on identifying the vital few factors.

Once attention has been narrowed down to the important factors affecting the process, the next step is to determine the best setting of these factors to achieve the desired objective. Depending on the product or process under investigation, this objective may be to either increase yield or decrease variability or to find settings that achieve both at the same time.

Once the optimal settings of the factors have been determined, it is important to make the product or process insensitive to variations that are likely to be experienced in the application environment. These variations result from changes in factors that affect the process but are beyond the control of the analyst. Such factors (e.g. humidity, ambient temperature, variation in material, etc.) are referred to as noise or uncontrollable factors. It is important to identify such sources of variation and take measures to ensure that the product or process is made insensitive (or robust) to these factors.

This final stage involves validation of the best settings by conducting a few follow-up experimental runs to confirm that the process functions as desired and all objectives are met.

There are many methods of design of experiment (DOE) like Multi-vari chart, Variable search, Full factorials, Taguchi methods etc. Out of several methods of DOE, Full factorial analysis is a power full and popular homing in technique and hence frequently used DOE method. Fig.2.1 shows the commonly used DOE method. Almost all the methods follow some basic methodologies which are appended below:

- Identify the important variables or parameters that effect quality through extensive brainstorming with different expert opinion/participation
- Separates those variables into different categories, generally not more than 4 important and most severe variables which are known as Red X (most serious variable that effects quality) and pink X (Moderately serious which has moderate impact on quality)
- Reduce variations of Red X and pink X through redesign and process improvement
- Other than Red X and Pink X there may be lot many variable that do not effects quality should not take into consideration for controlling for minimizing the cost.

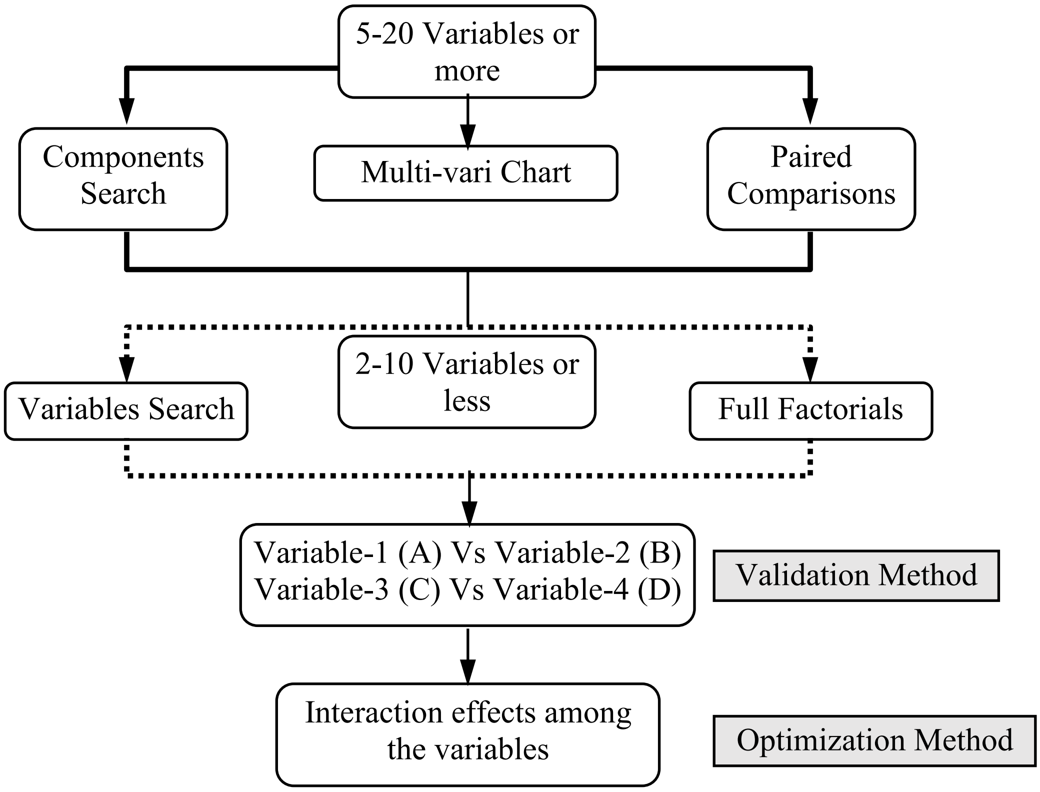


Fig.2.1 Commonly used DOE methods

2.3 Full Factorial Analysis for Pulsed Jet MQL Applicator

In full factorial analysis in investigation involving 4 variables and two levels of each factor is called 2^4 factorial analysis which involve 16 groups of test or combinations. Normally not more than 4 factors/variables at a time are taken to segregate the critical variables effect on the experimental setup. Full factorial DOE method is one of the powerful and popular tools for identifications of the most severe variables which may cause or affect the performance of the product. Basic principle of the analysis is that every variable can be tested with all levels (generally two) of every other variable. Experimental testing of all possible combinations of pre-selected variables and levels allows for the systematic separation and quantification of all main and interaction effects, thereby giving the chance of narrowing down the number of variables to one or two which are comparatively more severe. The complete full factorial analysis involves two main steps such as preparation of combinatorial matrix which identifies the impact of all individual variables having two levels for each variables and preparation of ANOVA table to identify main effect and interaction effect.

First of all visualize the components of the applicator and identify the variables that affect the performance of the applicator functionality. Identify also the response variable i.e. independent variable and dependent variable and some other factors which are not that important but have some impact on the overall performance after interacting with each other's. These variables are:

- Container size (length and diameter), material and sealing
- Volume of the container
- Height of the container of the cutting oil from the fuel pump
- RPM of the motor running the fuel pump
- Number of nozzles of the fuel pump to be used
- Diameter of the nozzle injector
- Milling cutter type and material
- Pressure and flow of the cutting fluid
- Process parameters (cutting velocity, table feed and depth of cut)
- Machining responses (surface roughness, cutting force and flank wear)
- Angle of the spray pattern

After several brain storming session with concern technical staff and all levels of experts, it has been provisionally identified that out of the above mentioned variables, depending on the severity following 4 variables as shown in Table 2.1. Table 2.1 are seems to be vulnerable for the optimized performance of the applicator.

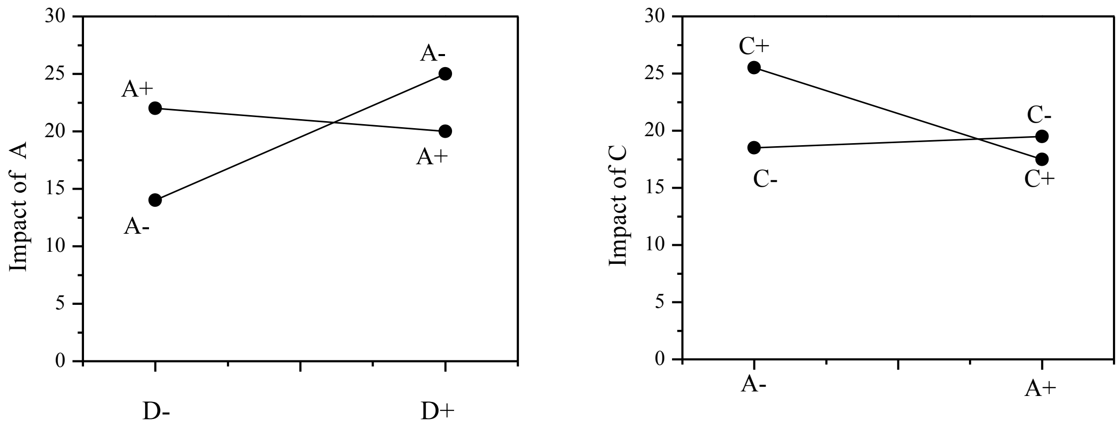
Table 2.1 Most severe variables that effects performance of the MQL applicator

Symbol	**Factors or variables**	**Level (- or +)**	
		Present Value (-)	**Experimental(+)**
A	Diameter of the nozzle injector	1 mm	0.5 mm
B	Volume of the container	250 cc	100 cc
C	Angle of the spray pattern	60°	30°
D	Pulsing frequency	1450	800

Several experiments with the above 4 variables each with 2 levels are performed and roughness is recorded. A total of 2^4 or 16 groups were to be tested and among the different combinations, the ones with the best response outcome (surface roughness) in this case are selected.Due to the time and resource constrained only 8 runs were taken and the surface roughness was recorded. Preliminary experiments were conducted using a single jet configuration to find out the viability of MQL application for hard milling and to find a set of fluid application parameters that can provide minimum surface roughness. The p-value and f-value of the variables are as shown in Table 2.2. This analysis was carried out to identify the significance of the fluid application parameters on output performance using Minitab 17.0 software. The interaction curve of the factors is shows in Fig. 2.2.

Table 2.2 F-value and P-value of the parameters from ANOVA analysis

Symbol	Factors or variables	F-value	P-value
A	Diameter of the nozzle injector	0.02	0.901
B	Volume of the container	3.05	0.131
C	Angle of the spray pattern	0.15	0.708
D	Pulsing frequency	3.05	0.131



(a) (b)

Fig.2.2 Graphs(a) and (b) shows the interaction effects between A &D and A & C

2.4 Fabrication of Pulsed Jet MQL Applicator

Based on outcome of full factorial analysis, parameters of the rotary liquid nitrogen applicator are finalized as shown in Table 2.3 and the components of the applicator are describe below.

Table 2.3 Selected parameters for final design of pulsed jet MQL applicator

Symbol	Factors or variables	Present Value (-)	Experimental (+)	Selected parameters for final design
A	Diameter of the nozzle injector	1 mm	0.5 mm	1 mm
B	Volume of the container	250 cc	100 cc	250 cc
C	Angle of the spray pattern	60°	30°	30°
D	Pulsing frequency	1450	800	1450

The nozzle injector is one of the critical parts of the pulsed jet MQL applicator. The pulse is provided with the help of a fuel pump. The fuel pump has a plunger with helical groove which can rotate about its axis and the degree of rotation of the plunger presets the quantity of fluid delivered per stroke. There is a provision for rotating the plunger so that the quantity of fluid delivered per stroke can be controlled accurately. The plunger reciprocates as an AC motor rotates and delivers one pulse of cutting fluid for each revolution through the fluid injector. The fluid flow alternates in four different outlets. Three of the outlets are closed and only one outlet is connected with the nozzle injector. A regulator is used to provide variable speed of the motor which eventually controls the pulsing frequency of the cutting fluid. The fluid coming out of the nozzle injector consists of tiny droplets of 68 grade cutting oil. The experimental setup facilitates independent variation of frequency of pulsing, rate of fluid application. A container was placed above the fuel pump to provide 68 grade cutting oil. The regulator on the fuel pump was used to control the amount of the cutting oil in each pulse. The nozzle injector was attached with the outlet of the fuel pump by means of a semi flexible channel. The channel was used to provide the nozzle injector the provision to move closer to the milling cutter during the machining process.

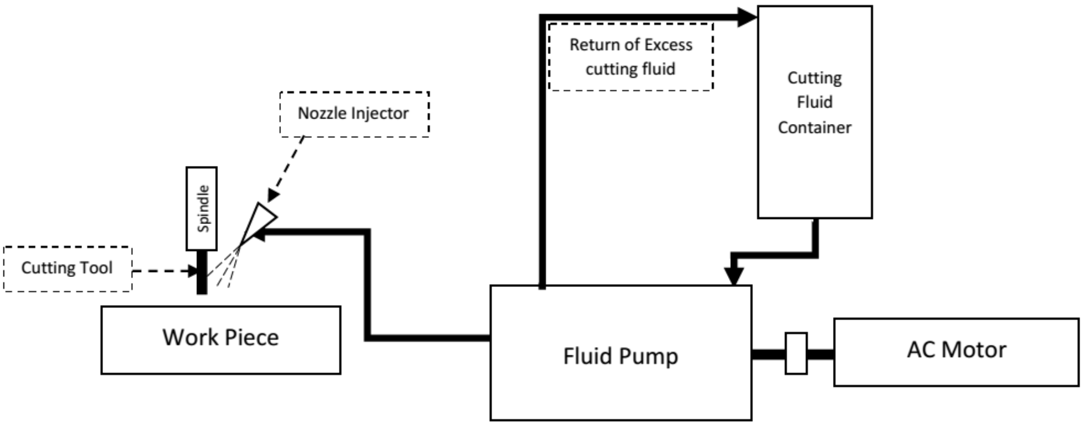


Fig.2.3 Schematic view of Pulsed Jet MQL Applicator

The nozzle injector delivers cutting fluid at single pulse per revolution. This facilitates the application of a minute amount of cutting fluid to be used per pulse during the machining process. For example, if Q is the amount of fluid application in ml/min and F is the frequency of pulsing in pulses/min, fluid application per pulse can be expressed as Q/F. Pulsing jet aids in fluid minimization without compromising the velocity of individual particles as the pressure at the fluid injector remains constant at the set value. If the frequency of the pulsing can be varied, the rate of fluid delivery can also be controlled. If Q is as low as 1 ml/min and the frequency F is 1000 pulses/min then the amount of fluid delivered per pulse is equal to 0.001 ml.

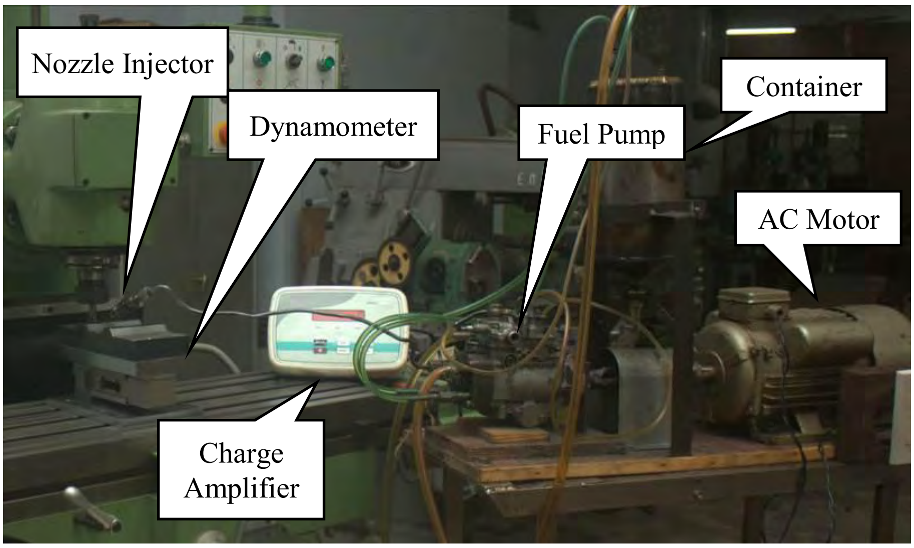


Fig.2.4 Photographic view of the Pulsed Jet MQL Applicator

Two types of nozzle injector were used to test the setup and find the minimum surface roughness during the experiment. The nozzle injector varied in respect of the spray angle where one had an angle of 30° and the other had an angle of 60°. The spray angle does not remain constant as spray length increases. To ensure the continuity of the flow rate the nozzle injector was tested at different MQL rates and the repeatability of the system was plotted as shown in Fig. 2.4. From the plot it is seen that the repeatibilty of the process is always above 95 percent which ensures the consistency of the flow rate during the experiment. Six different flow rates were tested by running the setup a total of ten minutes for each flow rate and calculating the amount of the fluid after each minute.Also a number of factors are responsible to determine the nozzle diameter size as well as the spray angle of the nozzle injector. Depending on the flow rate and fluid type the nozzle diameter and spray pattern varies.Liquids more viscous than water form smaller spray angles, or solid streams, depending upon nozzle capacity, spray pressure, and viscosity. Drop size increases with the decrease in spray pattern and high pressure process streams force narrower spray angles. To achieve a wide spray angle normally low pressure streams are used. As illustrated in the Fig.2.6 below, the spray angle tends to collapse or diverge with increasing distance from the orifice. Spray coverage varies with spray angle. The spray angle is assumed to remain constant throughout the entire spray distance.

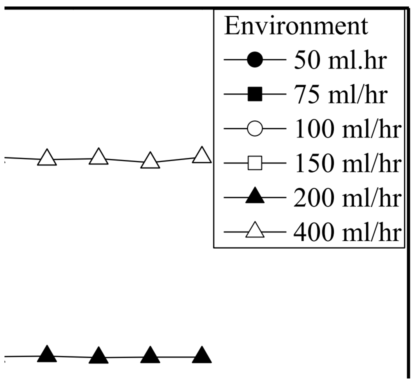


Fig.2.5 Repeatability check of the MQL applicator for different flow rates

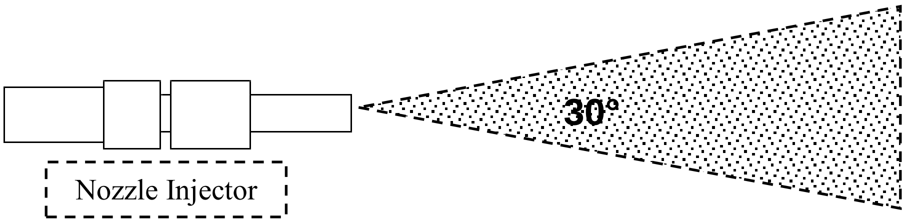


Fig.2.6 Schematic view of spray pattern of the cutting fluid

Fig.2.7 Photographic view of spray pattern of the cutting fluid

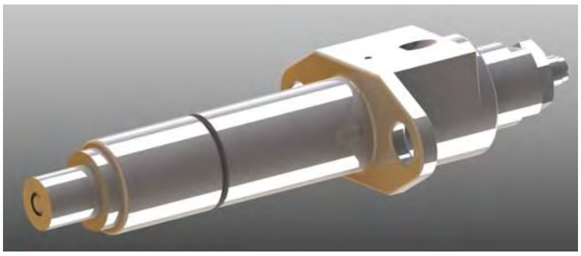


Fig.2.8CAD view of the nozzle injector **Fig.2.9**Sectional view of nozzle injector

Fig.2.10 Photographic view of Nozzle Injector during milling process

Chapter-3

Experimental Investigations

3.1 Material Preparation

AISI4140 has many applications as forgings for the aerospace and oil and gas industries, along with myriad uses in the automotive, agricultural and defense industries. Typical uses are forged gears and shafts, spindles, fixtures, jigs and collars. The steel is suitable forinduction or flame hardening. Pre hardened and tempered 4140 can be further surface hardened by flame or induction hardening and by nitriding. This grade of steel is considered for its wide range of application in the industry. It has a composition as shown in the Table 3.1.

Table 3.1 Chemical composition of the work material

Element	Fe	Cr	Mn	C	Si	Mo	S	P
Content (%)	96.785 - 97.77	0.80 - 1.10	0.75 - 1.0	0.38 - 0.43	0.15 - 0.30	0.15 - 0.25	0.04	0.035

The AISI 4140 used in the thesis was a plate of 200mm length, 100mm breadth and 40mm thickness. Fig.3.1 presents the photographic view of the work piece used in this investigation.

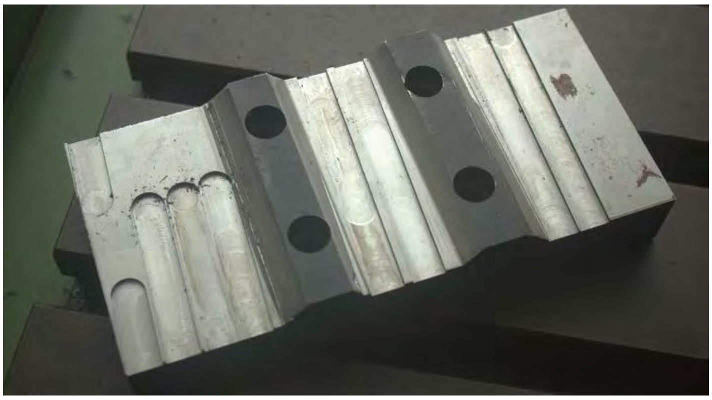


Fig.3.1 Photographic view of AISI4140 hardened steel

AISI 4140 was heated using an electric furnace (RG-3000C, 240 V, 32 amps) to attain hardness level.Before loading the work piece, the furnace had to be made oxygen free to avoid oxidation because a scale is formed on the surface of the work material during hardening. Two ceramic pipes of internal diameters of 3 mm and 4.5 mm were connected with the inlet and outlet of the furnace. The other end of the 3 mm internal diameter pipe was attached to an argon gas cylinder. The electric furnace was sealed and isolated from the atmosphere by placing an asbestos sheet on the door. Argon gas was then passed at 7 liters/min and 130 bars pressure through the furnace chamber to drive out air to make an inert environment. After a few minutes, the furnace was turned on and the delivery rate of argon gas was dropped to 5.5 liters/min at a pressure of 130 bars. It took three hours to raise the temperature to 900°C and the material was kept at the heating chamber for one and a half hour.

For quenching the material a tank of 600 liter capacity was used. Thetemperature of the quench bath was around 40°C.This oil reduces the absorption of atmospheric gases that, in turn reduces the amount of bubbles.As a result, the metal surface is drenched with oil, which cools the surfacemore rapidly than water andremoves a large percentage ofany scale that may be present.The work piece was taken out from the furnace using a tong and was immersed vertically into the oil quenching tank without any intermediate delay. The oil is stirred vigorously for about 20 minutes for uniform cooling and was continued until the specimen is cool enough.

While quenching several internal stresses like residual stresses are built inside the material. To relieve the internal stresses and reduce brittleness, tempering should be done. It was done by heating the workpiece to a specifictemperature (300^0C), holdingit at that temperature for two hours, andthen cooling it, usually inair. The resultant strength,hardness, and ductility depend on the temperature towhich the specimen is heated during the tempering process.

3.2 Selection of Cutting Tool

A four flute end mill cutter was used surface mill hardened AISI 4140 steel. The end mill cutter had a diameter of 12 and a 30-degree helix angle. The length of the flute is 20 mm with a shank of 65mm. The tool's square end creates sharp, unrounded cuts, and the center-cutting design has cutting teeth at the end of the tool, so it can be fed into the workpiece like a drill bit. Four flutes produce a better finish than fewer flutes.

End mills are designed to remove material and create multi-dimensional shapes and profiles. They have cutting edges along the outside diameter and flutes that remove chips from the cutting area and allow cooling fluids to enter.

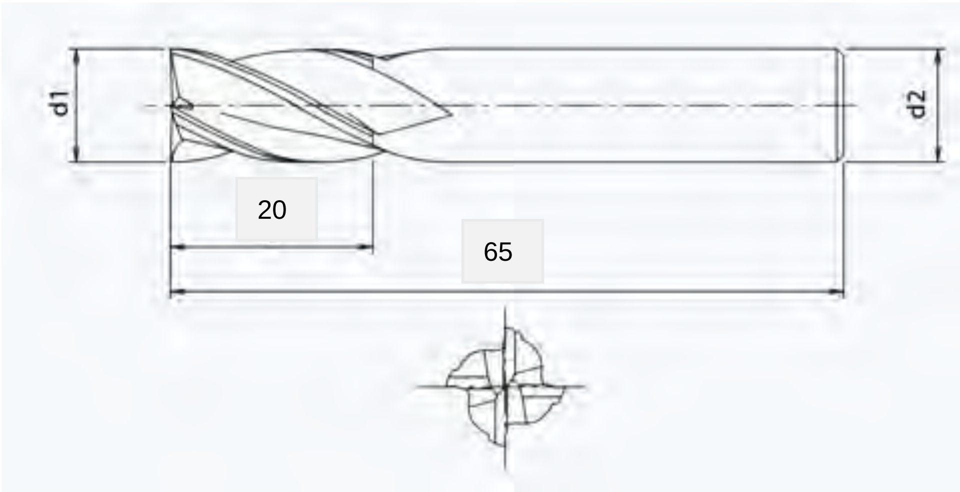


Fig.3.2 Schematic view of four flute end milling cutter

Fig.3.3 Photographic view of four flute end milling cutter

3.3 Experimental Procedure and Conditions

Compared to the traditional flood cooling, MQL has a number of advantages, the experiment was primarily performed to find out the effect of MQL application on surface milling of hardened AISI4140 steel in terms of surface roughness, cutting force and flank wear of the cutting tool.

The machining test has been carried out by milling of hardened steel in a column and knee type vertical milling machine (7.5 hp, Sunlike, China) by four flutecarbide milling cutter at different cutting velocities (V_c) and feeds (S_o) under dry and MQL cutting condition.The conditions under which the machining tests have been carried out are briefly given in Table 3.2.

Table 3.2 Experimental conditions

Machine Tool	: Vertical Knee and Column type Milling Machine, China
Work Materials	: AISI4140 Hardened steel (dimension: 200x100x40 mm)
Hardness	: 40 HRC
Cutting Tool	: Carbide End Milling Cutter (Ø12 mm)
Process Parameters	
Cutting speed	: 12, 16, 22, 27 and 32 m/min
Table feed	: 22, 34, 44 and 68 mm/min
Depth of cut	: 1.0 mm
Cutting Fluid	: VG 68 Straight cut cutting oil
Environment	: Dry and MQL
MQL Flow rate	➢ 50 ml/hr ➢ 75 ml/hr ➢ 100 ml/hr ➢ 150 ml/hr ➢ 200 ml/hr

Carbide end mill cutter (Ø12 mm) which has helical higher positive cutting edges as shown in Fig.3.2 was used in the investigation with straight shank. Cutting force was measured using a dynamometer. It consists of a load cell type dynamometer with charge amplifier. The surface roughness of the machined surface after each operation was measured by a Talysurf roughness checker(Surtronic 3^+, Rank Hobson, UK) using a sampling length of 0.8mm.The width of the flank wear was measured using metallurgical microscope (Carl Zeiss, Germany) fitted with micrometer of 1μm resolution.

3.4 Experimental Results

In the present work, surface roughness, cutting force and flank wear have been investigated to study the role of Pulsed Jet MQLand to compare with dry milling at different cutting velocities and table feeds. The cutting speed started from 12 m/min reaching 5 different levels while table feed started from 22 mm/min at 4 levels and the depth of cut was 1.0 mm during the surface milling. Tool life tests were conducted at a cutting velocity of 32 m/min, table feed 68 mm/min and depth of cut 1.5 mm. Measurements of surface roughness, cutting force and tool wear were done at specific intervals during each experiment.

3.4.1 Surface Roughness

Surface roughness indicates the state of a machined surface.The shape and size of irregularities on a machined surface have a major impact on the quality and performance of that surface, and on the performance of the end product. Measurement of surface roughness, is necessary to maintain high product performance. Surface integrity, in turn depends on surface roughness, oxidation, corrosion, residual stresses and surface and subsurface microcracks.

Surface roughness is an important characteristics to attain during machinability and is influenced by a number of factors, primarily on tool-work combination and speed-feed rate combination.

Surface roughness was measured at two different stages,during the calculation of cutting force, a surface milling operation of 40 mm was done with a depth of cut of 1.50 mm to calculate the surface roughness at different feed and cutting velocity combinations. The second calculation was done during the measurement of the flank wear where a new four flute end mill cutter was used to perform the machining operation. After specific preset machining time, the flank wear of the tool and the surface roughness was measured. The surface roughness attained during milling of the hardened AISI4140 steel at various cutting speed and table feed combinations under dry and MQL cooling conditions are shown in Fig.3.4, Fig.3.5, Fig.3.6, Fig.3.7, and Fig.3.7 respectively. The variation of roughness observed with progress of milling of AISI4140 hardened steel at a particular set of cutting velocity and table feed under dry, MQL cooling conditions have been shown in Fig.3.13.

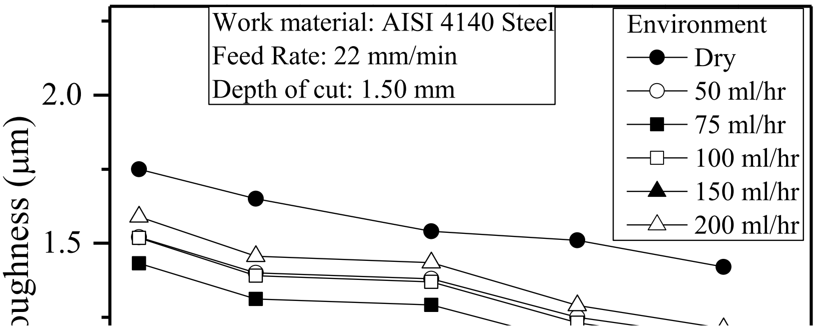


Fig.3.4 Variation of surface roughness with that of cutting velocity at 22 mm/min table feed under dry and MQL with different flowrates.

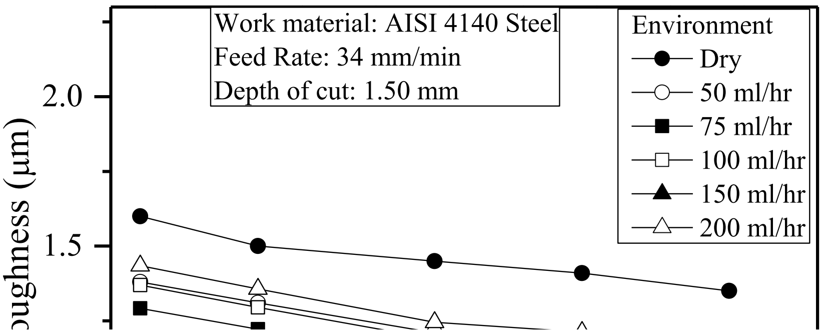


Fig.3.5 Variation of surface roughness with that of cutting velocity at 34 mm/min table feed under dry and MQL with different flowrates.

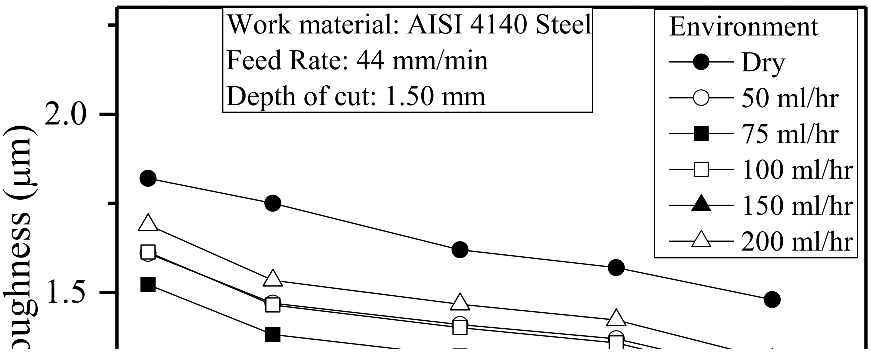


Fig.3.6 Variation of surface roughness with that of cutting velocity at 44 mm/min table feed under dry and MQL with different flowrates.

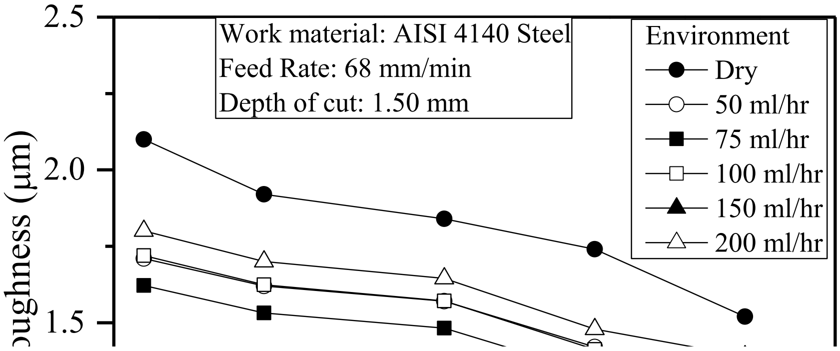


Fig.3.7 Variation of surface roughness with that of cutting velocity at 68 mm/min table feed under dry and MQL with different flowrates.

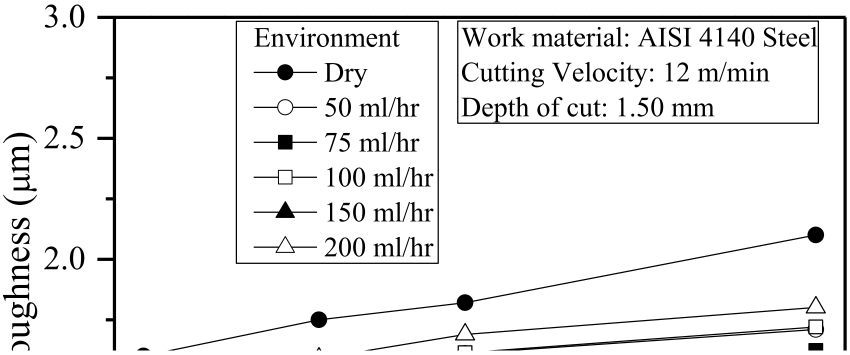


Fig.3.8 Variation of surface roughness with that of feed rate at 12 m/min cutting velocity under dry and MQL with different flowrates.

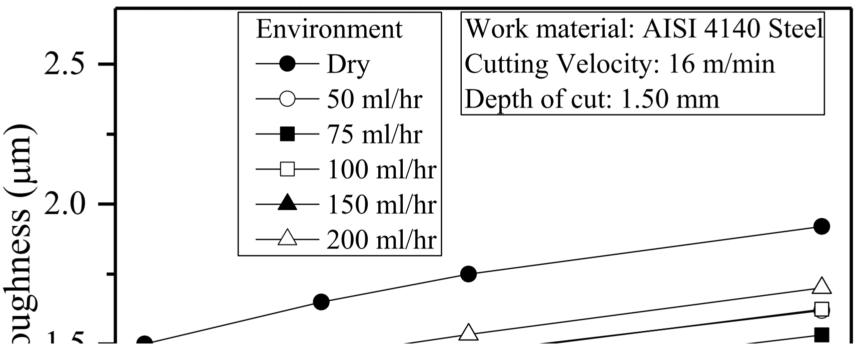


Fig.3.9 Variation of surface roughness with that of feed rate at 16 m/min cutting velocity under dry and MQL with different flowrates.

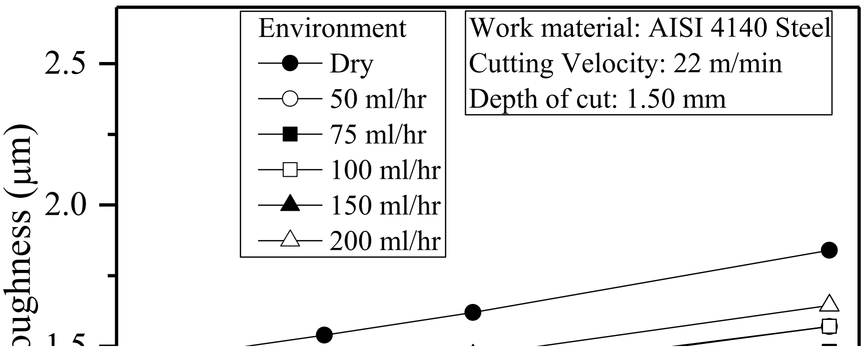


Fig.3.10 Variation of surface roughness with that of feed rate at 22 m/min cutting velocity under dry and MQL with different flowrates.

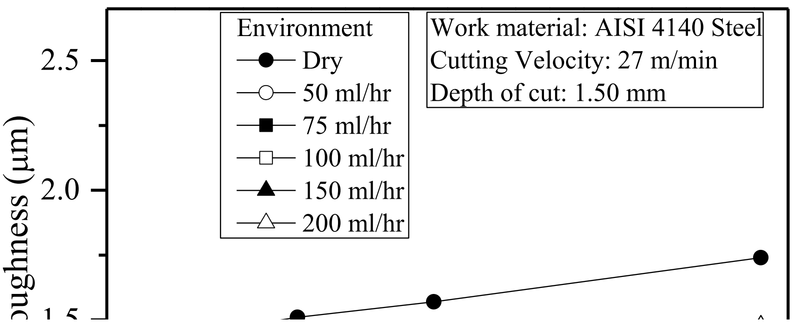


Fig.3.11 Variation of surface roughness with that of feed rate at 27 m/min cutting velocity under dry and MQL with different flowrates.

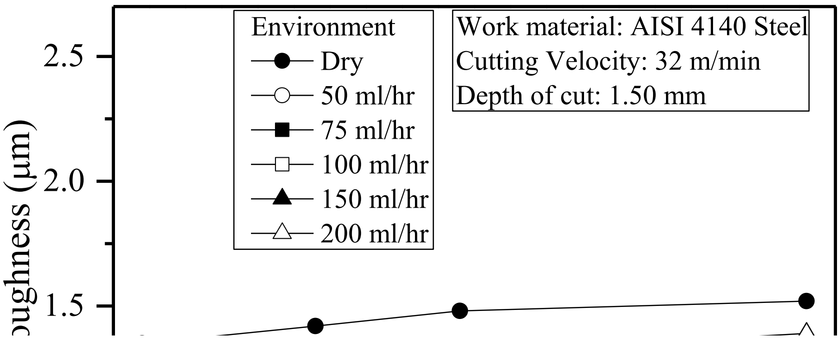


Fig.3.12 Variation of surface roughness with that of feed rate at 32 m/min cutting velocity under dry and MQL with different flowrates.

Fig.3.13 Variation of surface roughness with time at 32 m/min cutting velocity and 68 mm/min table feed rate under dry and MQL.

3.4.2 Cutting Force

In milling, cutting forces are exerted in three planes to deform and shear away material in the form of a chip.Forces experienced by a tool during cutting are detrimental in design of mechanical structure of cutting machine, predicting power consumption, determining the tool life and increasing the productivity. Tangential cutting forces overcome the resistance to rotation and accounts for 70 percent of the total force. Feed forces account for 20 percent of the total force. Radial forces tend to push away the tool and account for 10 percent of the cutting forces.Cutting forces are generally resolved into components in mutual perpendicular directions for convenience of measurement, analysis, estimation of power consumption and for design of machine-fixture-tool-work systems. In the present work, the magnitude of cutting force has been monitored by dynamometer at different cutting velocity and table feed combinations under dry andMQL conditions. The effects of MQL on the cutting force under different machining conditions have been shown in Fig.3.14, Fig.3.15, Fig.3.16, Fig.3.17, Fig.3.18, Fig.3.19, Fig.3.20, Fig.3.21, and Fig.3.22respectively. The variation of cutting force observed with progress of milling of AISI4140 hardened steel at a particular set of cutting velocity and table feed under dry, and MQL conditions have been shown in Fig.3.23.

Fig.3.14 Variation of cutting force with that of cutting velocity at 22mm/min table feed rate under dry and MQL with different flowrates.

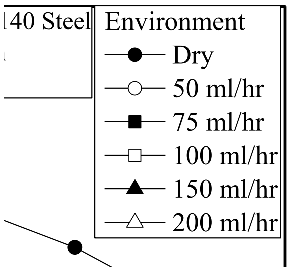


Fig.3.15 Variation of cutting force with that of cutting velocity at 34mm/min table feed rate under dry and MQL with different flowrates.

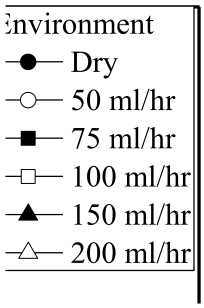


Fig.3.16 Variation of cutting force with that of cutting velocity at 44mm/min table feed rate under dry and MQL with different flowrates.

Fig.3.17 Variation of cutting force with that of cutting velocity at 68mm/min table feed rate under dry and MQL with different flowrates.

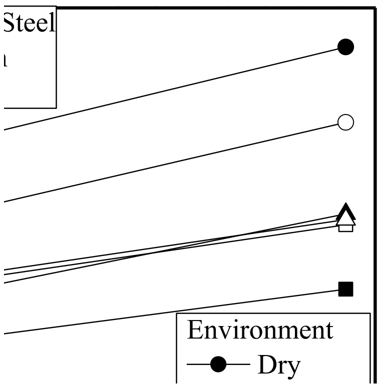


Fig.3.18 Variation of cutting force with that of feed rate at 12m/min cutting velocity under dry and MQL with different flowrates.

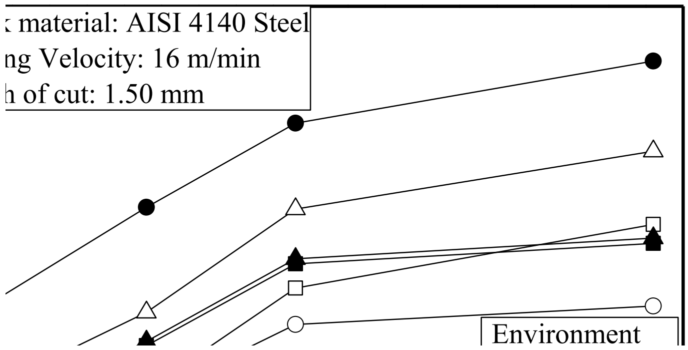


Fig.3.19 Variation of cutting force with that of feed rate at 16m/min cutting velocity under dry and MQL with different flowrates.

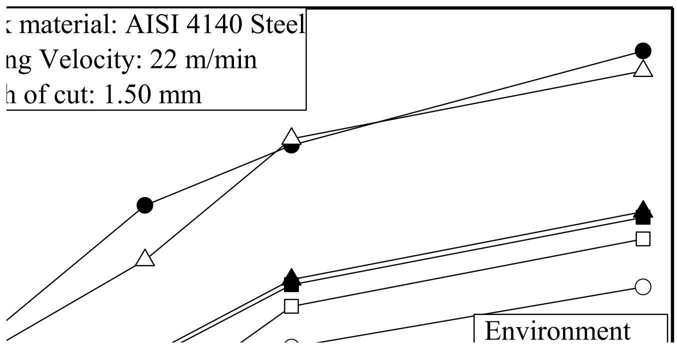


Fig.3.20 Variation of cutting force with that of feed rate at 22m/min cutting velocity under dry and MQL with different flowrates.

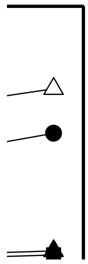


Fig.3.21 Variation of cutting force with that of feed rate at 27m/min cutting velocity under dry and MQL with different flowrates.

Fig.3.22 Variation of cutting force with that of feed rate at 32m/min cutting velocity under dry and MQL with different flowrates.

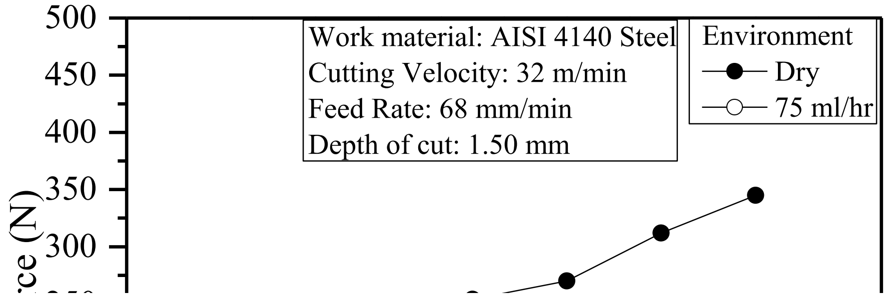


Fig.3.23 Variation of cutting force with time at 12m/min cutting velocity and 68 mm/min table feed rate under dry and MQL.

3.4.3 Flank Wear

Cutting tool wear is a critical phenomenon during machining process. During milling, the cutting tool generally fails by abrasion, adhesion, diffusion, chemical erosion etc. depending upon the tool-work materials and milling condition. Tool wear initiates with a faster rate, commonly known as break-in-wear, which is caused by micro chipping at the sharp cutting edge. Premature fail often occurs by mechanical breakage and plastic deformation under adverse milling conditions. However, in the present investigations with the cutter and work material and the milling conditions undertaken, the tool failure mode has been mostly gradual wear.

The growth of flank wear of the four flute end mill cutter has been measured at preset time intervals of milling operation while recording the cutting force and second, with the progress of machining time. The growth of flank wear attained after preset intervals of milling at a specific cutting speed and table feed combination under dry and MQL conditions are shown in Fig.3.24. The growth of flank wearand corresponding cutting force with progress of milling at a particular set of cutting velocity and table feed under dry and MQL conditions have been shown in Fig.3.25.

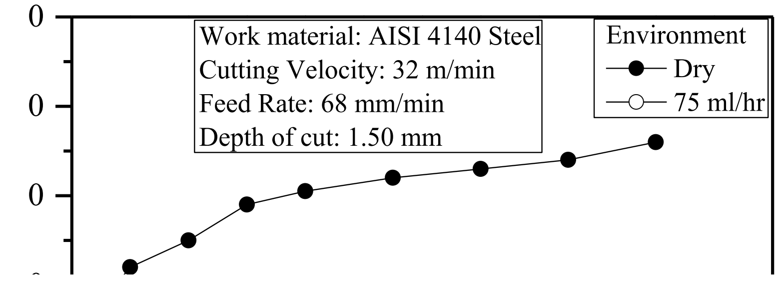


Fig.3.24 Growth of tool wear with time at 32m/min cutting velocity and 68 mm/min table feed rate under dry and MQL.

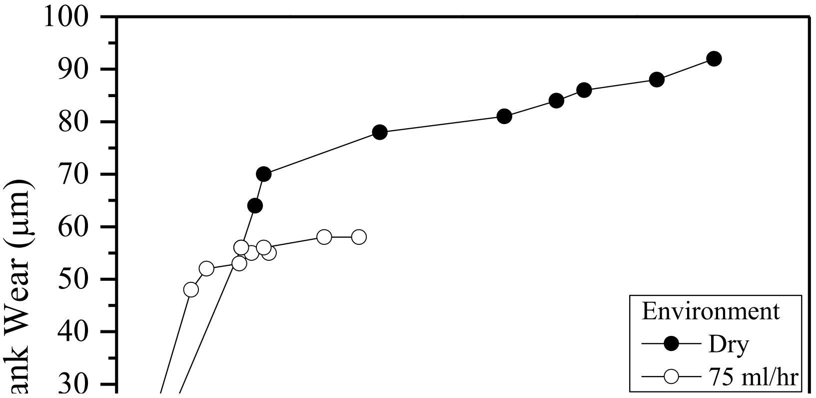


Fig.3.25 Variation of flank wear with that of cutting force at 32m/min cutting velocityand 68 mm/min table feed rate under dry and MQL.

The relationship between cutting velocity, feed rate and surface roughness are shown in Fig.3.26, Fig.3.27, Fig.3.28, Fig.3.29, Fig. 3.30 and Fig.3.31 for different cutting conditions. A comparison of the same parameter under different cutting conditions is shown in Fig.3.32.

Fig.3.26 Variation of surface roughness with that of feed rate and cutting velocityunder dry condition.

Fig.3.27 Variation of surface roughness with that of feed rate and cutting velocityunder 50 ml/hr MQLcondition.

Fig.3.28 Variation of surface roughness with that of feed rate and cutting velocityunder 75 ml/hr MQLcondition.

Fig.3.29 Variation of surface roughness with that of feed rate and cutting velocityunder 100 ml/hr MQLcondition.

Fig.3.30 Variation of surface roughness with that of feed rate and cutting velocityunder 150 ml/hr MQLcondition.

Fig.3.31 Variation of surface roughness with that of feed rate and cutting velocityunder 200 ml/hr MQLcondition.

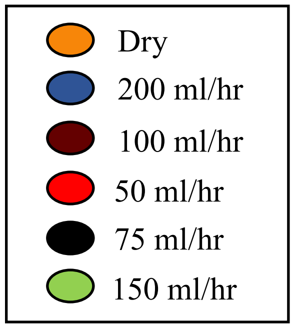


Fig.3.32 Variation of surface roughness with that of feed rate and cutting velocityunder dry and MQL with different flowrates.

Chapter-4

Discussion on Experimental Results

4.1 Surface Roughness

A number of parameters are attributed to define the quality of a workpiece after different machining processes. The quality of a work material is the main determinant of its functional ability throughout its service life. A significant proportion of component failure starts at the surface due to either an isolated manufacturing discontinuity or gradual deterioration of the surface quality.

Mass finishing processes have been widely adopted throughout industry as the optimum methodology for producing controlled edge and surface finish effects on many types of machined and fabricated components. In recent years, mass-media finishing processes have gained widespread acceptance in many industries, primarily as a technology for reducing the costs of producing edge and surface finishes. Variations in the surface texture can influence a variety of performance characteristics. The surface finish can affect the ability of the part to resist wear and fatigue; to assist or destroy effective lubrication; to increase or decrease friction and/or abrasion with mating parts; and to resist corrosion. As these characteristics become critical under certain operating conditions, the surface finish can dictate the performance, integrity and service life of the component.Surface finish is also an important index of machinability or grindability because performance and service life of the machined/ground component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface microcracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part(s). Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining. Even if it is to be finally finished by grinding, machining prior to that needs to be done with surface roughness as low as possible to facilitate and economize the grinding operation and reduce initial surface defects as far as possible.

Cutting fluid improves the surface integrity of work material. As it reduces the temperature, leading to less wear of the tool, the surface finish of the work material improves. Moreover, cutting fluid acts as a lubricant that enhances the surface integrity of the material. However, excessive usage of the cutting fluid not only creates environmental impact and adheres to the increased cost of manufacturing. Although most of the cutting fluid used in flood cooling is not completely used in the machining process. In this scenario, use of Pulsed Jet Minimum Quantity Lubricant has improved the surface roughness in a number of ways. The MQL process enhances the chip breakability during machining and reduces the tendency of chip's adhesion to the tool resulting in less scratch on the surface finish. Smaller roughness measurements reflect better surface quality of the workpiece. Surface finish is largely influenced by the cutting force, tool wear and chip formation. For the current investigative study, surface roughness has been considered as the main parameter to define quality of the machined work material under dry and MQL cutting.

Fig.3.4 to Fig.3.32 shown in the previous chapter have expressed a number of significant impacts of different parameters on the quality of the work material. Fig.3.4 to Fig.3.7are showing how and to what extent surface roughness has improved with the increase of the cutting velocity. It is evident from the figures that use of MQL in different amounts improves the surface finish of the work material, but to different degrees. The figures express that in almost all the cases, an improvement of the surface finish is found compared to dry condition. Out of the different flow ratesMQL with 150ml/hr flowrate has shown the most significant improvement in terms of surface finish under different cutting velocity. The improvement in surface roughness by increasing the cutting speed can be explained by being an easy deformation process because of the increasing temperature at high speeds, i.e. the easydeformation of workpiece type at the cutting side and around the tip radius. The easily deformed materials can be formed without being torn.By working at low speeds, the considerable improvement in surface roughness by increasing thecutting speed reveals the effect ofcutting speed on the surface roughness clearly. Fig.3.8 to Fig.3.12 depict the change of surface roughness with the change in feed rate under different cutting conditions. In all the figures it is seen that at a specific cutting velocity the increase in feed rate decreases the surface integrity i.e. increases the surface roughness. Although in all the cases, the surface roughness increases with the increase in the feed rate, the amount of increase varied under dry and different MQL conditions. The percentage reduction in surface roughness attained by dry and MQL cooling condition for different cutting velocity and table feed has been extracted from the previous figures and shown in Table 4.1.

It is evident from figuresthat MQL cooling could provide good improvement in surface finish at the beginning of machining with the fresh cutting edges. This has been more or less true for all the experimental combinations undertaken as can be seen in Fig.3.4 to Fig.3.12. This improvement in surface finish by MQL cooling might be due to the thrust force along with the cutting fluid, reduction in break-in wear and also possibly reduction or prevention of built-up edge formation depending upon the work material and cutting condition.

Surface roughness was also measured at different intervals during the measurement of the tool wear. It was found that with the increase of the machining time, surface roughness grew substantially. This can be attributed to the increase in the flank wear with the increase of the machining time. Fig.3.13 also exhibits the same phenomenon but in most of the readings that were taken, the surface roughness in the dry machining was higher compared to that of machining with MQL cooling system. Comparison of the Fig.3.24 with those from Fig.3.13 reveals that the pattern of growth of surface roughness bears close similarity with that of growth of flank wear in particular. This observation strengthens the presence of the correlation between flank wear and surface roughness during dry and MQL cooled machining. Wear at the tool flanks is caused mainly by micro-chipping and abrasion unlike crater wear where adhesive and diffusion wear are predominant particularly in machining steels by uncoated carbides. The minute grooves produced by abrasion and chipping roughen the cutting edge at the tool-tip, which is directly reflected on the finished surface.Thus it is evident from Fig.3.13 that millingAISI4140 hardened steel by carbide milling cutter results increase in surface roughness but at different degrees in dry and MQL cooled machining. However, the degree at which the surface roughness increased is found more in dry machining than that of MQL cooled machining.Thus, it can be concluded that MQL shows substantial improvement in respect of surface finish than dry machining.

Table 4.1 Reduction in surface roughness due to dry and MQL cooling in milling AISI4140 hardened steel

Feed Rate (mm/min)	Cutting Velocity (m/min)	Environment						Percentage Reduction in Surface Roughness				
		Dry	MQL (ml/hr)									
			50	75	100	150	200	50 ml/hr	75 ml/hr	100 ml/hr	150 ml/hr	200 ml/hr
		Surface Roughness (µm)										
22.0	12	1.60	1.38	1.29	1.37	0.86	1.43	13.75	19.25	14.41	46.53	10.37
	16	1.50	1.31	1.22	1.30	0.81	1.36	12.67	18.53	13.65	45.85	9.57
	22	1.45	1.21	1.12	1.19	0.75	1.25	16.55	22.62	17.98	48.26	14.11
	27	1.41	1.18	1.09	1.16	0.73	1.21	16.31	22.55	17.91	48.11	14.03
	32	1.35	1.08	0.99	1.05	0.67	1.10	20.00	26.52	22.11	50.40	18.44
34.0	12	1.75	1.52	1.43	1.52	0.94	1.59	13.14	18.17	13.26	46.15	9.17
	16	1.65	1.40	1.31	1.39	0.87	1.46	15.15	20.48	15.71	47.39	11.74
	22	1.54	1.38	1.29	1.37	0.86	1.43	10.39	16.10	11.07	44.44	6.88
	27	1.51	1.25	1.16	1.23	0.78	1.29	17.22	23.05	18.43	48.68	14.58
	32	1.42	1.18	1.09	1.16	0.73	1.21	16.90	23.10	18.48	48.48	14.64
44.0	12	1.82	1.61	1.52	1.61	1.00	1.69	11.54	16.37	11.36	45.15	7.17
	16	1.75	1.47	1.38	1.46	0.91	1.53	16.00	21.03	16.29	47.92	12.34
	22	1.62	1.41	1.32	1.40	0.87	1.47	12.96	18.40	13.50	46.04	9.42
	27	1.57	1.37	1.28	1.36	0.85	1.42	12.74	18.34	13.44	45.90	9.36
	32	1.48	1.27	1.18	1.25	0.79	1.31	14.19	20.14	15.34	46.80	11.35
68.0	12	2.10	1.71	1.62	1.72	1.06	1.80	18.57	22.76	18.13	49.51	14.27
	16	1.92	1.62	1.53	1.62	1.00	1.70	15.63	20.21	15.42	47.69	11.43
	22	1.84	1.57	1.48	1.57	0.97	1.65	14.67	19.46	14.62	47.10	10.60
	27	1.74	1.42	1.33	1.41	0.88	1.48	18.39	23.45	18.86	49.40	15.03
	32	1.52	1.34	1.25	1.33	0.83	1.39	11.84	17.63	12.69	45.34	8.57

4.2 Cutting Force

Cutting force is one of the key concerns of any machining process. Cutting force, along with other parameters attribute to the product quality, functionality and machining cost. Cutting force increases with the increase of the material strength, shear strength to be specific. Increase in the cutting force during machining is always detrimental as it decreases the tool life and increases the surface roughness. Numerous researches have been carried out to decrease the magnitude of the cutting force during machining.The figures from Fig.3.14 to Fig.3.22demostratethe change of cutting forces with respect to different cutting parameters. In almost all the figures representing cutting force as a function of cutting velocity, it is evident that with the increase in cutting velocity, the required cutting force decrease although the degree of the change differs with different machining conditions. However, it is seen that with the increase in table feed rate the required amount of cutting force increases. This can be attributed to the fact that with the increase of the table feed rate, the amount of energy required to remove the material increases. The percentage reduction in cutting force attained by dry and MQL cooling condition for different cutting velocity and table feed have been extracted from the previous figures and shown in Table 4.2. It is evident from the figures that the cutting force required are comparatively low in MQL cooled milling processes and an MQL condition of 150 ml/hr has provided the best result in terms of improved surface roughness and lesser cutting force as well as 75 ml/hr.Fig.3.23 shows the variation of cutting force with machining time while milling AISI4140 hardened steel by carbide milling cutter under different conditions. The figure depicts that the cutting force increases with the machining time, along with the increase of the flank wear, evident from Fig.3.24. Thus it can be concluded that the increase of the substantial cutting force is mainly due to the increase of the tool wear during the machining process. However, the degree of increase of thecutting force is more in the dry cutting condition than in the MQL condition of 75 ml/hr.

Table 4.2 Reduction in cutting force due to dry and MQL cooling in milling AISI4140 hardened steel

Feed Rate (mm/min)	Cutting Velocity (m/min)	Environment						Percentage Reduction in Cutting Force				
		Dry	MQL (ml/hr)									
			50	75	100	150	200	50 ml/hr	75 ml/hr	100 ml/hr	150 ml/hr	200 ml/hr
		Cutting Force (N)										
22.0	12	15.0	12.0	10.4	11.6	10.4	11.8	20.00	30.67	22.35	30.40	21.65
	16	14.0	10.8	9.8	11.0	9.4	11.1	22.86	30.00	21.60	32.89	20.90
	22	12.0	9.2	8.2	9.2	8.0	9.3	23.33	31.67	23.47	33.30	22.78
	27	11.5	8.7	7.5	8.4	7.6	8.5	24.35	34.78	26.96	34.18	26.30
	32	10.0	7.5	7.2	8.1	6.5	8.1	25.00	28.00	19.36	34.75	18.64
34.0	12	18.5	15.8	12.5	14.0	13.7	14.1	14.59	32.43	24.32	25.70	23.65
	16	17.0	13.8	11.8	13.2	12.0	13.3	18.82	30.59	22.26	29.38	21.56
	22	15.4	12.2	10.5	11.8	10.6	11.9	20.78	31.82	23.64	31.08	22.95
	27	14.2	11.8	9.8	11.0	10.3	11.1	16.90	30.99	22.70	27.70	22.01
	32	12.5	10.2	8.7	9.7	8.9	9.8	18.40	30.40	22.05	29.01	21.35
44.0	12	21.2	19.0	15.0	16.8	16.5	17.0	10.38	29.25	20.75	22.03	20.05
	16	19.3	17.0	13.8	15.5	14.8	15.6	11.92	28.50	19.92	23.37	19.20
	22	16.8	15.0	12.1	13.6	13.1	13.7	10.71	27.98	19.33	22.32	18.61
	27	15.3	13.1	11.8	13.2	11.4	13.3	14.38	22.88	13.62	25.51	12.85
	32	13.4	11.5	10.3	11.5	10.0	11.6	14.18	23.13	13.91	25.34	13.14
68.0	12	23.8	21.5	16.4	18.4	18.7	18.5	9.66	31.09	22.82	21.41	22.13
	16	21.0	19.0	14.3	16.0	16.5	16.2	9.52	31.90	23.73	21.29	23.05
	22	19.0	16.8	13.5	15.1	14.6	15.3	11.58	28.95	20.42	23.07	19.71
	27	17.2	14.8	12.1	13.6	12.9	13.7	13.95	29.65	21.21	25.14	20.51
	32	15.3	12.8	11.8	13.2	11.1	13.3	16.34	22.88	13.62	27.22	12.85

4.3 Flank Wear

Flank wear is another critical part of any machining process. Flank wear attributes to the increase of the surface roughness as well as the increase of the cutting force, requiring substantial amount of energy for machining. The four flute end mill cutter used in the surface milling exhibited different types of flank wears under different conditions. Although both dry and MQL condition cutting was performed using the four flute end mill cutter, no sudden failure of the tool or catastrophic failure was found. The premature failures mainly happen because of the plastic deformation or macro fractures in the tool that propagates during machining process.It is also evident from Fig.3.24 that dry millinghas a higher tool wear rate than that of MQL cutting condition. This can be attributed to the retention of hardness and sharpness of the cutting edge of the four flute end mill cutter because of the precise cooling at the chip tool interface, protecting the newly formed fresh material surface from oxidation and corrosion. MQL also helped in preventing the BUE and increasing the rate of chip removal during the machining process. During the dry machining process the rate of flank wear propagation was higher than that of the MQL condition which indicates that the tool life increases with the MQL applicator.

Fig.3.26 to Fig.3.31 depicts the variation of surface roughness with cutting velocity and feed rate and from the comparison it is evident that with the decrease of the cutting velocity surface roughness increases and also with the increase of the feed rate surface roughness decreases. Fig 3.32 depicts comparison between different machining conditions and reveals that during dry machining, surface roughness is found to be highest and an MQL flow rate of 150 ml/hr shows the least amount of surface roughness.

Chapter-5

Conclusions and Recommendation

5.1 Conclusions

i. In depth investigation of the effect of Pulsed Jet MQL Applicator in surface milling of AISI4140 hardened steel is performed on the basis of surface roughness, cutting force and tool wear.

ii. Surface roughness is found to improve at a substantial rate at different MQL rates compared to that of dry machining.

iii. Different MQL rates showed different degrees of improvement, the figures have shown that an MQL rate of 150 ml/hr has the maximum reduction of surface roughness, around 45%.

iv. Pulsed Jet MQL Applicator reduced the cutting force when compared to dry cutting by substantial amount.

v. Different MQL rates have shown different degrees of reduction of cutting force. It is evident from the figure that an MQL rate of 150 ml/hr has the maximum reduction of cutting force, around 30%.

vi. Improvement of surface roughness and decrease in the amount of cutting force can be attributed to the lower cutting temperature, favorable chip-tool interaction, retention of the cutting edge sharpness, prevention of Built Up Edge during the machining process.

vii. Substantial reduction in the flank wear eventually increases the tool life, enabling a longer machining time with the same tool with the use of Pulsed Jet MQL Applicator. The reduction of tool wear might also be attributed to retardation of abrasion and notching, decrease or prevention of adhesion decreasing the growth of flank wear.

5.2 Recommendations

i. Pulsed Jet MQL Applicator may be further studied to analyze its impacts on different hardened work materials.

ii. Use of different cutting oils as an alternative to 68 grade cutting oil might be introduced to see its impact on the work material.

iii. The frequency of the pulsing system should be synchronized with the speed of the milling cutter to attain the best possible result in terms of machining and surface integrity.

iv. Use of multiple nozzle injector can be introduced to maximize the effect of MQL application during the machining process.

v. A facility to remove the oil mist created during the MQL application should be introduced to reduce health hazard during the machining process.

vi. Nozzle injectors with narrower spray cone should be introduced to deliver the cutting fluid pinpointing the tool work interaction point.

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