EFFECT OF AIR AND CHILLED EMULSION MINIMUM QUANTITY LUBRICATION (ACEMQL) IN MACHINING HARD TO CUT METALS

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DECLARATION OF THE CANDIDATE AND SUPERVISOR

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Dr AKG Punchihewa

ABSTRACT

Effect of Air and Chilled Emulsion Minimum Quantity Lubrication in Machining Hard to Cut Metals

A novel approach of cutting fluid application was developed and its performance in machining hard to cut metalswas investigated. The study focused on turning AISI P20 and D2 tool steels using coated carbide cutting tools. For this study, an improved minimum quantity lubrication (MQL) method named, air and chilled emulsion minimum quantity lubrication (ACEMQL) method was developed to evaluate its effect on tool life and surface finish of material being machined. Trials were carried outfor ACEMQL with cutting fluid temperatures from 5°C to 20 °C in steps of 5 °C.In order to obtain a benchmark for comparison of results, set of trials were carried out for dry cutting and flood cooling at 25 °C while all other parameters kept same as in ACEMQL method. Trials for ACEMQL method resulted in better tool life and surface finish for both AISI P20 and AISI D2 tool steels when compared with dry cutting and regular flood cooling methods. Minimum tool wear in machining AISI P20, was observed at 15 °C with ACEMQL, and it has shown a trend of increasing tool wear when temperature was lowered to 10 °C and 5 °C. A tool wear reduction of 97% from dry cutting, and 93% of flood cooling, is observed with ACEMQL at 15 °C. At 10 °C also ACEMQL has shown a reduction in tool wear by 94% compared with dry cutting and 86% compared with flood cooling. However, at 20 °C, it is observed that there is an increase in tool wear compared to flood cooling by 29%. Similarly, in machining AISI D2, minimum tool wear was observed at 15 °C with ACEMQL, and it has shown a trend of increasing tool wear when temperature was further lowered to 10 °C and 5 °C. A tool wear reduction of 96% from dry cutting, and 93% of flood cooling, is observed with ACEMQL at 15 °C. At 10 °C also ACEMQL has shown a reduction in tool wear by 71% compared with dry cutting and 57% compared with flood cooling. Although use of ACEMQL shows an improvement in surface finish in machining both AISI P20 and D2, it has not shown significant difference with reduction of temperature in the investigated steps of temperatures. For AISI P20, the least surface roughness obtained is 0.97 µm Ra and it is at 5 °C. It is a 35% reduction with respect to dry cutting condition and 31% reduction in comparison with flood cooling condition. For AISI D2, the minimum surface roughness obtained is 0.82 µm Ra and it is at 5 °C. It is a 49% reduction with respect to dry cutting condition and 40% reduction in comparison with flood cooling condition.Research on the effect of cutting velocity, feed rate and depth of cut, on tool life and surface finish with ACEMQL is suggested as future work. Further, economic feasibility analysis is suggested to find out the suitability of ACEMQL in local die and mould manufacturing industry, and also research on relationship between chip colour and cutting condition, and reasons for the colourisation is suggested as future work.

ACEMQL, MQL, Surface roughness, P20, D2, Tool life, Coated carbide tools

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LIST OF ABBREVIATIONS

Abbreviation	Description
ACEMQL	Air and Chilled Emulsion Minimum Quantity Lubrication
AISI	American Iron and Steel Institute
BUE	Built Up Edge
CAMQL	Chilled Air with Minimum Quantity Lubrication
CBN	Cubic Boron Nitride
CF	Cutting Fluid
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CVD	Chemical Vapour Deposition
HRA	Rockwell Hardness Grade A
HRC	Rockwell Hardness Grade C
MWF	Metal Working Fluid
MQL	Minimum Quantity Lubrication
MQL_EP	MQL in Extreme Pressure
NDM	Near Dry Machining
SFPM	Surface Feet per Minute
SME	Small and Medium scale Entrepreneurs
WP	Work-piece

LIST OF APPENDICES

1. INTRODUCTION

1.1. Background

Heat generation in metal cutting processes is a critical problem in machining operations, and itis caused due to three major reasons [1], namely, primary deformation and shearing of work-piece, friction, and secondary deformation in chip. Reduced tool life due to reduction of tool hardness in elevated temperatures, thermal damages to the work-pieces, and loss of energy are some of the major problems caused by the generated heat. Although the heat generation cannot be completely eliminated, by careful selection of machining parameters, it can be reduced. This reduction of heat generation is not effective in machining of some material. Especially, machining of hard metals would generate more heat and it needs a heat removal method to prevent undesirable damages to the cutting tool and work-piece. Typically a fluid is used to transfer the heat generated, out of the cutting area. This is known as Cutting Fluid (CF) or Metal Working Fluid (MWF). Most common type of fluid used in metal cutting is emulsion cutting fluid. According to a survey by Brockhoff and Walter [2] the cutting fluid expense in European automotive industry is to be nearly 20% of the total manufacturing cost. The cost of tools was only 7.5% of the total manufacturing cost, making the cutting fluid cost to be comparatively high. As metal cutting operations generate a large amount of heat during operations, it is evident that most of the energy consumed by the process is converted into heat[1].

1.2. Motivation

The Sri Lankan die and mould making industry uses many metal cutting operations for hard metals such as tool steel, which requires expensive tooling. However, over the last few decades, there had been a gradual decline of this industry[3]. One of the reasons is the high production cost of the industry. Tooling cost is a major factor in deciding the production cost. Therefore a reduction in tool cost is vital in reducing the production cost. It has been proven that high cutting temperature reduces tool life and flood cooling method, which is widely used to reduce the cutting temperature is less effective in machining of hard to cut metals. Although tool material and machine tools are developed to have longer tool life, and better surface finish, these solutions are infeasible for this particular industry. Those new types of tools are found too expensive for this industry, and acquiring of new and improved machine tools are also found to be infeasible. Therefore, a simple and inexpensive cooling solution is essential for this industry.

1.3. Aim and Objectives

1.3.1. Aim

To develop an effective cooling method for metal cutting operations using Minimum Quantity Lubrication (MQL) principle, so that the tool life can be increased.

1.3.2. Objectives

- To identify the parameters that govern cooling of work pieces and tools in machining operations.
- To develop a simple and inexpensive CF cooling system, which can be used with existing machine tools as an attachment to the machine.
- To examine the effect of the developed MQL based CF application method on hard-to-cut metals used in Sri Lankan metal machining sector with typically used tools for those metals.

1.4. Methodology

A comprehensive study of mechanics in metal cutting, heat generation in metal cutting, cooling methods in metal cutting, tribology of CF, and related areas were done. Literature on previous research on the said areas were searched and reviewed. A hypothesis was developed based on this study, "Cooling the cutting fluid with ACEMQL method will increase the tool life and provide better surface finish in the work-piece". Following the background study, a survey on tool material, work material and cutting fluids in the industry was carried out. A sample of 11 individual participants was selected from die and mould manufacturers in Sri Lanka.

A newly developed concept called Air and Chilled Emulsion Minimum Quantity Lubrication (ACEMQL) was used for the experiment apparatus. The apparatus was designed to produce chilled emulsion CF in predetermined steps of temperatures and spray chilled fluid on to a work-piece using pneumatic. This apparatus consists of a

CF reservoir, coolant pump system, a spray paint gun, and CF cooling system. Design concept of the system is further discussed in 4.1in page 45. A manual horizontal lathe machine is used for the turning operation done in the trials. Mitsubishi Chemical Vapour Deposition (CVD) coated carbide turning tool was used to machine both AISI P20 and AISI D2 work-piece material. Each trial was repeated for 3 times, each with a new tool tip, while keeping all machining parameters constant. These values for machining parameters were selected based on the manufacturers' recommendations, by reviewing past literature. Based on the survey results, Caltex AquaTex 3180 CF was used and it was mixed with water with a ratio of 1:9, oil to water. A circular solid rod of 45 mm diameter and 100 mm length was used as the work-piece. A total of 54 work-pieces with 27 pieces from each material were used. A total of 500 mm cutting length was used. After fabrication, the experimental setup was calibrated. The nozzle was calibrated spray 160 ml of chilled CF per hour with 7 bar air pressure. The lathe machine was set to cut a length of 10 mm in each pass. After calibration, a pilot run was carried out with room temperature to measure and calculate the rate of nose wear in the tool. Based on this further refining of the machining parameters were done. Empirical method to manually regulate CF temperature in the reservoir was formulated. Based on the literature review, industrial survey, and the tool manufacturers' recommendations, an initial set of parameters were selected and based on the outcome of the pilot run final settings were decided. A factorial experiment of three levels was designed. Work material, cooling method, and ACEMQL CFtemperature were varied in the experiments. Throughout the experiment, some of the machining and CF system parameters were kept controlled. All the trials were carried out in a random order to avoid experimental biasness and each of the trial was repeated for three times with same conditions. A break was given between trials to avoid any experimental error due to effects from previous trial. Trials were done in controlled ambience. The total amount of CF required for all the trials was prepared as a single batch. Tools were stored in numbered compartments in a container and the end of each trial, the used tip of the tool insert was marked to prevent reusing it.Using a Computer Numerical Control (CNC) Coordinate Measuring Machine (CMM), tool wear is measured. The CMM has a resolution of 0.0001 mm. At first it was intended to take tool nose radius as the indicative measurement for tool wear, but curve approximation done for the tool tip in the CMM lead to errors, as picking points on the worn edge with the CMM was vague. Direct nose wear was used as the indicative measure for tool wear. A measuring jig was used to measure tool nose wear. A digital surface roughness tester was used to take the average surface roughness of the work-pieces. Each work-piece was labelled with the experiment number, and measurements were taken of work-pieces in random number. Average roughness Ra was measured by a reader who is unknown of the machining conditions. In each work-piece surface roughness was measured in three locations on its periphery, and were taken parallel to the principal axis, across the lay.

The second chapter contains the literature review done in the fields of metal machining, metal cutting mechanics, CFs and application methods, and other related. Reviews on gathered literature on past research on these areas are also presented here. The third chapter describes the methodology used in research in detail. A stage-wise detailed discussion of the methodology is included. Information on experimental plan, apparatus, set up, selection of parameters, conducting of experiments, measuring methods, and analysis methods, are elaborated in this chapter. The fourth chapter presents the results obtained in the research. Results of the industrial survey, tool wear measurements, and surface roughness measurements are presented here. Further, the observations regarding the colour variations in the chip also presented. In chapter five, the conclusions made by the research is discussed and future work is suggested. Next chapter presents all the references used in this research.

2. LITERATURE REVIEW

2.1. Heat generation in machining

Heat generation in material removal processes is caused by three major reasons and this generated heat produces many adverse effects in machining[1]. Although these cannot be completely eliminated, by careful selection of machining parameters, it can be reduced. However, this reduction of heat generation is not sufficient to prevent adverse effects in machining of some material. Especially, machining of hard metals would generate more heat and it needs assistance from some type of heat removal method. The three major reasons for heat generation is as follows. First is the Primary Deformation which is the heat generation due to shearing of material and deformation of material before shearing [4]. The second reason is the Friction that occurs between the tool, the work-piece, and the chip that is removed from the work-piece. Since the chip removed from the work-piece rubs the rake face of the tool, there is friction between the chip and the tool. This generates heat during the process. In addition to this, the flank of the tool also rubs the work-piece which cause additional friction and hence more heat generation. The third reason for heat generation is called Secondary Deformation. That accounts the heat generated due to deformation of the chip after being removed from the work-piece.

The main heat generating regions on the work piece and tool is given inFigure 2.1. By a research carried out by Abukhshim et al. [5]have developed a finite element based computer model to simulate the thermal distribution in work-piece and tool during the cutting process. The same thermal distribution was obtained by Majumdar et al. [6] using infrared pyrometers, and finite element method. Both models have shown that the maximum temperature occurs at the tool-chip interface.

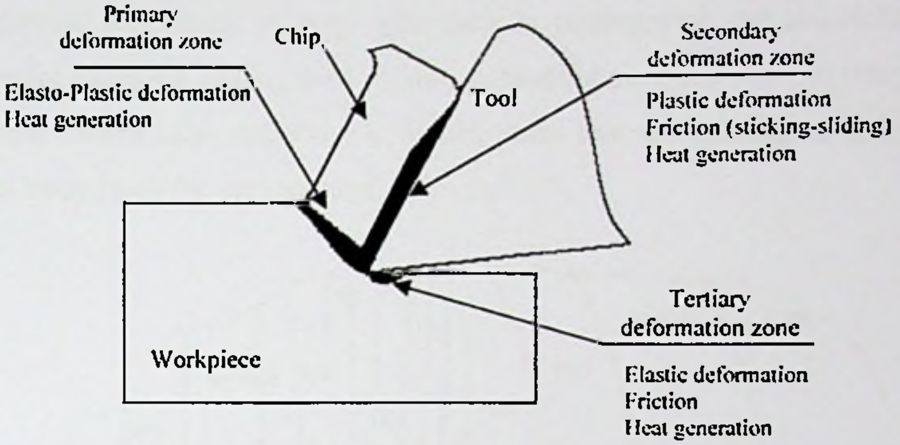


Figure 2.1:Heat generation zones in orthogonal cutting (Source:[5])

Ng et al. [7] have obtained a good correlation between above two techniques to determine thermal distribution in metal cutting, and they also have proven that the maximum temperature is at the tool-chip interface. Hong and Ding [8] have pointed that intense temperature change in confined to a very small area on the tool and hence it is possible to minimize coolant requirement by cooling only selective area.

It has shown by Ng et al. [7], and by Khan et al. [9] that the heat generation and maximum temperature in primary and secondary temperature zones depends on,

i. Combination of physical and chemical properties of work-piece and cutting tool materials.
ii. Cutting parameters to a greater extent, and
iii. Cutting tool geometry and CF to less extent.

Another research has shown that machining of low alloy steel with cemented carbide tool, the cutting temperature increased with the cutting speed and the feed rate. Moreover the cooling effect of air and water has shown to be decreased when cutting speed is increased. De Silva et al. [10] have explained that cutting temperature depends on the contact length between tool and chip. They have concluded that the cutting temperature increases with increase of contact length in machining of aluminium in orthogonal cutting.

Komanduri and Hou[11] have investigated the combined effect of primary heat source, i.e. heat generated at the shear plane and the secondary heat source i.e. frictional heat dissipation at the tool and the chip interface, on the temperature distribution on work-piece and tool. They have deployed a model developed by them in conventional machining of steel with carbide cutting tool and aluminium with single crystal diamond cutting tool. Figure 2.2andFigure 2.3shows the temperature distributions ineach case respectively. It illustrates that the maximum temperature occurs far away from the cutting edge.

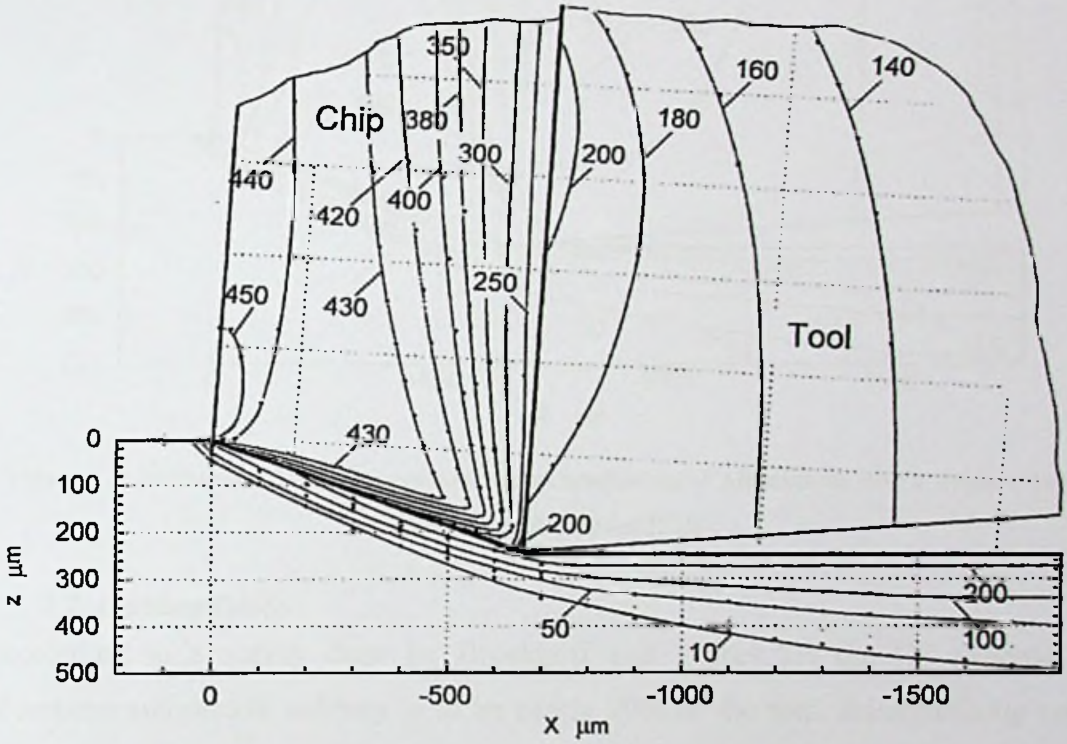


Figure 2.2:Isotherms of the temperature rise in machining of steel with carbide tool (Source:[11])

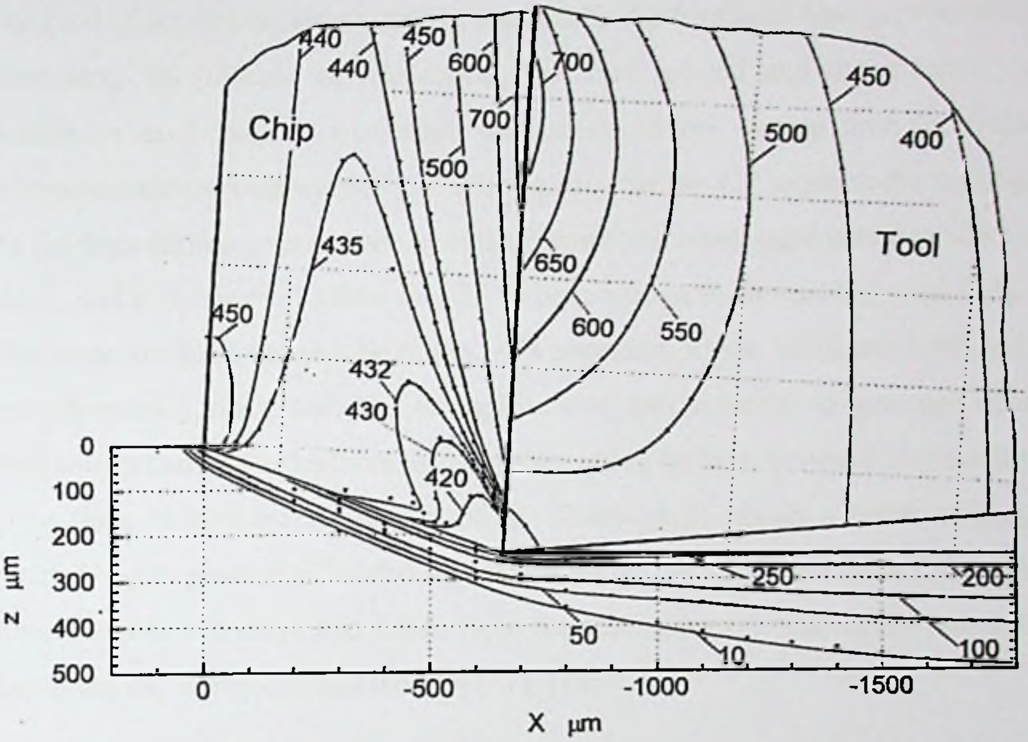


Figure 2.3: Isotherms of the temperature rise in machining of Aluminium with a single-crystal diamond tool (Source:[11])

2.2. Cutting fluids

According to a survey done by Brockhoff and Walter [2] the CF expense in European automotive industry is to be nearly 20% of the total manufacturing cost. The cost of tools were only 7.5% of the total manufacturing cost, making the CF cost to be comparatively high. Metal cutting operations generate a large amount of heat during operations. It has been shown that most of the energy consumed by the process is converted in to heat. This heat will adversely affect the work-piece and the cutting tools. Many problems occurred in machining are due to the generated heat and the high temperature caused by it[1].

Since heat generation is inevitable in machining, there has to be measures to reduce heat generation and removal of generated heat. CFs can be solutions in both reduction in heat generation as well as heat removal. Basically there are three main functions are expected from the CFs used in machining operations [1], [12]. Mostly the CF is expected to remove the heat generated during the cutting process and there by prevent the work-piece or the tool reaching in to critical temperatures. The main property that affects this functionality of a CF is its heat capacity. Secondly, it is expected to act as a lubricant, and hence reduce the frictional heat generation during machining. In the case of lubrication, the load applied and the material cutting conditions used, makes continuous lubrication of the cutting area by fluid film lubrication almost impossible [13].It is not easy for the CF to reach the cutting area. As the high cutting pressure in the cutting point and small gaps between chip, work-piece, and tool does not allow the CF to penetrate in to the cutting zone [14], [15]. Therefore to obtain better lubrication, it is necessary to use lubricants with additives that chemically react with the workpiece and tool material to generate chemical compounds that allow the lubrication of the cutting surface. However, lubrication has to be done in conjunction with cooling. Therefore to obtain a better cooling, the cutting area is generally flooded by lubricant [16]. In addition to that CFs assists to expel the removed chips and debris from the cutting area, to reduce the possibility of damaging the workpiece and the tool [17], [18].

2.3. Types of cutting fluids

In many literature it is suggested that CFs also known as metal working fluids can be categorised in to three or four categories [4], [17], [19]. Some of these categorisations have omitted gaseous CFs or has considered semi-synthetic and synthetic CFs in the same category. However, by considering various factors, CFs in conventional machining are categorized in to five basic categories,

1. Neat cutting oils
2. Water-soluble oils
3. Semi-synthetic oils
4. Synthetic oils
5. Gases

Neat oils which is also called as Straight oils, are used without dilution with any other fluids. These provides an excellent lubricity, with long service life and are easy to manage. However, these oils causes excessive heat generation, and are a fire hazard. It is also very slippery, which makes it dangerous when handling metals, and also produces high mist of oil [20]. Water-soluble oils contains a high amount of mineral oil but those are designed to be diluted in water to form a milky solution. These will give good lubricity and it is also easy to manage [21]. However, causes a large amount of oily residues, and produces mist or smoke. Semi-synthetics oils consists of a low to moderate oil amount, with water and some other performance additives. These are casing better heat removal, cleaner in operation, and better lubricity, but at the same time it is possible to create foam. Synthetics oils does not contain any mineral oil. These contains only water and water-soluble additives. These are very good in heat removal, very clean, low foam formation, and the mixture is transparent which enables better observation of the cutting operation. However, these produces less lubricity and lacks of protective oil layer formation in work-pieces. The first four types are liquids and used in different cutting operations while the last category is gaseous. Conventional CFs cannot penetrate in to the tool-chip interface at higher speeds. On contrary, gaseous CFs can penetrate better than liquids [8]. In general, reduction in cutting temperature will reduce the wear rate and increase tool life. However, the temperature reduction can increase the shear stress on the work-piece and hence can increase the required cutting force. Conventional CFs cause lot of health and environmental problems. Chemical dissociation, breakdown due to increased temperature, water pollution, soil contamination on final disposal, operators health and safety because of coming fumes, smoke, dermatological problems due to physical contact, bacteria, odour, and many more[22].A previous study has shown that each machine tool requires volume around 100 l of fluids [23]. Use and disposal of this quantity of CFs cause a big environmental effect.

2.4. Coolant application methods

The most basic CF application method is applying by hand. In this method the CF is applied manually by hand intermittently [14]. The machine operators decide when to apply the CF by visual inspection. Therefore, it cannot be guaranteed for sufficient amount of CF is applied to remove the heat from the cutting area. Since there is no continuous application of CF, the lubrication is also poor in this method, and the chip removal is also poor. This method is basically limited for small scale machining operations with low machining conditions.The most widely used cooling technique in metal cutting is flood cooling technique[1]. Pressurised CF is flooded over the cutting area. The fluid flow is directed to the required area through a nozzle. These nozzles can be directed to tool rake face, clearance face, or any area that is been concerned. The CF flow rate is typically around 10 l/min. Once the fluid is used it is filtered and recirculated again over the cutting area. A medium scale machine tool would generally requires around 100 l of CF to fill the reservoir [23]. As the CF is flown to the cutting area, it produces better lubrication, as it can penetrate into narrower gaps in the cutting area. However, when machining less machinable material, this method has shown poor performance. One of the main concern is that effectiveness of heat removal is low at those conditions [1], [14]. Since the fluid is flowing at a high rate, the contact time between the fluid and the cutting area is said be too low for effective heat transfer from cutting area to the fluid.

In order to overcome some of the drawbacks of flood cooling, high pressure cooling is used. In this method the conventional emulsion coolants are used with high pressure around 100 bar [15]. Jets of emulsion CF are directed to tool-chip interface, or tool flank area. Cooling of the fluid is not done in this method. Even though the penetration by the fluid to the cutting area is better, heat removal is limited as the contact time between the fluid and the heat sources are further reduced as the velocity of fluid flow is increased [24], [25]. Cryogens such as liquid nitrogen are used as the CF,to further improve the heat removal capacity of the CF. CF can absorb very large amount of heat because of the very low temperatures in it. There are two basic approaches in cooling with cryogens. One is, flowing the cryogen directly over the working area, and the other is heat transfer without direct contact of cryogens with the working area. Cryogenic jet cooling follows the first method.In this approach, it is concerned on removing heat from the cutting point. Especially it is focused on cooling the tool-chip interface with cryogens. Liquid nitrogen is injected in a form of a jet over the cutting area or sprayed in to the cutting area using nozzles, and hence the consumption of liquid nitrogen is high in this method [4], [26].Cryogenic indirect cooling, which is also known as cryogenic tool back cooling or conductive remote cooling, the cooling takes place without any contact of cryogenic with the work-piece or the tool [8]. Cooling is done by heat conduction from the work-piece and the tool to the cryogenic chamber placed at the tool face or the tool holder. There are three main types of nozzle arrangements [25]. Jet directed to the tool-chip interface with an external nozzle, jet directed to the clearance between tool flank and the machined surface, and jet directed to tool-chip interface through the tool rake face, are the different types used [18]. However, cryogenic cooling methods are expensive as well as provides a hazardous environment. Therefore this method is currently limited to extreme machining conditions.

Minimum Quantity Lubrication (MQL) is a more recent advancement in cooling methods.In this method, a very small amount of CF is mixed with high-pressure air and the resulting aerosol is directed to the cutting area. This aerosol invade the cutting area at high speed through a nozzle. Air in the spray provides the cooling function and chip removal, while theCF provides lubrication and by droplet evaporation it provides cooling also [27]. TheCF will get evaporated when the heat is absorbed, and to a lesser extent vaporisation of the CF also happens. It guarantees a good level of lubrication, but the cooling action is relatively small and the chip removal mechanism is obtained by the air flow used to spread the lubricant. The flow rate of CF is typically 50 – 400 ml/hour [2]–[4], . MQL is also known as "Near dry lubrication" (NDM) [28]. There are two different mixing methods used in MQL [30]. First method is mixing air and CF inside a nozzle and the second method is mixing them outside the nozzle. In many instances, it has been shown that the cooling capacity of MQL is low. With MQL chip, work-piece, and tool holder will have a low amount of CF residue, making the cleaning after machining is easier and cheaper. Since the working area is not flooded during machining, if necessary, the cutting operation can be observed. However, as MQL lack in cooling capacity, it is not able to provide better results, if it is used in a cutting operation where cooling action is strongly required, such as in grinding [29].

2.5. MQL based past research

Ay and Younghave concluded from their experimental investigation on temperature distribution of the work-piece and tool in orthogonal cutting[31]. They had used thermocouples and infrared thermovion for temperature measuring. The work-piece materials used are cast iron, AISI 1045 steel, copper, and 6061 aluminium, along with a uncoated carbide inserts as the cutting tool.Figure 2.4 shows the obtained temperature distribution in cutting AISI 1045 steel. This study also has verified that the maximum tempareture occurs at the rake face of the toolas of shown by [32].

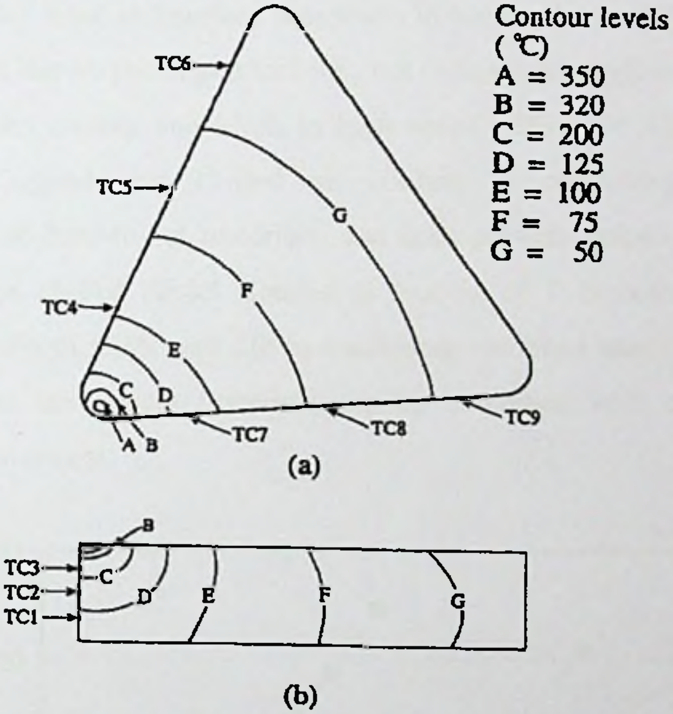


Figure 2.4: Temperature distribution- (a) Rake face, -(b) Flank face (Source:[31])

In their method, refrigerated compressed air has been used to remove heat from the cutting zone. Very small amount of cutting oil may be added to the air flow to compensate for the poor lubrication property of air. Instead of lowering the temperature to cryogenic, chilled air cooling lowers the temperature of the fluid only to around 0 to -20°C. Alternative processes with the same concept uses, gases such as nitrogen, and carbon dioxide. Refrigeration of the coolant fluid can be done with various refrigeration methods, such as liquid-nitrogen refrigeration, vapour-compression refrigeration, adiabatic expansion refrigeration, and vortex tube refrigeration. There have been attempts of removing heat generated from cutting operations with other means such as with refrigerated air.

Su et al. [33] have studied the effect of cooling air cutting on tool wear, surface finish and chip shape in finish turning of Inconel 718 and AISI D2 steel. Their experiments were done in dry cutting, MQL, chilled air, and combined Chilled Air and Minimum Quantity Lubrication (CAMQL), cooling and lubrication approaches in machining. They have obtained results presented inFigure 2.5 and Figure 2.6. They found that application of chilled air cooling and CAMQL have resulted drastic reduction in tool wear and surface roughness in turning Inconel 718. Further chilled air cooling has shown prolonged tool life, but with slightly higher surface roughness than that for dry cutting and MQL in high speed milling of AISI D2. With these results they argued that chilled air cooling in machining would improve machinability of hard-to-cut materials, and does provide safe-to-use coolant. They have stated that chilled air jet directed to tool tip of Ti-N coated tool has shown increased to 30% of CBN tool life in machining hardened steel. This directs to the conclusion that hard-to-cut materials can be machined with chilled air cooling method at a lower cost.

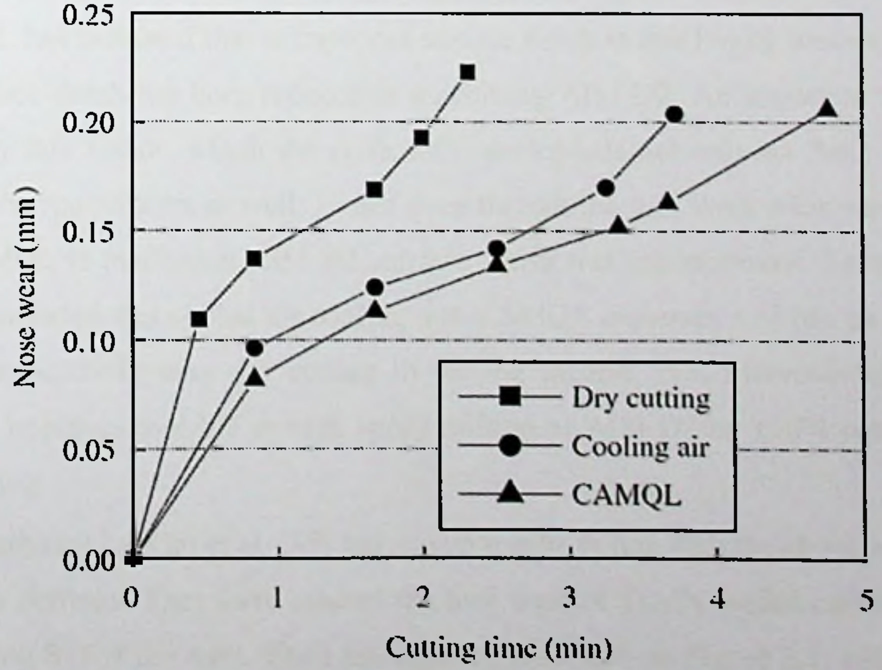


Figure 2.5: Nose wear curves in machining Inconel 718 (Source:[33])

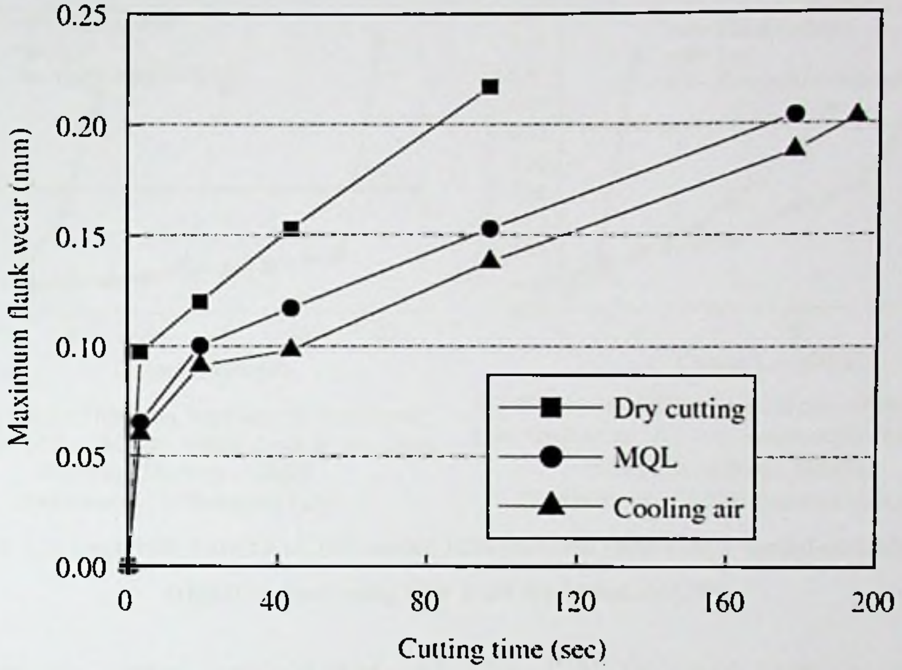
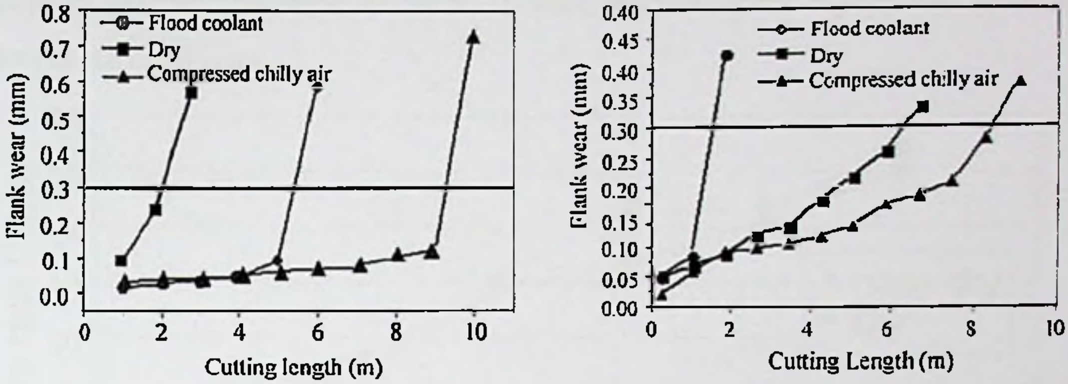


Figure 2.6: Maximum tool flank wear curves in milling AISI D2 (Source:[33])

Rahman et al. [34] have pointed out that chilled air cooling in milling ASSAB 718HH steel has reduced tool wear in low cutting speeds and low feed rates. That indicates chilled air combined with MQL has given better tool life than chilled air and dry cutting. However their study on surface finish obtained with machining with CAMQL has indicated that it improves surface finish in machining Inconel 718, but the surface finish has been reduced in machining AISI D2. An important remark is made by this author, which the surface finish depends not only on flank wear but some other parameters as well. Hence even though the tool flank wear was reduced by CAMQL in machining AISI D2, surface finish was not improved. These authors have concluded that chilled air cooling and CAMQL improves tool life by 78% and 124% respectively over dry cutting in turning Inconel 718. Moreover chilled air cooling improves tool life in high speed milling of AISI D2 by 130% compared to dry cutting.

An experiment by Kim et al. [35] has shown results in line with the above mentioned research findings. They have studied the tool wear of TiAlN coated carbide tool in machining STF 4 die steel. Their findings are presented on Figure 2.7, explains that the tool wear is reduced.



(Cutting speed : 210m/min, Feed rate : 0.1mm/tooth,
Axial depth of cut : 0.5 mm, Radial depth of cut : 2mm,
Workpiece hardness : HRc28
Tool material : HSS (coated TiN))

(Cutting speed : 210m/min, Feed rate : 0.1mm/tooth,
Axial depth of cut : 0.5 mm, Radial depth of cut:2mm,
Workpiece hardness : HRc50,
Tool material : Carbide (coated TiAlN))

Figure 2.7: Tool wear pattern of TiN coated HSS tool (left) and TiAlN coated carbide tool (right) in machining STF 4 die steel (Source:[35])

In a research carried out byAutret and Liang,[12] has used MQL cooling for machining high carbon steel with CBN tool. Their results have shown increase of cutting forces with respect to feed. However, in their study, the use of MQLhas not affect the force level in a noticeable manner. According to them, the thermal softening of material does not seem to occur with such a small amount of fluid. In Figure 2.8, they have shown the rise of temperature at tool shim corresponding to various feed rates. They have defined the temperature rise as the change of temperature during the first second of machining. It is seen that the temperature drops on the order of 5 to 10% with the use of MQL. The application of MQL is observed to improve the high temperature on chip which is better as it has absorbed more energy which could have been absorbed by the much important tool or the work-piece.

Under the used depth of cut of 0.012 inch, surface cutting speed of 450 sfpm and feed of 0.006 in/rev, the chip formation has seen smooth with no side flow present, making the feed marks clearly distinguishable. They have concluded that the effect of MQL is to lower the surface finish by about 50% with all fresh tools and under the given set of cutting conditions. However, the same amount of finish improvement was not consistently observed when other feed conditions were tested. According to them in general, the effect of MQL is more evident under higher feed rates and deeper cut conditions.

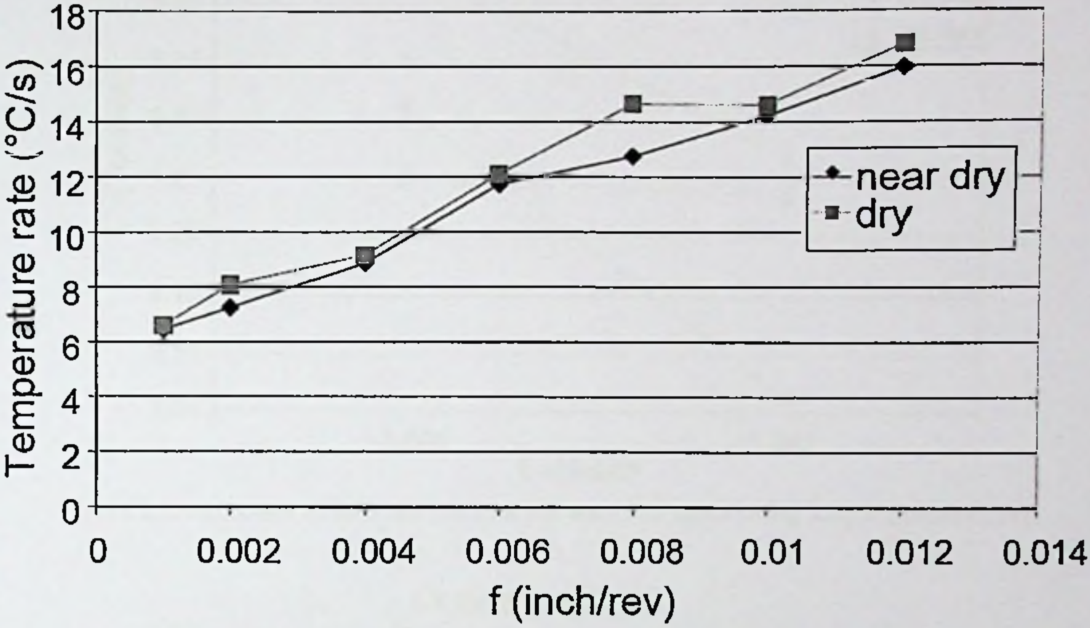


Figure 2.8: Temperature rate under various feed (Source:[12])

Attanasio et al. [14] have studied the effect of feed rate on tool life with MQL machining, with 100Cr6 steel using CNMG tool. They have studied the effect of MQL with the nozzle focused to the rake face and flank face, for two cutting lengths. Figure 2.9 shows the results from them, with feed rate varied for dry, MQL on rake face, and MQL on flank face conditions, with 200 mm cutting length. It has shown that the cooling in flank face has given better tool life than cooling on rake face. Figure 2.10 shows the result for 50 mm cutting length, and similarly it has also shown better tool life with cooling on flank face.

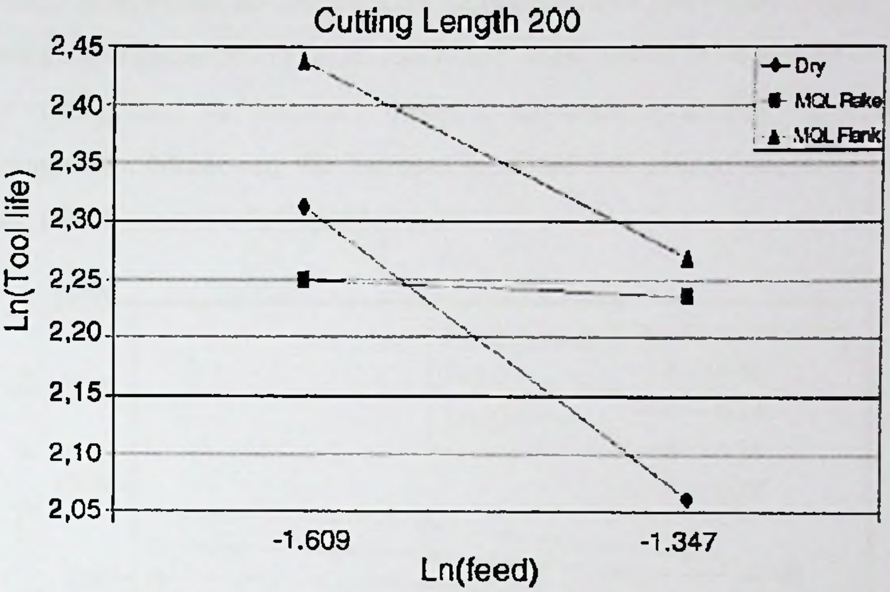


Figure 2.9: Influence of feed rate on tool life with 200 mm cutting length (Source:[14])

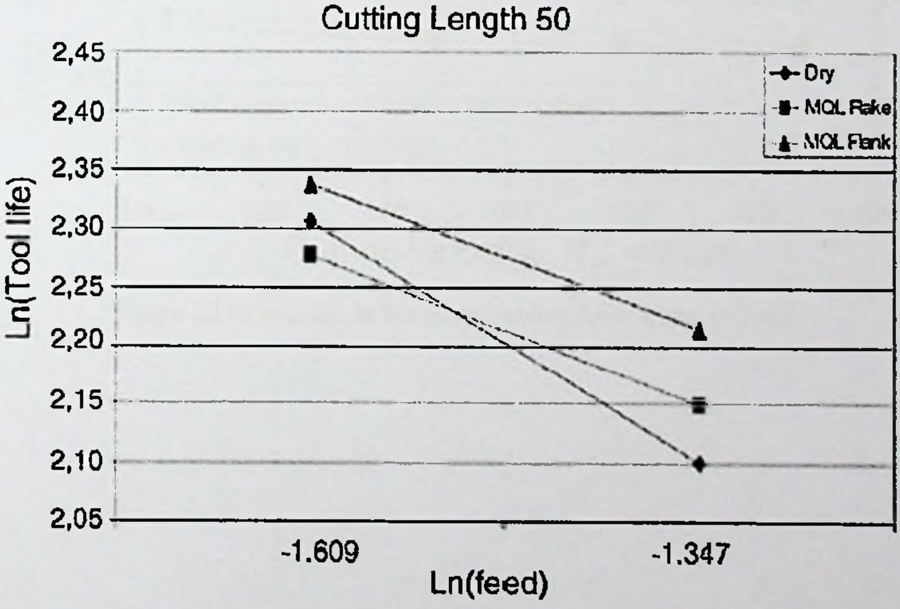


Figure 2.10: Influence of feed rate on tool life with 50 mm cutting length (Source:[14])

Choudhury et al. [36] have studied the effect of MQL in cutting medium carbon steel with P30 steel tool. They have varied the feed rate and has studied the effect on main cutting force on the tool and surface roughness obtained in the work-piece. Their study shows that at any feed rate, MQL has shown low cutting force than dry cutting, increase of feed rate has cause an increase in the cutting force too. However, it has shown that the effect of cutting velocity on the cutting force when other parameters are constant, is a trivial as Figure 2.11 explained. As shown in Figure 2.12 the surface roughness measured in MQL machined work-pieces to be low in comparison with dry cutting, and has shown noticeable influence of cutting velocity on the surface roughness. Moreover, the increase feed rate has caused decrease in surface roughness, which creates a favourable result.

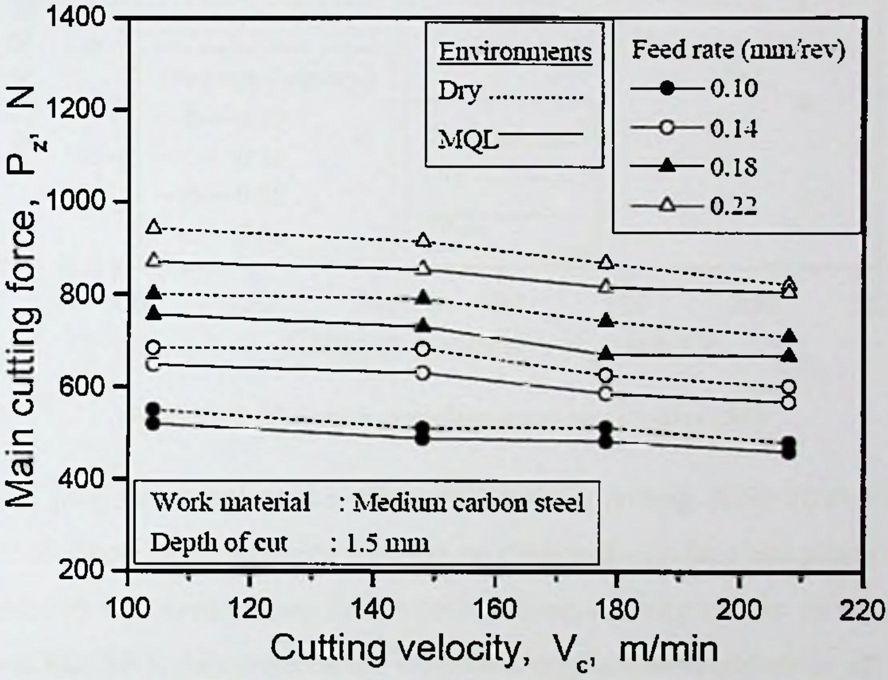


Figure 2.11Variation in the main cutting force (Source:[36])

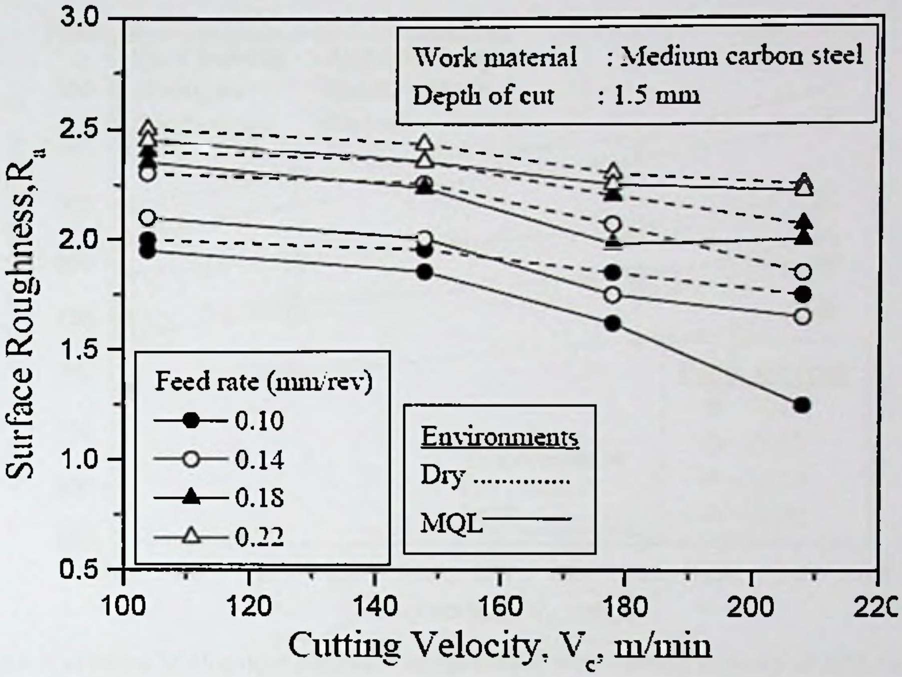


Figure 2.12: Variation of surface roughness (Source:[36])

Dhar et al. [30] have studied the effect of MQL in cutting AISI 1040 steel with SNMM tool. Their study has been focused on chip-tool interface temperature versus cutting velocity and main cutting force versus cutting velocity effects. In Figure 2.13, it is shown that MQL has reduced the chip-tool interface temperature in all the feed rates examined and in both dry and MQL cutting, the chip-tool interface temperature increases with the increase of the cutting velocity.

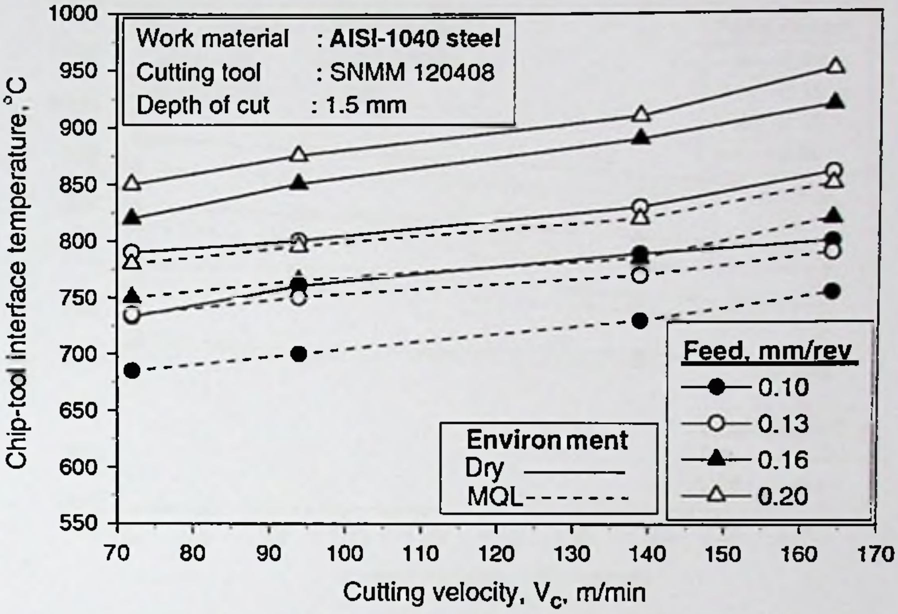


Figure 2.13: Variation in chip-tool interface temperature with cutting velocity at different feed rates (Source:[30])

Figure 2.14 shows the variation of the main cutting force with cutting velocity at different feed rates. It explains that cutting force has reduced with increasing cutting velocity, and with increasing feed rate the main cutting force has been increased also. According to them, reduction in main cutting force is a result of reduction in friction and reduction in formation of built-up-edge (BUE). In comparison of MQL and dry cutting, MQL has given lower main cutting force in given conditions.

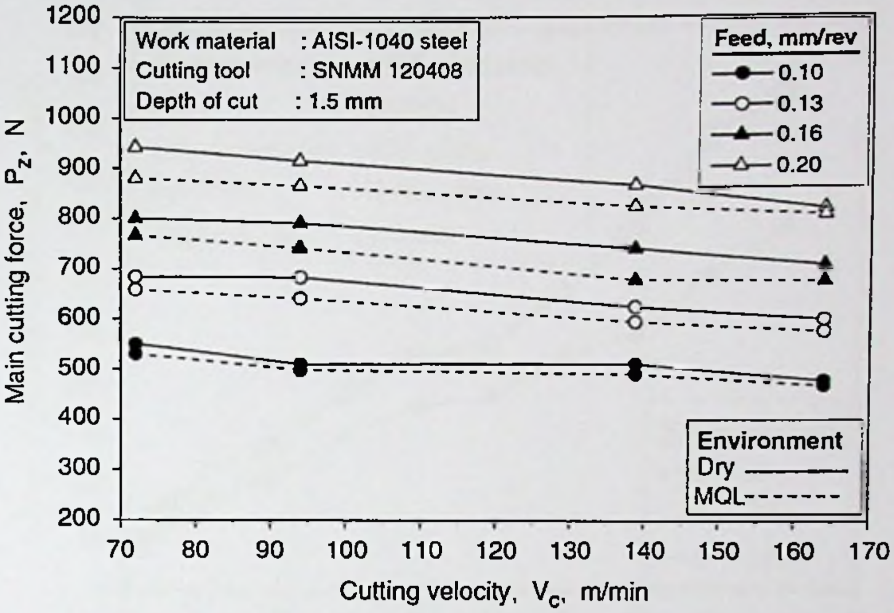


Figure 2.14: Variation in main cutting force with cutting velocity at different feed rates (Source:[30])

A study done by Dhar et al. [37]on cutting AISI 1040 steel with uncoated carbide tool using MQL, has concluded that the cutting performance of MQL machining is better than that of conventional machining with flood CF supply. Further, they have added that MQL has provided benefits mainly by reducing the cutting temperature, which improves the chip-tool interaction and retains the sharpness of the cutting edges. According to them the dimensional accuracy has been improved mainly because of the reduction of wear and damage at the tool tip by the application ofMQL.

Dhar et al. [38] have studied the effect of MQL in machining AISI 4340 steel using uncoated carbide tool. Figure 2.15 shows the progression of the flank wear over time. It shows that MQL has given less flank wear than dry cutting and wet cooling.

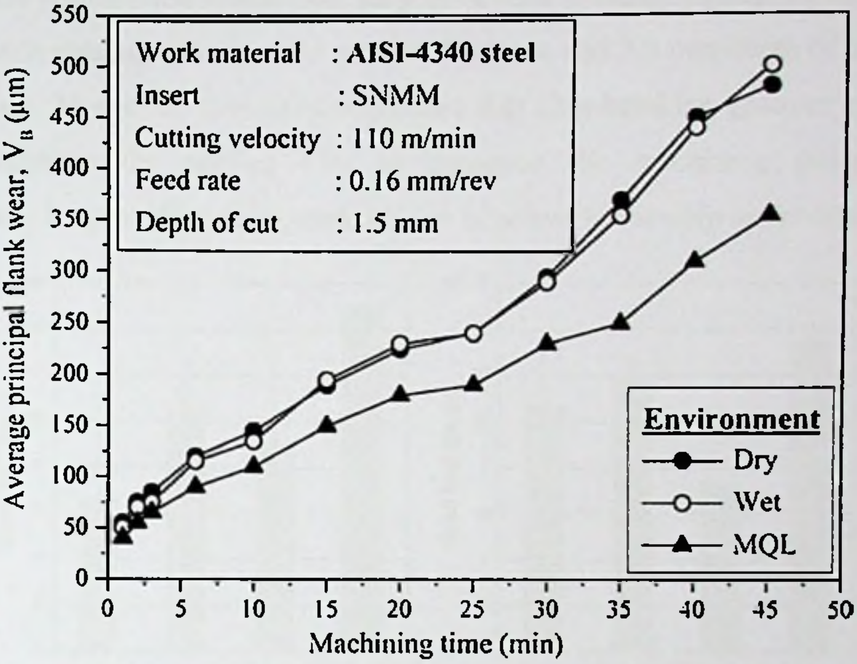


Figure 2.15: Growth of average principal flank wear with time (Source:[38])

In a research carried out by Hameedullah and Abhnag, [39] has studied the effect of 10% boric acid with SAE-40 oil in MQL conditionin cutting EN41 steel usingcoated carbide tool.They have concluded that MQL method can be reduce the chip-tool interface temperature by 20 to 30% in the used conditions. The reduction in cutting temperature in MQL method was high at lower level of machining parameters and low at higher level of machining parameters. MQL has reduced the cutting forces by about 5 % to 12%. According to them, that is mainly because of the favourable change in the chip-tool interaction and retention of cutting edge sharpness due to reduction of cutting zone temperature. Further, they have concluded that MQL machining reduces chip thickness up to 12 to 17% over dry turning and that is also favourable for chip formation in compare to dry machining.Surface finish in the investigated conditions was also significantly improved mainly due to significant reduction wear and damage at the tool tip by the application of MQL.

However, in a study conducted byJayal and Balaji[40], has shown uncommon results compared to similar other researches. They have machined AISI 1045 steel using coated carbide tools in dry, MQL, and MQL in Extreme Pressure (MQL_EP) conditions and has seen reduction in mean tool life as shown in Figure 2.16. In comparison with similar researches, they have used extreme cutting conditions with 400 mm/min cutting velocity, 0.35 mm/rev feed rate and 2.0 mm depth of cut in their experiments. Moreover, they have concluded that chip-breaking grooves on the tool surface allowed the applied CFs to influence the machining process more significantly by providing them some degree of access to the chip underside.

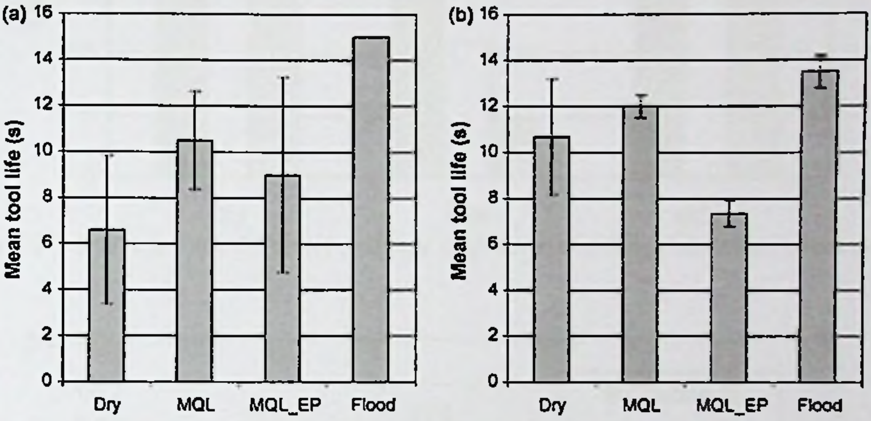


Figure 2.16: Mean tool life in different cutting fluid applications (a) Flat faced PVD tools (b) Grooved PVD tools (Source:[40])

In another research by Kamata and Obikawa[41] used MQL method with bio degradable ester to machineInconel 718 using a CNMG tool has seen lesser performance of MQL than conventional flood cooling . They have used tools with three different coatings, (A) TiCN/Al_2O_3/TiN, (B) TiN/AlN super-lattice, and (C) TiAlN for the turning operation in dry, wet, and MQL cutting conditions.Figure 2.17 and Figure 2.18 shows the tool life and surface roughness obtained with each of three tool coatings in the employed three cooling conditions. In this study MQL has shown significantly lower performance than flood cooling method. They have further studied the effect of the air pressure on tool life and surface roughness. They conducted an experiment with air pressure of 0.4 MPa and 0.6 MPa, and the lower pressure has given better tool life and surface finish. Further, in their study they have shown that increase of cutting speed in MQL under the used conditions has increased the surface finish, but has lowered the tool life.

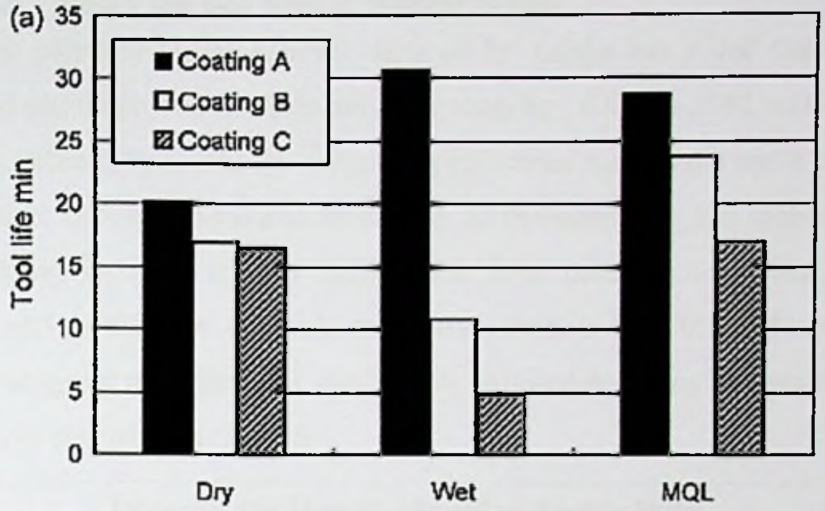


Figure 2.17: Tool life with different coatings at different cooling conditions (Source:[41])

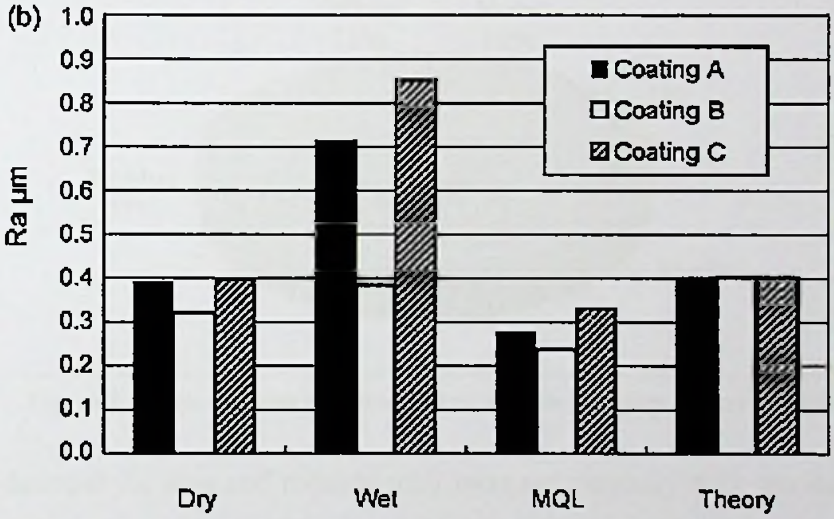


Figure 2.18: Surface roughness with different coatings at different cooling conditions

Some of the past researches in the fields related to the work are summarized in Table A.1 presented inAPPENDIX –A. It presents the different cutting tools, work-piece material, CFs, cooling methods, and machining parameters, which had been used in those work. This summary has been taken in to consideration, when selecting suitable parameters for the work carried out.

2.6. Sri Lankan Die and Mould Making Sector

In a report prepared by the Central Bank of Sri Lanka has stated that Sri Lankan rubber and plastic production industry has grown by 16.5% in 2011 and by 41.1% in 2010 [42]. According to this the supporting industries such as die and mould making industry have to be expanded and developed. At the same time, the rubber and plastic manufacturing industry is only behind the food products and wearing apparel industry, and is third in the industrial production index (IPI). Moreover, many literature suggests that, dies and moulds are required by many industrial sectors in Sri Lanka, as given in Figure 2.19.

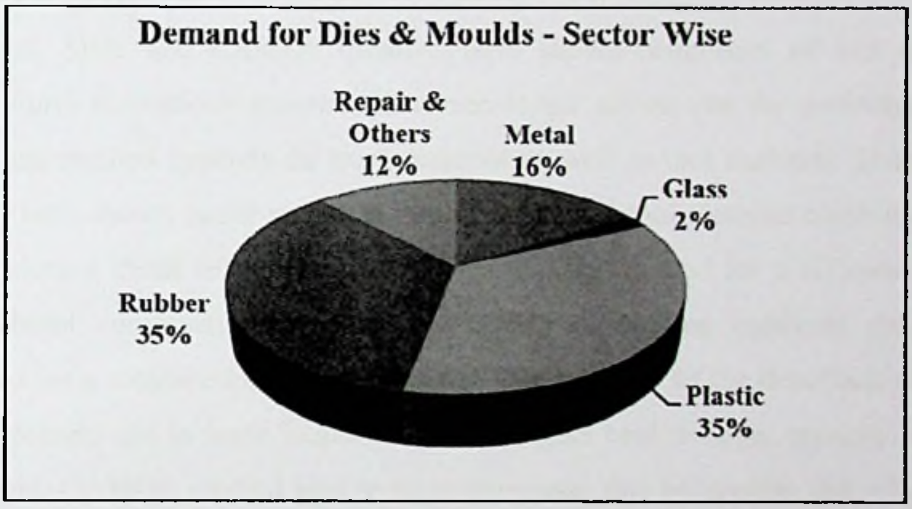


Figure 2.19: Sector wise requirement of dies and moulds (Source:[43])

The total demand for dies and moulds may increase annually with the development of other manufacturing industries too[43]. Nevertheless, over the last decades, the Sri Lankan die and mould making industry has faced many challenges and still agonises with numerous issues. Despite the growth of rubber and plastic manufacturing industry in the country, die and mould making industry has been in gradual decline over the years for the last two decades. One major observation was that there is a large technological gap between local die and mould manufacturers and their international counterparts. Sri Lankan die and mould manufacturers are mostly small and medium scale entrepreneurs (SME). Over the last two decades die and mould making in Sri Lankan industry has declined gradually and imports were increased drastically. According to some analyses, the inability of high capital investment, lack of awareness of global environment, and lack of technology, are identified as the major challenges for the industry. Higher production costs, sub-standard quality of the dies and moulds, and outdated technology are identified as the main reasons for lower turnover in the local die and mould makers [3]. In 1993 nearly 45% of the local die and mould demand were supplied by local die and mould manufacturers, but in 2007 that has reduced to 20%. This particular industry is in dire need for methods to reduce the cost of production. As of their inability of high capital investment, they have been stuck in outdated technology, and would not be able to change over to completely novel technologies by abandoning the existing.

2.7. Summary

In general, MQL and CAMQL methods have shown betterment of tool life and surface finish for various material. However, it has shown that the performance of the cooling method depends on work material as well as tool material. Thus, these methods have shown better results in certain work and tool material combination, it is inconclusive about the performance of the cooling method for a different work-tool material combination.Therefore, the effect of cooling methods should be examined for a combination of work and tool material.One of the drawback of MQL method pointed out in some literature is that it lacks heat removal capacity. On the other hand, CAMQL method said to have overcome this by cooling the oil and air mixture. CAMQL method uses chilled air to reduce the temperature in oil and air mixture. Since air is having less heat capacity, it is less effective in reducing the temperature of the oil and air mixture.

Die and mould manufacturing industry in Sri Lanka is facing deterioration, and in a dire need of methods for reduction of production cost. As MQL and CAMQL has shown betterment of machining performance for many work-tool material combinations, it could provide a better solution for Sri Lankan industry too. However, it is vital to find work-tool material combinations that are typical to this industry. Moreover, it has shown that Sri Lankan industries are not having sufficient financial capabilities to acquire expensive modern technologies. Therefore, it is important that a solution given should not cause abandoning of existing technologies, but altering them in a minor extent.

In the next chapter, the methodology used in this research is described.

3. RESEARCH METHODOLOGY

3.1. Background Study

A comprehensive study of mechanics in metal cutting, heat generation in metal cutting, cooling methods in metal cutting, tribology of CF, and related areas were done. Literature on previous research on the said areas were searched and reviewed. Books, course notes, research journal papers, theses, commercial literature, handbooks, catalogues, internet sites, videos and documentaries, and professional opinions, related to fields concerned were searched and gathered. By reviewing the collected literature a hypothesis was developed, "Cooling the cutting fluid with ACEMQL method will increase the tool life and provide better surface finish in the work-piece"

3.2. Survey on commonly used tool material, work material and cutting fluids in Sri Lankan die and mould making sector

A group of representatives from 11 different die and mould manufacturing companies were interviewed, face-to-face or over the telephone. The criteria of selection for selecting these 11 firms were, that the firm has at least one CNC milling machine, has at least one manual milling and lathe machine, and undertakes fabrication of dies and mould for polymer product manufacturing or metal forming. A sample of the questionnaire used is given in APPENDIX –D.

3.3. Design and fabrication of an experimental setup

An apparatus was designed to cool CF to a pre-set temperature and mix with pressurised air to create an aerosol of air and CF. Themajor parts of the system is, the CF cooling unit and the CF distribution unit. A schematic diagram of the system is shown inFigure 3.1. In the CF cooling unit, the CF reservoir and the cooling chamber was integrated together for simplification. A pump was attached for pumping CF from a machine tool CF tank, if required. Stirring mechanism was not fabricated at this stage and stirring was done manually. The cooling unit can supply chilled CF for multiple distribution units, to facilitate either multiple sprays on cutting area or use for several machine tools simultaneously. For the current stage one distribution unit was fabricated. The device is designed to be fitted with any type of machine tool without altering the machine tool. An assembly drawing of the designed device is given in APPENDIX- E.

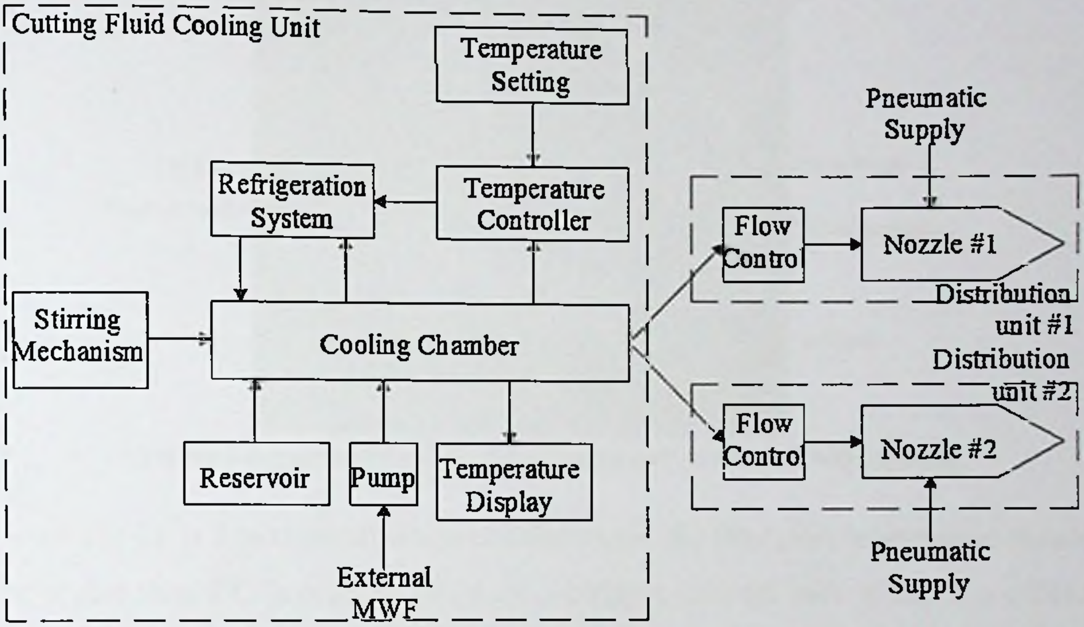


Figure 3.1: Schematic diagram of ACEMQL system

3.3.1. Designing of the cooling system

The CF cooling system consists of a CFreservoir, coolant pump system, a spray paint gun, and CF cooling system. A photograph of the actual system is shown in Figure 3.2. A newly discussed concept of CF cooling and application was developed as further discussed in 4.1in page 45. This newly developed concept called Air and Chilled Emulsion Minimum Quantity Lubrication (ACEMQL) was used for the experiment apparatus.

A cooling system was designed to hold approximately 35 litres of CF and lower the fluid temperature down to 2°C.Considering the ease of fabrication and time need for fabrication, it was decided to modify a split type air conditioner unit and build a cooling unit for CF. MQL method consumes less than 200 ml of CF in an hour. Therefore, a small reservoir would suffice for this purpose, but at the same time, the reservoir has to be built around the existing evaporator coil. Having a large reservoir will enable to store a large amount of CF that made as a single batch. This is useful in avoiding any errors due to composition of the CF. Therefore it was decided to proceed the design with a reservoir built around the evaporator with final holding capacity of 35 l.

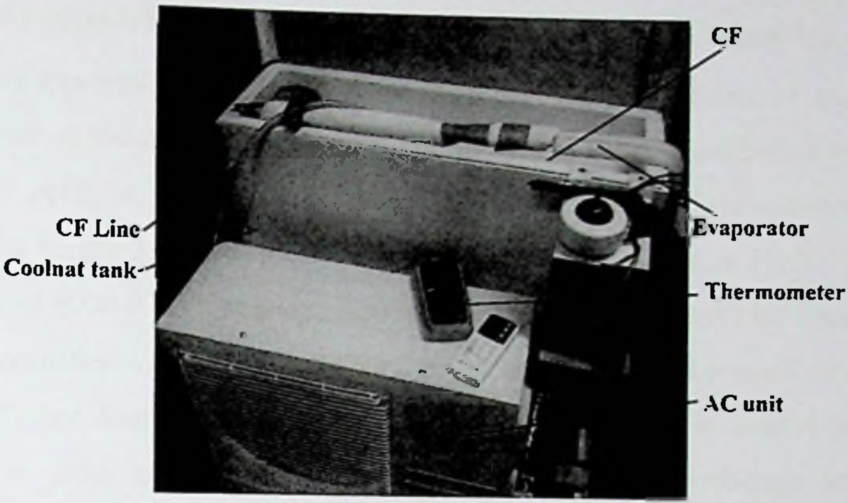


Figure 3.2: Fabricated cutting fluid cooling unit of the ACEMQL system

Since the CF is a mixture of mineral oil and water, the minimum temperature should be higher than 0°C in order to avoid ice formation. The CF bath which is a cuboid shaped tank without a top cover was fabricated with all five sides with Styrofoam insulation. Due to this arrangement, with some stirring of the CF, the temperature of the CF was able to be maintained constant for more than 15 minutes. It was observed that when the fluid is chilled, there is a temperature gradient in the CF bath. Between top and bottom of the fluid volume there was a temperature gradient of approximately 5°C. Therefore with further trial-and-error practice it was found that lowering the temperature of the CF 2°C than the final required temperature and stirring would provide the temperature in exactly at the required temperature. In order to have consistent measurements, temperature readings were taken at the mid height of the CF bath. The evaporator of the cooling system is fully immersed in the CF inside the CF bath. Temperature of the CF inside the CF bath was continuously measured using a digital thermocouple thermometer and the compressor of the cooling system was set off when the fluid temperature was 2°C below the required temperature. Then during the experiment the CF was stirred manually while the chilled fluid is drawn in by the paint gun. CF is drawn in to the paint gun via a 6 mm diameter tube which had its CF inlet placed at the mid height of the CF bath. Temperature readings were taken at the inlet of the tube. A low pressure air spray gun made of spray painting was used as the CF spraying nozzle which is shown in Figure 3.5. The fluid spray was directed to the rake face of the tool and the nozzle was held manually by hand during the experiment as shown in Figure 3.3.

The spray gun was held in a vertical plane perpendicular to the axis of rotation of the work piece as indicated in Figure 3.4. The spray gun was pre calibrated to spray 160 ml of CF per hour, and created a layer of CF in the tool rake face and work-piece as shown in Figure 3.3. A domestic air conditioner unit shown in Figure 3.2, with a capacity of 9000 BTU was adapted as the cooling unit of the system. The thermostat of the controller is removed as the air conditioner is designed to cool air only down to 16 ^{o}C. Ice formation sensor attached to the evaporator is also removed from system in order to allow the evaporator to be cooled to sub-zero temperatures allowing it to cool the CF in to temperatures such as 5 ^{o}C.

Figure 3.3: Manually held spray nozzle

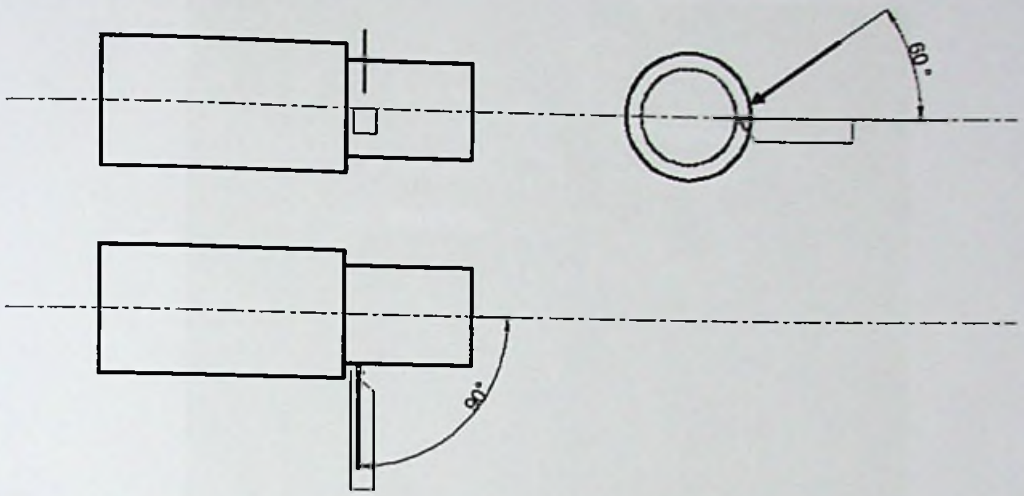


Figure 3.4: Target direction of the nozzle

CF in the experimental setup was cooled using an evaporator immersed in the CF bath. A domestic air conditioner unit with suitable capacity was used to cool the CF with its evaporator immersed in the CF bath. However, controlling of the temperature was seemed to be difficult as it had to be done manually. Controller in the air conditioner unit was not designed to regulate temperatures below 16 °C. Therefore, its temperature sensor was removed along with the evaporator ice formation sensor and regulating was done manually. Since the evaporator was immersed in the fluid, there was a temperature gradient in the CF inside the bath. Low temperature was observed at the bottom of the tank, while the top of the bath was measured with up to 5°C temperature above bottom temperature. With constant stirring of the CF inside the bath, it was possible to maintain a constant temperature at the inlet to the nozzle which was placed at mid-height of the tank for the entire duration of the experiment.

3.3.2. Fabricated ACEMQL system

Custom designed ACEMQL system was fabricated for the research. Design of the CF cooling system is discussed in Designing of the cooling systemin page 29. The CF distribution system comprises of a low pressure, low volume spray nozzle and an air compressor unit. The spray nozzle is a commercial paint spray gun with its reservoir removed as shown in Figure 3.5.

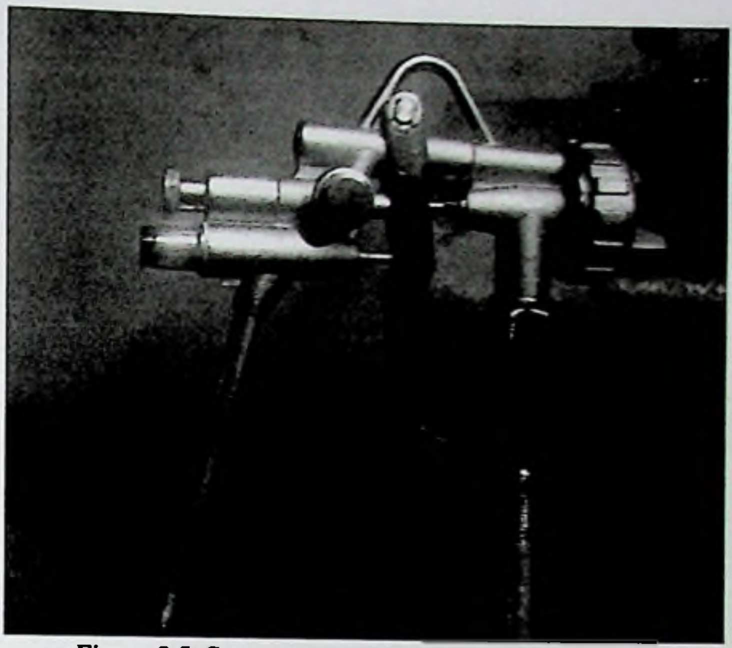


Figure 3.5: Spray gun used in the ACEMQL system

The temperature of the CF at the inlet of the supply hose to the nozzle was continuously measured using a digital thermocouple. Fabrication of the ACEMQL system was done at the department of mechanical engineering, University of Moratuwa, with the resources available at the refrigeration and air conditioning lab, sheet metal shop, and welding shop. The ACEMQL system in operation creates a thin layer of CF on the tool rake face and on the work-piece as shown in Figure 3.6.

During operation, the nozzle was clogged with small particles, and sedimentation from the CF. A paper filter was used to entrap sedimentation and small debris entering the nozzle. When a new filter was used, it doesn't affect the CF flow but over time it made starving of CF. In order to overcome this problem filter area was increased.

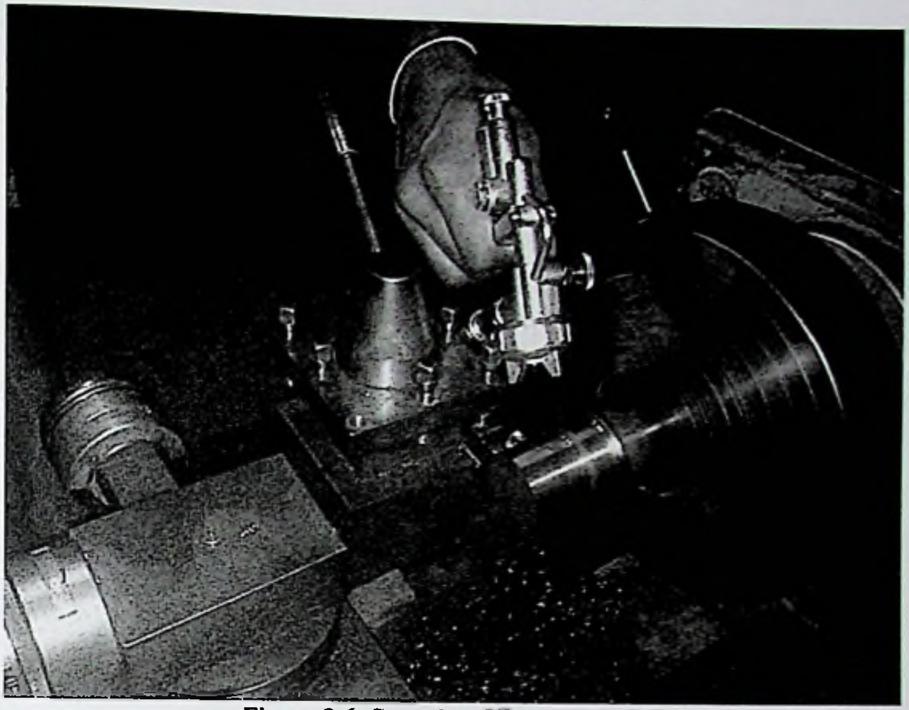


Figure 3.6: Spraying CF on to the WP

3.3.3. Tool inserts

Each trial was repeated for 3 times, with a new tool tip. Feed rate and depth of cut is set to 0.5 mm/rev and 0.5 mm respectively. Mitsubishi TCMT16T304 CVD coated carbide (UE6110) turning tool was used to machine both types of work-piece material. These values are selected based on the manufacturers' recommendations. Dimensions of the tool insert is shown in Figure 3.7.

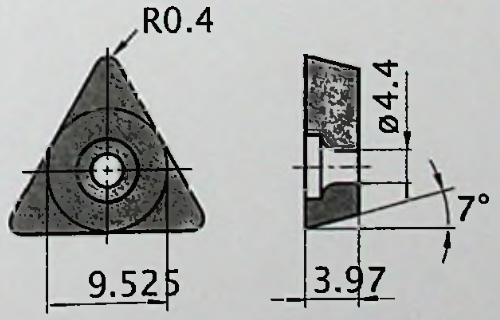


Figure 3.7: Cutting tool geometry of TCMT16T304 (Source:[44])

Due to the limitations of tools, tree trials which were using the same tool was carried out with TCMT16T308 tool. The only difference between TCMT16T304 tool and the TCMT16T308 tool is the tool nose radius. The radii are 0.4 mm and 0.8 mm respectively. This tool insert is recommended for medium cutting. It has a coating layer of Accumulated TiCN-Al_2O_3-Ti compound applied with CVD technique and has a hardness of 90.3 HRA. Its recommended cutting speed for steel is 200 mm/min (150-220 mm/min).

3.3.4. Lathe machine

Colchester Bantam 2000 lathe machine, which is a manual 3.0 kW horizontal lathe machine shown in Figure 3.8 is used for the straight turning operation done in the trials. Recommended surface speed for the tool is 150-240 m/min [44]. Considering the recommended range, 200 m/min was selected as the surface cutting speed for the iteration. Through the theoretical calculation, spindle speed required was 1414.7 rpm. However, the closest spindle speed obtainable in lathe machine was 1220 rpm. Equation 1 is used to calculate the spindle speed using the surface cutting speed. Cutting speed (v), diameter of the work-piece (D), rotational (spindle) speed (n) are used in the equation. With the spindle speed of 1220 rpm, the cutting speed is 172.5 m/min, which is within the recommended range.

$$v = \pi D n \qquad \textbf{Equation 1}$$

Figure 3.8: Lathe machine used for the trials

3.3.5. Work-piece

A total of 54 work-pieces with 27 pieces from AISI P20 and 27 pieces from AISI D2 tool steels were used for the trials. Diameter of this cylindrical work-pieces are 45 mm and has a length of 100 mm. The length of the cut in one pass was only 50 mm and for each work-pieces 10 passes of the tool was performed making a total of 500 mm cutting length. A 4-jaw chuck is used to hold the work-piece in the lathe machine as shown in Figure 3.9. Some key properties of the used work material as specified by the material manufacturer is shown in Table 3.1[45], [46].

Table 3.1: Key properties of work material

	AISI P20		AISI D2	
Density	7800 kg/m^3 at 20 °C		7700 kg/m^3 at 20 °C	
Hardness	52 HRC		62 HRC	
Chemical Composition	Chromium	2.00%	Chromium	11.30%
	Manganese	1.40%	Carbon	1.55%
	Nickle	1.00%	Vanadium	0.80%
	Carbon	0.37%	Molybdenum	0.80%
	Silicon	0.30%	Manganese	0.40%
	Molybdenum	0.20%	Silicon	0.30%

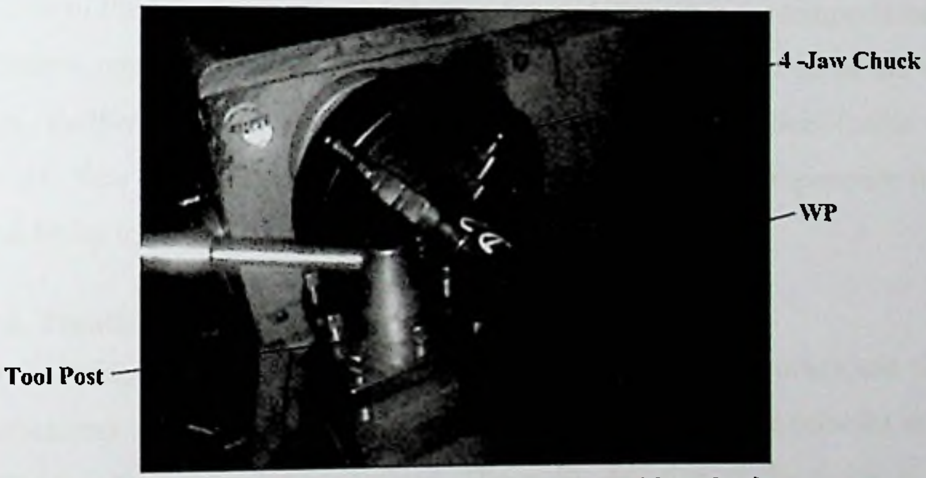


Figure 3.9: Work-piece mounted on the 4 jaw chuck

3.3.6. Cutting fluid

The lathe machine used to conduct the experiments was also using one of the Caltex product i.e. Caltex AquaTex 3180 cutting fluid, and it was decided to use the same CF for the study as well. This emulsion CF is mixed with water with a ratio of 1:9, CF to water.

3.4. Calibration of the experimental setup

The nozzle was calibrated spray 160 ml of chilled CF per hour. Pneumatic supply with 7 bar pressure was supplied to the nozzle and it was connected to hose. The other end of the hose was immersed in a measuring cylinder filled with CF and kept in a height as same as the ACEMQL system CF reservoir. Spraying with the nozzle was done at the same height as the lathe machine tool height to avoid any head difference in calibration process and actual usage. Then the nozzle is activated and jet size was adjusted and finalised. After that time taken to spray 5 ml CF is measured and fluid flow control valve of the spray gun is adjusted with trial and error method, until it deliver fluid at a rate of 160 ml per hour.

3.5. Pilot Run

First a pilot run was carried out with room temperature to measure and calculate the rate of nose wear in the tool. Then the same trial was carried out at 5 °C temperature also, as initial hypothesis was that least tool wear would be in the lowest temperature. With this the machining time required to produce a measurable wear in the tool was found. Cooling of the CF was done to various temperatures and the condition of the CF was scrutinized. It was observed that when the temperature of the CF reaches zero, it tends to form ice crystals near the evaporator coil of the cooling system. Further, it was observed that there is a temperature gradient inside the CF reservoir. Near the top surface of the CF mass showed higher temperature than the bottom by up to 5 °C.

3.6. Finalising of the parameters and controlled factors

By considering the findings in the literature review, industrial survey,and the tool manufacturers' recommendations, an initial set of parameters were selected and after the pilot run they were further refined. The main objective of the research was to study the influence of ACEMQL cooling method. In order to obtain benchmark to compare the performances, trials were done under dry cutting condition and flood cooling method while maintaining all other parameters unchanged. Then the temperature for the ACEMQL method to test was selected. As the used CF contains approximately 90% of water by volume, it cannot be cooled to or below 0 °C. Therefore, 5 °C was selected as the lowest temperature for the study.In absence of any cooling, the temperature of the CF was measured and found to be around 25 – 27°C. Therefore the first step of cooling was selected as 20°C. Due to the practical difficulties in maintaining temperature in the CF reservoir, it was decided to vary temperature in steps of 5 °Cfrom 5 °C to 20 °C.According to the conclusion made in the survey of work-piece material, tool material and CFs used in the concerned industry, there were selected.

3.6.1. Experiment plan

A factorial experiment of three levels was designed. Work material, cooling method, and ACEMQL CF were varied in the experiments. Developed experiment plan is shown in Figure 3.10.

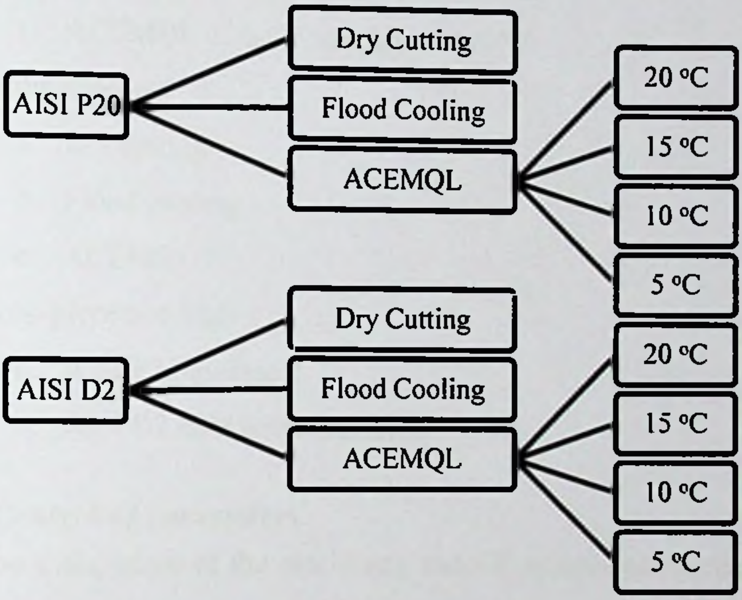


Figure 3.10: Experiment plan

3.6.2. Varyingparameters

1. Coolant temperature
    a. Dry cutting at room temperature
    b. Flood cooling at room temperature
    c. ACEMQL withCFtemperature 05 °C
    d. ACEMQL with CF temperature 10 °C
    e. ACEMQL with CF temperature 15 °C
    f. ACEMQL with CF temperature 20°C
2. Cooling method
    a. Dry cutting
    b. Flood cooling
    c. ACEMQL
3. Work-piece material
    a. AISI P20 tool steel
    b. AISI D2 cold work tool steel

3.6.3. Controlled parameters

Throughout the trials, some of the machining and CF system parameters were kept controlled. These were controlled as given in Table 3.2. Values for these parameters were chosen by referring to user survey carried out, literature review done, hand books, and manufacturers' catalogues. Straight turning operation was selected as it had been used by many previous researchers, so that the results of this study would be able to compare with those, and also because of the simplicity of the machining operation and ease of operation. Feed rate and depth of cut were selected based on the tool manufacturers' recommendation as well as considering the findings of the literature survey. Surface cutting speed and hence the spindle speed was selected following the tool manufacturers' recommendation. Length of the cut was determined by the results of the pilot run. MQL fluid flow rate, pneumatic pressure, nozzle target location and nozzle direction was selected considering the finding of the literature review.

Table 3.2: Controlled parameters for the experiments

Parameter	Value
Type of Machining Operation	Straight Turning
Feed Rate	0.5 mm per revolution
Depth of Cut	0.5 mm
Length of the Cut	500 mm (in 10 passes)
Surface Cutting Speed	150 m/min
Spindle Speed of the Lathe Machine	1220 rpm
ACEMQL Fluid Flow Rate	160 ml/ hour
Pneumatic Pressure	7 bar
Flood Cooling Flow Rate	9 l/min
Nozzle Target Area	Tool Rake Face
Nozzle Angle	Approx. 60° to Horizontal
Nozzle distance	150 mm

3.7. Conducting of the experiment

All the trials were carried out in a random order to avoid experimental bias. The order of the trials are shown in theTable 3.3. Each trial was repeated for three times. A 15 minute rest was given between trials to avoid any experimental error due to effects from previous trial, such as heating or cooling of tool holder, or operator biasness. Trials were done in an air conditioned environment, which has prevented any possible variation in changes in the ambience. Total amount of CF required for all the trials was prepared only in once, and the same batch was used throughout the trials. This has prevented any error due to variation of oil concentration in CF mixture.Tools were stored in numbered compartments as shown in Figure 3.11 to avoid any mixing of tools. At the end of each trial, the used tip of the tool insert was marked with a "dot", to prevent a used tip being used again in consecutive trials.

Figure 3.11: Storing of tools for measurements

Table 3.3: Order of the trials conducted

Trial		Condition	T (°C)	Tool No	WP
Order	No.				
1	6	ACEMQL	20	A2	P20
2	25	ACEMQL	10	B4	D2
3	1	Dry	25	A1	P20
4	11	ACEMQL	10	A4	P20
5	17	Dry	25	B1	D2
6	3	Dry	25	A1	P20
7	4	ACEMQL	20	A2	P20
8	27	ACEMQL	10	B4	D2
9	2	Dry	25	A1	P20
10	23	ACEMQL	15	B3	D2
11	21	ACEMQL	20	B2	D2
12	13	ACEMQL	5	A5	P20
13	15	ACEMQL	5	A5	P20
14	10	ACEMQL	10	A4	P20
15	9	ACEMQL	15	A3	P20
16	28	ACEMQL	5	B5	D2
17	18	Dry	25	B1	D2
18	29	ACEMQL	5	B5	D2
19	14	ACEMQL	5	A5	P20
20	20	ACEMQL	20	B2	D2
21	22	ACEMQL	15	B3	D2
22	30	ACEMQL	5	B5	D2
23	16	Dry	25	B1	D2
24	5	ACEMQL	20	A2	P20
25	7	ACEMQL	15	A3	P20
26	19	ACEMQL	20	B2	D2
27	12	ACEMQL	10	A4	P20
28	26	ACEMQL	10	B4	D2
29	8	ACEMQL	15	A3	P20
30	24	ACEMQL	15	B3	D2
49	50	Emulsion Flood	25	D5	P20
50	54	Emulsion Flood	25	D4	D2
51	52	Emulsion Flood	25	D5	P20
52	49	Emulsion Flood	25	D4	D2
53	54	Emulsion Flood	25	D5	P20
54	51	Emulsion Flood	25	D4	D2

3.8. Measuring the tool nose wear

A CNC-CMM, modelDe Meet 443, was used for measuring tool tip radius, and distance between tip and reference point as the method explained below. The CMM has a resolution of 0.0001 mm. Initially it was planned to take tool nose radius as the indicative measurement for tool wear. Radius of the tool nose after the tool was used for turning 500 mm of work-piece, was measured using the CMM. Upon usage, a reduction in the tool nose radius was expected but there were odd results which gave higher tool nose radius than the initial. Further investigation on this matter reveals that the curve approximation done for the tool tip in CMM leads to errors. Picking points on the worn edge with the CMM was vague and hence it was leading in to erroneous results. Since tool nose radius readings were given unexpected results, it was decided to use direct nose wear as the indicative measure for tool wear. A measuring jig was prepared by measuring several samples of unused tools and creating a recess in a steel block as shown in Figure 3.12, using a CNC machining centre. Used tool was inserted in this block and distance between the worn nose and reference point in the jig was measured as illustrated in Figure 3.13. Tool nose wear was found by taking the difference in tool nose and reference point distance with used tool and unused tool.

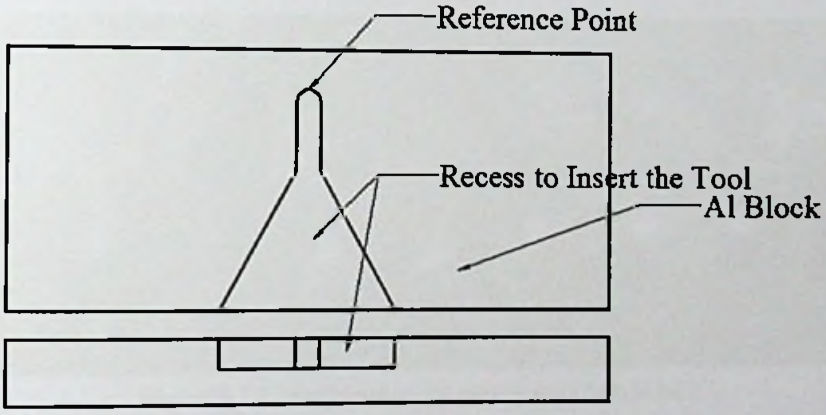


Figure 3.12: Tool nose wear measuring jig

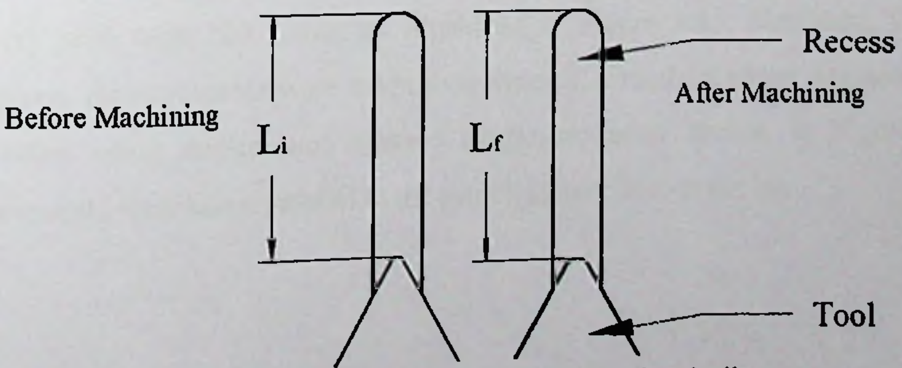


Figure 3.13: Measuring of the nose wear using the jig

Tool wear was calculated by the difference in reference length, before and after using the tool, using Equation 2.

$$\text{Tool Wear} = L_f - L_i \qquad \text{Equation 2}$$

3.9. Measuring the surface roughness

A Mitutoyo SJ-301 surface roughness tester was used to take the average surface roughness of the work-pieces. Average roughness Ra was measured by this digital instrument. It has a resolution of 0.01 µm and a cut-off length of 2.5 mm was used for the readings. Out of the 100 mm length in each work-piece, only 50 mm length is cut in each pass. Each work-piece was labelled with the experiment number as shown in Figure 3.14. Surface measurements were taken of work-pieces in random number. In order to avoid any reader biasness, measurements were taken by a reader who is unknown of the machining conditions, as each of the work-piece referred only by the number assigned to it.

Figure 3.14: Machined work-pieces with labels on

In each work-piece surface roughness was measured in three locations on its periphery with each 120 ° apart as illustrated in Figure 3.15. Similarly, for each work-piece, measurements were taken four times in a random order. Measurements were taken using theSurtronic surface roughness tester shown in Figure 3.16. Measurements were taken parallel to the principal axis, across the lay.

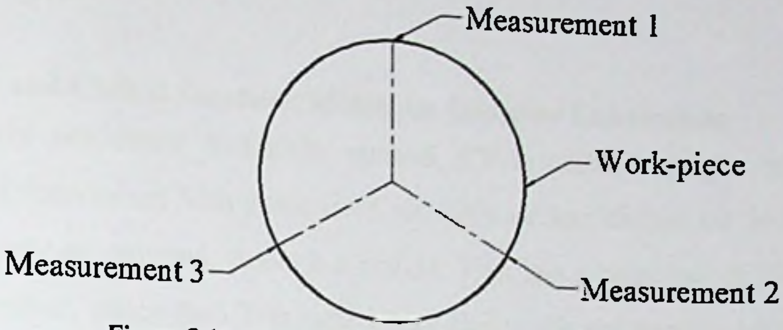


Figure 3.15: Measuring locations in the work-piece

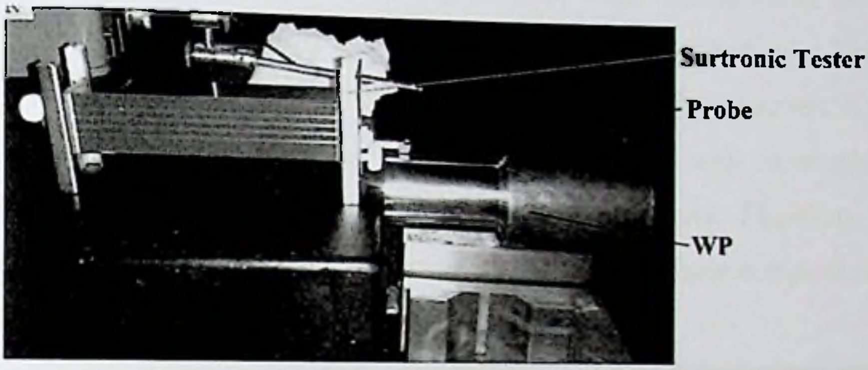


Figure 3.16: Measuring with surface roughness tester

All the results obtained by following the methodology described in this chapter are presented in the next chapter.

4. RESULTS

4.1. Air and Chilled Emulsion Minimum Quantity Lubrication

In this newly introduced ACEMQL method, CF is chilled using a refrigeration method, and then mixed with pressurised air. This air and chilled CF is directed to the cutting area as required, through a nozzle. This has a principal difference with CAMQL method, which the CF is mixed with chilled air and used in MQL. Air has less specific heat capacity than that of CF, therefore when chilled air is mixed with CF, the final temperature of the mixture cannot be lowered effectively. Cooling of the air and CFmixture is less effective in CAMQL method. However, if the CF, which is having higher heat capacity is cooled and then mixed with air which has less heat capacity, would produce lower temperature in the mixture. Therefore, cooling of, the air and CF mixture is much effective in ACEMQL. Major components of the ACEMQL system is shown in Figure 4.1.

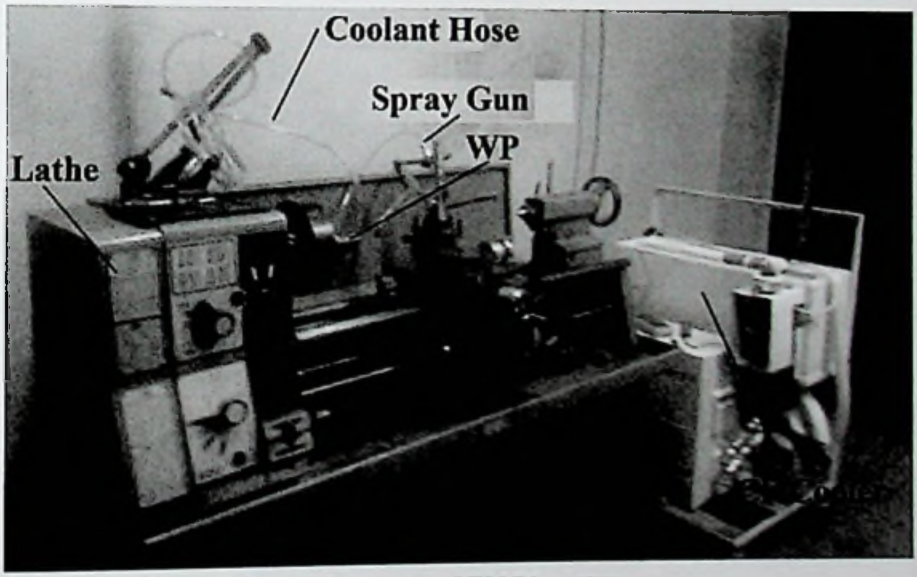


Figure 4.1: ACEMQL system

4.2. Survey on work and tool material, and cutting fluids used in Sri Lankan die and mould making sector

Complete results of the survey is shown in**Error! Reference source not found.**ofAPPENDIX –B. Conclusions made based on this survey is explained on the following text.

4.2.1. Types of most common work material in die and mould manufacturing industry

As shown inTable 4.1, all the participant firms are using AISI P20, tool steel in their die and mould fabrications. The next mostly used tool material for the same, was AISI D2 which 91% of the participants were said to using. Therefore, these two tool steels were selected for the study.

Table 4.1: Work material usage in the industry

Material	**AISI P20**	**XW 10**	**AISI D2**	**Mild Steel**	**DIN 2083**	**DIN 2085**	**X45**	**AISI W2**	**AISI A2**	**AISI H13**	**AISI M2**
No. of Users	11	1	10	2	1	1	1	2	1	2	1
	100%	9%	91%	18%	9%	9%	9%	18%	9%	18%	9%

4.2.2. Hard-to-cut metals in Sri Lankan industries

Through the survey carried out in Sri Lankan die and mould manufacturing industry, it was found that AISI P20 and D2 tool steels are the most commonly used work material in the industry. Hardness of AISI P20 and AISI D2 are 30-55 HRC and 60-65 HRC respectively. In the global perspective, hard-to-cut metals means much more hard and less machinable material such as titanium alloys.

4.2.3. Commonly used tool types, material, and brands

As the results shown inTable 4.2, it was concluded that tool brand "Mitsubishi" has been used by 82% of the sample of mould manufacturers, and hence it was selected for the study. The type of tools used to machine AISI P20 and D2 were coated carbide tools of the respective brand in each of all the participant firms.

Table 4.2: Tool brands used in the industry

Tool Brand	**Mitsubishi**	**Unbranded**	**Diamond**	**SANDVIK**	**Domer**	**SECO**	**SANT**	**Amana**	**Nine9**	**Santon**	**ISCAR**	**DJTOL**	**Rixin**
No. of Users	9	2	1	3	2	1	1	1	1	1	1	1	1
	82%	18%	9%	27%	18%	9%	9%	9%	9%	9%	9%	9%	9%

4.2.4. Commonly used cutting fluids

Table 4.3shows the CF brands used by the participants. It was only the brand that was considered as the same CF manufacturers are producing several variations of water-soluble emulsion CFs. Some of the participant are using few different brands of CFs for their different machines, based on the cost of CF and based on the machine tool manufacturers' recommendation. Some of the participants were not adequately aware of the CF that has been used in the respective firm or for some reason opted not to divulge the information. Some of the participants informed that there is trend in the industry to use sub-standard substitute CFs. However, out of the acquired information, it shows that 73% of the participants are using a Caltex water soluble emulsion CF product for their fleet of machines.

Table 4.3: Cutting fluid brands used in the industry

CF Brand	**Caltex**	**Chevron**	**SUPRACO**
No. of Users	8	1	1
	73%	9%	9%

4.3. Tool nose radius after machining

The reading of the tool nose radius from the CMM, before and after machining is shown in Table 4.4.

Table 4.4: Tool nose radius after and before machining

Tool No.	Tool Nose Radius (mm)				
	After Machining				Before
	Tip #1	Tip #2	Tip #3	Average	
A1	0.4408	0.4379	0.3598	0.4128	0.4000
A2	0.7264	0.7510	0.7608	0.7461	0.8000
A3	0.3695	0.3937	0.4526	0.4053	0.4000
A4	0.4017	0.3892	0.3839	0.3916	0.4000
A5	0.3893	0.4021	0.3672	0.3862	0.4000
B1	0.3762	0.5004	0.3428	0.4065	0.4000
B2		0.3949	0.3740	0.3845	0.4000
B3	0.3827	0.4600	0.3862	0.4096	0.4000
B4	0.4529	0.4888	0.4065	0.4494	0.4000
B5	0.4023	0.3813	0.4377	0.4071	0.4000

4.4. Toolnose measurements before machining

Using method discussed in paragraph3.8, first the unused tools were measured and an average for the distance L_i was calculated. Readings taken by the CMM is shown in Table 4.5.

Table 4.5: Distance between tool nose and jig reference point in tools before machining

TCMT16T304			TCMT16T308		
2.590 mm	2.573 mm	2.645 mm	3.011 mm	2.999 mm	3.014 mm
2.561 mm	2.607 mm	2.614 mm	3.002 mm	3.003 mm	2.981 mm
2.625 mm	2.639 mm	2.612 mm	3.009 mm	3.007 mm	3.007 mm
2.607 mm	2.613 mm	2.605 mm	3.014 mm	2.981 mm	3.013 mm
2.592 mm	2.643 mm	2.614 mm	3.002 mm	3.012 mm	3.006 mm
Average		2.609 mm	Average		3.004 mm

4.5. Tool nose measurementsafter machining

After machining, the tool tips were measured against the measuring jig using the CMM. The readings were averaged for each tool. Tool wear was obtained by the difference in unused and used tool. The calculated tool wear for each tool is shown in Table 4.6.

Table 4.6: Tool nose wear

Tool	Distance (mm)				Tool wear (mm)
	Tip #1	Tip #2	Tip #3	Avg.	
A1	2.667	2.678	2.676	2.674	0.064
A2	3.046	3.036	3.037	3.040	0.036
A3	2.608	2.614	2.611	2.611	0.002
A4	2.612	2.616	2.613	2.614	0.004
A5	2.620	2.625	2.623	2.623	0.013
B1	2.676	2.644	2.642	2.654	0.045
B2	2.623	2.628		2.626	0.016
B3	2.611	2.609	2.614	2.611	0.002
B4	2.624	2.618	2.625	2.622	0.013
B5	2.633	2.637	2.638	2.636	0.027
C1	3.014	3.009	2.997	3.007	0.003
C2	3.098	3.065	3.020	3.061	0.057
C3	3.030	3.057		3.044	0.039
C4	3.021	3.005	3.061	3.029	0.025
C5	3.006	3.007	3.004	3.006	0.002
D1	3.011	3.133	3.008	3.051	0.047
D4	3.027	3.035	3.040	3.034	0.030
D5	3.033	3.036	3.028	3.032	0.028

4.6. Tool wear observations inmachining AISI P20 work-pieces

Tool wear obtained with different cooling conditions for AISI P20 is shown in Table 4.7. Figure 4.2 shows the graphical representation of the results. Dry cutting has given the highest tool wear comparatively less tool wear was observed with flood cooling. However, at 20°C ACEMQL has shown higher tool wear than flood cooling method. Minimum tool wear was observed at 15 °C with ACEMQL and it has shown a trend of increasing tool wear when temperature was lowered to 10 °C and 5 °C.A tool wear reduction of 97% from dry cutting, and 93% of flood cooling, is observed with ACEMQL at 15 °C.At 10 °C also ACEMQL has shown a reduction in tool wear by 94% compared with dry cutting and 86% compared with flood cooling. However, at 20°C, it is observed that there is an increase in tool wear compared to flood cooling by 29%. Similar to thisbehaviour with CAMQL in machining other tool-work material combination has been observed by other researchers too.

Table 4.7: Tool nose wear results for AISI P20 material

Cooling Condition	Avg. Tool Nose Wear (mm)	Reduction (from Dry)	Reduction (from Flood)
Dry	0.064	-	-
Emulsion flood cooling at 25 °C	0.028	56%	-
ACEMQL at 20°C	0.036	44%	-29%
ACEMQL at 15 °C	0.002	97%	93%
ACEMQL at 10 °C	0.004	94%	86%
ACEMQL at 05 °C	0.013	80%	54%

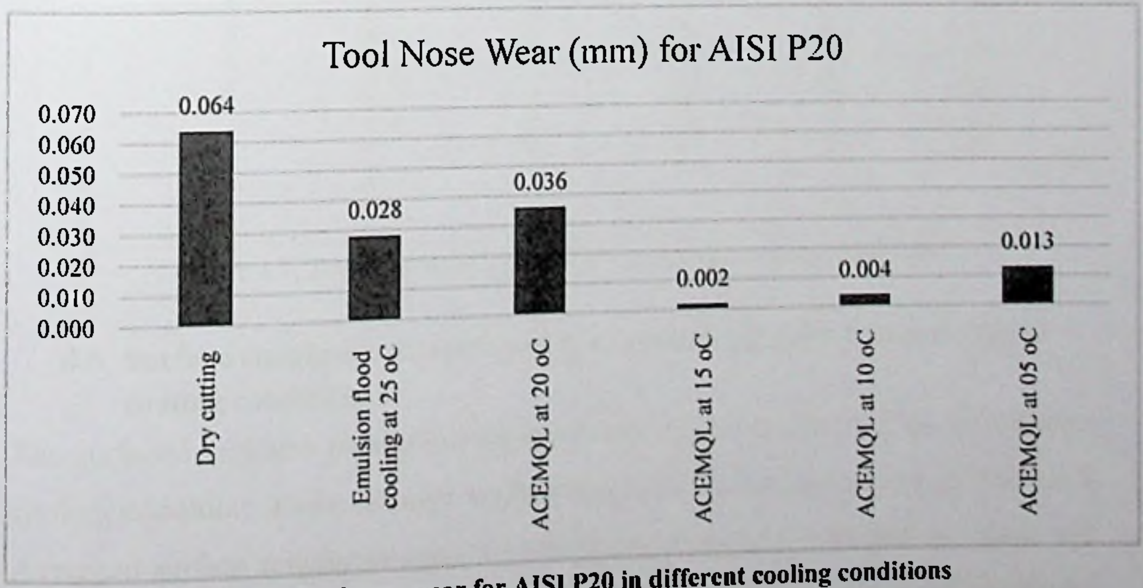


Figure 4.2: Tool nose wear for AISI P20 in different cooling conditions

4.7. Tool wear observations in machining AISI D2work-pieces

Tool wear obtained with different cooling conditions for AISI D2 is shown in Table 4.8. The graph in Figure 4.3is the graphical representation of the results. Dry cutting has given the highest tool wear comparatively less tool wear was observed with flood cooling. Minimum tool wear as observed at 15 °C with ACEMQL and it has shown a trend of increasing tool wear when temperature was lowered to 10 °C and 5 °C.

Table 4.8: Tool nose wear results for AISI D2 material

Cooling Condition	Avg. Tool Nose Wear (mm)	Reduction (from Dry)	Reduction (from Flood)
Dry	0.045	-	-
Emulsion flood cooling at 25 °C	0.030	33%	-
ACEMQL at 20°C	0.016	64%	47%
ACEMQL at 15 °C	0.002	96%	93%
ACEMQL at 10 °C	0.013	71%	57%
ACEMQL at 05 °C	0.027	40%	10%

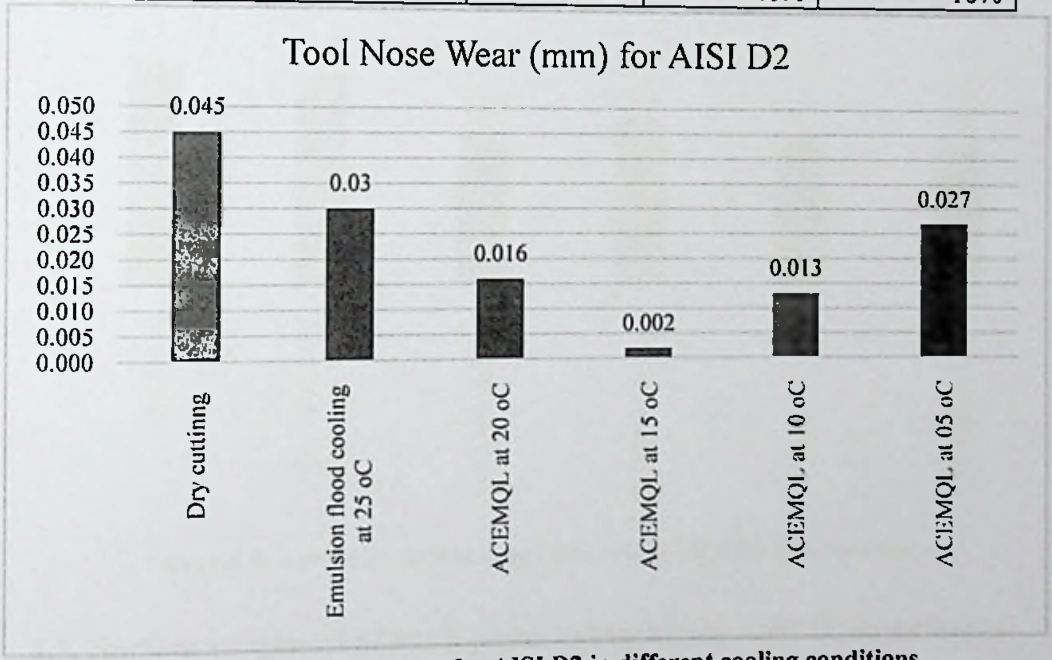


Figure 4.3: Tool nose wear for AISI D2 in different cooling conditions

4.8. Surface roughness of work-pieces in machining AISI P20 in different cooling conditions

The surface roughness measurements taken were averaged for each of the different cooling condition. These average surface roughness values are shown in Table 4.9. Averaged surface roughness against each cutting condition is plotted in Figure 4.4. Although use of ACEMQL shows an improvement in surface finish, it has not shown significant difference with reduction of temperature in the investigated steps of temperatures. The least surface roughness obtained is 0.97 μm Ra and it is at 5 °C. It is a 35% reduction with respect to dry cutting condition and 31% reduction in comparison with flood cooling condition.

Table 4.9: Averaged surface roughness measurements for AISI P20 material

Cutting Condition	Averaged SR (μm Ra)	Reduction (from Dry)	Reduction (from Flood)
Dry	1.51	-	-
Emulsion flood cooling at 25 °C	1.41	07%	-
ACEMQL at 20°C	1.03	32%	25%
ACEMQL at 15 °C	1.12	26%	19%
ACEMQL at 10 °C	1.03	32%	25%
ACEMQL at 05 °C	0.97	35%	29%

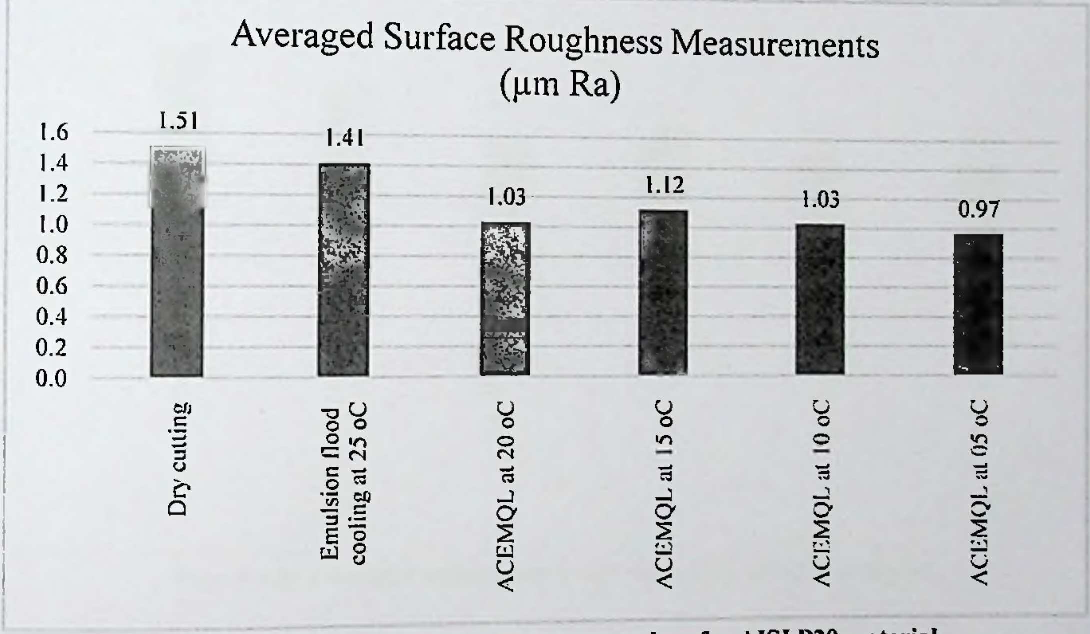


Figure 4.4: Averaged surface roughness values for AISI P20 material

4.9. Surface roughness of work-pieces in machining AISI D2 in different cooling conditions

The surface roughness measurements taken were averaged for each of the different cooling condition for D2 work-pieces. These average surface roughness values are shown in Table 4.10. Averaged surface roughness against each cutting condition is plotted in Figure 4.5. Use of ACEMQL has shown an improvement in surface finish, and has shown significant difference with reduction of temperature in the investigated steps of temperatures. The least surface roughness obtained is 0.82 μm

Ra and it is at 5 °C. It is a 49% reduction with respect to dry cutting condition and 40% reduction in comparison with flood cooling condition.

Table 4.10: Averaged surface roughness measurements for AISI D2 material

Cutting Condition	Averaged SR (µm Ra)	Reduction (from Dry)	Reduction (from Flood)
Dry	1.62	-	-
Emulsion flood cooling at 25 °C	1.37	15%	-
ACEMQL at 20°C	1.02	37%	26%
ACEMQL at 15 °C	1.03	36%	25%
ACEMQL at 10 °C	0.89	45%	35%
ACEMQL at 05 °C	0.82	49%	40%

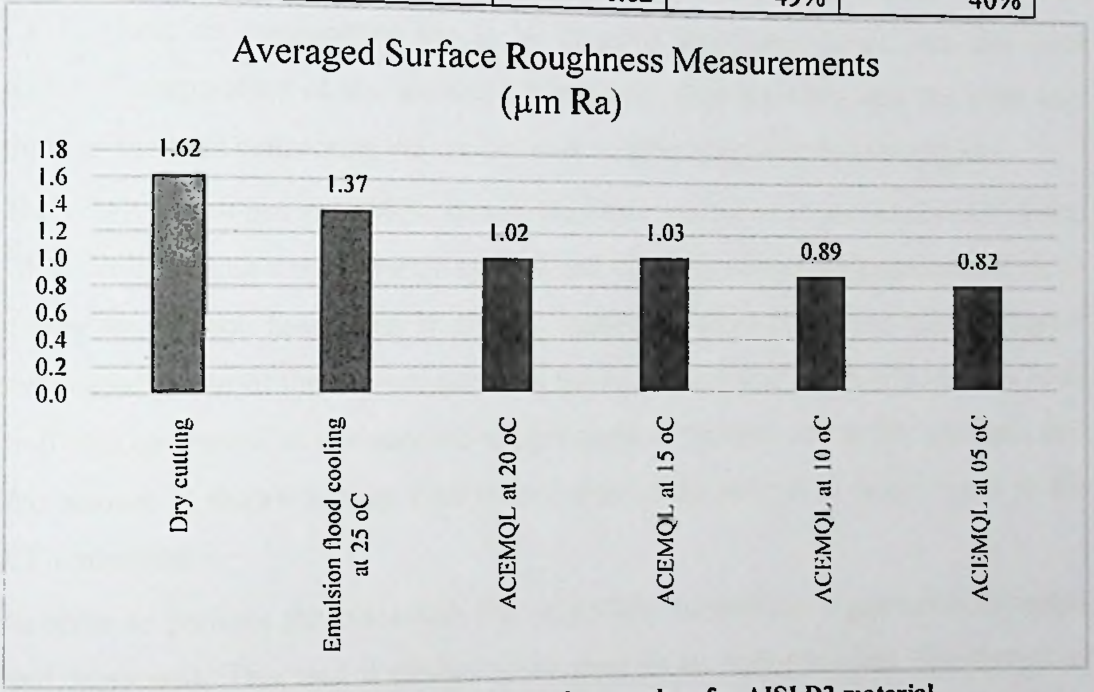


Figure 4.5: Averaged surface roughness values for AISI D2 material

In the next chapter, the results presented in this chapter is discussed and the conclusions of the research is presented. Suggested future work from this research also presented in the next chapter.

5. DISCUSSION

MQL method has shown better performances in machining several types of material. However, it has shown that MQL method is poor in cooling of the work-piece[29]. Cooling is one of the major functions expected from a metal working fluid. CAMQL method use chilled air to lower the temperature of the air and CF mixture. First, heat is transferred from air to refrigerant at the cooling unit, and then heat from CF is transferred to air at the mixing chamber[33]. Air, which has less heat capacity is used to absorb heat from CF which has higher heat capacity than air. This gives a disadvantage to the CAMQL process. In order to lower the temperature of the air and CF mixture, air temperature has to be dropped drastically lower than the final required temperature of the air and CF mixture. This indicates that the heat loss through the hose connecting the coolant tank and the spray nozzle is negligible.

The newly developed ACEMQL system produces aerosol of air and chilled CF. First, CF is chilled using a refrigeration system, and then it is mixed with pressurised air to create the aerosol. Since heat is directly transferred from CF which has the higher heat capacity out of the two constituents, the heat transfer is much effective. A brief trail was conducted to compare the temperatures at the inlet of the coolant hose and the aerosol. It shows that the final temperature of the aerosol is nearly equal to the CF temperature.

In order to perform the trials with the ACEMQL method, an apparatus is designed and fabricated. This unit is design to be used in an industrial site. The device is designed to be used with any type of machine tool. It can be attached to a machine tool without any modification to the machine tool. Therefore, it is highly suitable for Sri Lankan machining industry, as they can use this device to enhance their machining tool performances without modifying or abandoning the exist fleet of machine tools. Further, one CF cooling unit can cater several machine tools by accommodating multiple distribution systems.

ACEMQL has given significant amount of tool wear reduction for both the material used for the experiments. Moreover, the least tool wear was observed for both material with ACEMQL is at 15 °C. Tool wear with ACEMQL for AISI P20 at 15 °C is reduced by 97% of tool wear with dry cutting and 93% of flood cooling. Similarly, when machining AISI D2, the least tool wear is at the same temperature as AISI P20. At that temperature with D2 material, the tool wear was reduced by 96% of dry cutting tool wear, and 93% of flood cooling tool wear.

When the temperature was varied in steps of 5 °C, from 5°C to 20°C, the best reduction in tool wear is shown at 15 °CCF temperature for both material. Reduction in temperature may have reduced the effect of evaporative cooling. As the fluid temperature is decreased, evaporation and vaporisation of the CF is reduced. Therefore, heat absorbed by the CF due to latent heat of vaporisation and evaporation is reduced. This may have caused less heat absorption by the CF, which lead to reduce the tool life [40]. Figure 5.1 illustrates a possible increase in CF temperature in MQL method, with and without any cooling method. Without cooling of CF, starting temperature of CF would be at room temperature and during machining it may increase and reach vaporisation temperature. Upon this the fluid will absorb heat energy as latent heat and get vaporised. But as the starting temperature is lowered, the energy absorbed during machining may not be sufficient enough to reach vaporisation temperature. Due to the absence of state change of the CF and absence of heat absorbing due to latent heat, performance in the heat transferring is lowered. Evaporation can be occurred in any temperature but evaporation is reduced at lower temperature. Therefore, similar to vaporisation, heat transfer performance is reduced causing reduced machining performances.

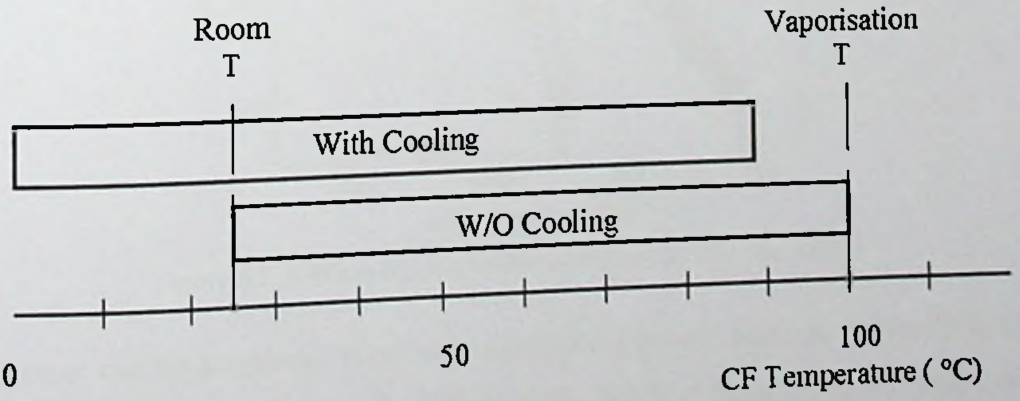


Figure 5.1: Temperature increase with and without cooling

ACEMQL has improved the surface roughness compared to dry cutting and flood cooling. With AISI P20 material, surface roughness reduction compared with dry cutting and flood cooling were by 35% and 31% respectively. Further, with AISI D2 material, surface roughness reduction compared with dry cutting and flood cooling were by 50% and 40% respectively. For both of the work material, best surface finish was seen at 5 °C. However, there is no noticeable difference in the surface finish in the investigated steps of CF temperature for AISI P20 material. Nevertheless, there is an improvement in the surface finish with decreasing temperature for AISI D2 material. When compared the surface roughness in work-piece for D2 at 20 °C and 5 °C, there is a 20% reduction in surface roughness at 5 °C.Effect of the cutting temperature is mainly because of it capability to lower the tool hardness. If the tool hardness is unaffected, then the sharpness of the tool retains, and thereby make the surface roughness lower. As the Figure 5.2 shows, tool hardness does not vary significantly at lower temperature. Therefore, due to the fact that the tool hardness is almost constant at lower temperatures, although the temperature is lowered the surface roughness is not affected significantly.

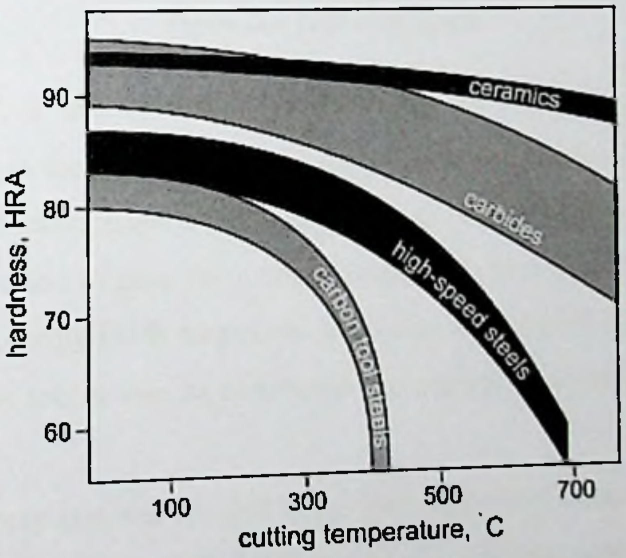


Figure 5.2: Hot hardness for some tool material (Source: [47])

Tool wear can be measured using both direct and indirect methods. Direct methods were chosen to have better representation of the tool life. There are many direct tool wear measuring methods, but tool flank wear and tool nose wear measurements are the most commonly used types of measuring methods. Some of the tool wear modes are shown in Figure 5.3. In order to make comparison of results with past researches, it was decided to use one of those two methods. However, summary of the past researches indicates that tool nose wear had been used more in the reviewed past researches. Further, measuring of flank wear requires specialised microscopes too. Moreover, flank wear rate is relatively low, and shown not the critical failure mode for most of the steels. Slow rate of wear dictates longer trials and practically it is difficult to conduct multiple trials with the flank wear measurements. Therefore, tool nose wear was selected as the indicative measure of tool wear.

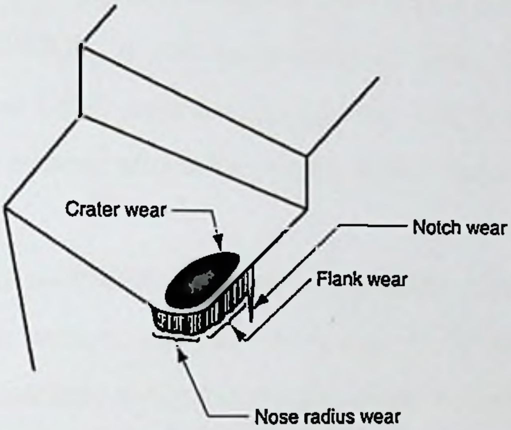


Figure 5.3: Tool wear modes

During the trials, it was observed that there was no occurring of Built-Up-Edge (BUE) formation in the tools. Since the cutting speed, the depth of cut, and the feed-rateused are from recommended range occurring of BUE is highly unlikely to occur. Further, it is expected to have the cutting temperature lowered, therefore it too can contribute to preventing BUW formation. However, as BUE did not occur during dry cutting conditions too, it can be concluded the cutting conditions does not favour BUE.

Holding of the spray gun was decided to be done manually. Because of the diameter of the aerosol spray at the specified distance of 150 mm was approximately 30 mm, and the rake face of the tool is widely opened, variations to the aerosol spray focus and direction was acceptable. Focused point of the aerosol spray has to travel with cutting tool has the cutting point shifts with the tool. Because of this if a holding mechanism is used, it has to move along with the cutting tool, preferably mounted on the tool post. Few mechanisms were tested but finally decided to conduct the trials without such mechanisms, as it obstructs the view of the cutting point.

5.1. Conclusions

- ACEMQL gives better tool life in machining AISI P20 and D2 material using coated carbide tools.
- The best tool life is obtained when the CF temperature is 15 °C.There is a noticeable improvement in surface roughness of the work-piece when ACEMQL is used.
- The leastsurface roughnessis observed when the CF temperature is 15 °C.
- By using ACEMQL, it can be avoided of using expensive cutting tool material such as CBN, ceramics, etc. and can achieve better performances in the machining system, still using comparatively cheaper coated carbide tool material.
- The developed ACEMQL application apparatus is suitable for machining industry. It can improve tool life and surface finish. Hence, the industry can improve their machine tool performances without doing any modifications to the machine tool or acquiring new machine tools.

5.2. Future Work

This work is done with cutting velocity, feed rate and depth of cut, which are the major dimensions of metal cutting to be fixed during the trials. However, it has been proven that these major dimensions of metal cutting does have effects on surface finish of the work-piece, and tool life. Therefore the effect of cutting velocity, feed rate and depth of cut, on tool life and surface finish has to be investigated.

It has been proven in previous literature that CF does influence the cutting forces and power. The effect of ACEMQL on cutting forces and power has to be investigated.

Economic feasibility analysis has to be carried out to find out the suitability of ACEMQL in local die and mould manufacturing industry. Feasibility study has to done for the targeted group of users.

Colour of the chip produced in the machining operation was observed to vary with the cutting conditions. It has to be further studied about this occurrences to determine the exact relationship between chip colour and cutting condition, and reasons for the colourisation.

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APPENDIX –A: Summary of MQL based past research

Table A.1: Summary of MQL based past researches

Reference	Work piece	Tool	Cutting fluid		Machining parameters		
	Material	Type / Material	Fluid	Cutting condition	Cutting speed (mm/min)	Feed rate (mm/rev)	Depth of cut (mm)
[12]	High carbon steel	CBN KD5625 Uncoated carbide K10	Triglyceride & propylene glycol	MQL 50 ml/h, 20 psi			
[14]	Normalized 100Cr6 steel (200–220 HB) bar	SandvikCoromant CNMG 12 04 04 PM—4025	Ester oil with EP additive (COUPEX EP46)	MQL on Flank / Rake, 20 mg/h, Air 2.5 bar	300	0.20, 0.26	1.0
[15]	Mild Steel (Ø20mm× 80 mm)	HSS (Miranda S-500)	Emulsion CF	MQL 200 ml/h, Air 6 bar,	63, 80, 93	0.035, 0.050, 0.820	0.80, 0.85, 1.00
[30]	AISI 1040	SNMM 120408 (P30) with PSBNR 2525M12(ISO)	Mobil Cut 102	Dry MQL 200 ml/h, Air 8 bar	72, 94, 139, 164	0.10, 0.13, 0.16, 0.20	1.5
[36]	Medium carbon steel	SNMG 120408 TTR (Widea P30)		Dry, MQL 100 ml/h, Air 20 bar	104, 148, 178, 208	0.10, 0.14, 0.18, 0.22	1.5
[37]	AISI 1040 steel (Ø 110mm×620mm)	Uncoated Carbide, SNMM 120408 P-30	Emulsion CF	Dry, Wet (flood cooling), MQL 60 ml/h, Air:7 bar,	64, 80, 110, 130	0.10, 0.13, 0.16, 0.20	1.0

Reference	Work piece	Tool	Cutting fluid		Machining parameters		
	Material	Type / Material	Fluid	Cutting condition	Cutting speed (mm/min)	Feed rate (mm/rev)	Depth of cut (mm)
[38]	AISI 4340 steel (Ø125×760mm)	Uncoated Carbide, SNMM 120408 P-30	Emulsion CF	Dry, Wet, MQL 60 ml/h, Air 7.0 bar	110	0.16	1.5
[39]	EN-31 steel (Ø50×500mm)	CNMA 120408, (diamond shape)	10% boric acid with SAE 40 base oil	Dry MQL 4-5 ml/h,	24, 39, 112, 189	0.06, 0.10, 0.15	0.4
[40]	AISI 1045	Single-layer PVD (TiN) coated cemented tungsten carbide Multi-layer CVD (TiN/Al2O3/TiCN/MT-TiCN/TiN) coated carbide Single-layer PVD (TiN) coated carbide cutting	Mineral oil-based soluble oil concentrate for MQL Fluid based on mixed natural esters of refined fatty acids, with EP additives (sulphur-based) for MQL_EP Soluble mineral oil, 5% solution of oil for Flood cooling	MQL 30ml/h, Air0.6 MPa MQL_EP 30ml/h, Air 0.6MPa Flood 9 l/min	400	0.35	2.0
[41]	Inconel 718	CNMG 120408, coatings: TiCN/Al_2O_3/TiN, TiN/AlN, TiAlN	Bio degradable synthetic ester (Diluted 1:30)	MQL 16.8 ml/h, Air 0.40 ~0.6 MPa	60	0.1	0.1

Reference	Work piece	Tool	Cutting fluid		Machining parameters		
	Material	Type / Material	Fluid	Cutting condition	Cutting speed (mm/min)	Feed rate (mm/rev)	Depth of cut (mm)
[47]	Inconel 718	CNMG 120408QM 1105		Dry, MQL 50 ml/h, 100 ml/h	90, 120, 150	0.10, 0.15	0.30, 0.50
[48]	100Cr6	Uncoated and TiN coated inserts.		Dry, MQL 24 ml/h, Air 125 l/min Only compressed air (125 l/min)	200	0.1	2.5
[49]	AISI 4340	SNMG120408 (TiCN and ZrCN Coated)	Mineral oil	Dry Wet MQL 10 MPa, 8 ml/min	35~ 55	0.05	1.5
[50]	Ti-6Al-4V	EM20-160-C20-2T	Oil (0.82 g/cm^3, 47 mm^2/s)	MQL,:20 ml/h, Air:88 l/min, 5.0 bar, -50°C	68	0.075	1
[51]	AISI 9310	Uncoated carbide, SNMG 120408 TTS P30 with PSBNR2525M12	Vegetable oil	Dry, Wet, 6 l/min, 0.5 bar MQL 100 ml/h, Air 6 bar	223, 246, 348, 483	0.10, 0.13, 0.16, 0.18	1
[52]	Mild steel	HSS Miranda S500		Wet, MQL, 6 bar, 200 ml/hr	63, 80, 93	0.035, 0.050, 0.820	0.80, 0.85, 1.00
[53]	High silicon aluminium alloy	Sinter Diamond tool K10	Rapeseed oil	MQL, 30 ml/h, Air:70 l/min Oil with Water droplets, Water:3 l/h	200, 800	0.05, 0.20	
[54]	AISI 4340	SNMM 120408 (P30)		Dry, Wet, MQL 60 ml/h, Air 7.0 bar	63, 80, 95,	0.10, 0.13, 0.16,	1.0, 1.5

Reference	Work piece	Tool	Cutting fluid		Machining parameters		
	Material	Type / Material	Fluid	Cutting condition	Cutting speed (mm/min)	Feed rate (mm/rev)	Depth of cut (mm)
					110, 128	0.20	
[55]	Brass (CuZn39Pb3) DIN12164:1998)	K10 Carbide:TCGX 16 T3 08-Al H10 (Sandvik)	Emulsion (Microtrend 321L)	MQL 50, 100, 200 ml/h	100, 200, 400	0.05, 0.10, 0.15	2
[56]	AISI 4340 (Ø60mm× 300 mm)	CBN insert TNMA160404 Grade PB250	Emulsion CF	Dry, MQL 10, 20ml/min, Air 6 bar, Wet	40, 80, 120	0.050, 0.075, 0.100	0.5, 1.0

APPENDIX –B: Most common work material, tool material, and cutting fluids used in Sri Lankan die and mould manufacturing industry

Table B.1: Results of survey on work material, tool Material and cutting fluids

Firm No	Work Material	Tool Brand/s	Cutting Fluid Brand/s
1	AISI P20 XW10 XW41 (AISI D2)	Mitsubishi	Caltex Aquatex 3180
2	AISI P20 AISI D2	Unbranded Diamond SANDVIK	Caltex Aquatex
3	Sverker 21 (AISI D2) ASTM P20	Mitsubishi	Chevron
4	Mild Steel 1730 DIN 2083 DIN 2085 AISI P20 AISI D2 X45	SANDVIK Domer Mitsubishi	Caltex
5	AISI P20 AISI D2 AISI W2	SECO SANT Unbranded	SUPRACO Caltex
6	AISI P20 AISI A2 AISI D2	Mitsubishi SANDVIK	Caltex
7	AISI P20 Mild Steel	Amana Tools Mitsubishi Nine9 Santon	Caltex Aquatex
8	AISI P20 AISI D2 AISI H13	Mitsubishi ISCAR	
9	AISI P20 AISI D2	Mitsubishi DJTOL	
10	AISI P20 AISI D2	Mitsubishi Rixin	Caltex
11	AISI P20 AISI D2 AISI H13 AISI W2 AISI M2	Domer Mitsubishi	Caltex

APPENDIX –C: Surface Roughness Measurements for AISI P20 and D2 Material in Different Cooling Conditions

Table C.1: Surface roughness measurements

Cutting Condition			WP	Surface Roughness Readings (μm Ra)			Average for WP
Coolant	Cooling method	T. (°C)					
None	Dry	25	D2	1.72	1.68	1.58	1.62
					1.59		
				1.63	1.65	1.52	
				1.70	1.62	1.50	
			P20	1.46	1.59	1.49	1.51
				1.48	1.58	1.47	
				1.50		1.50	
				1.42	1.60		
Emulsion CF	Flood	25	D2	1.48	1.30	1.39	1.37
				1.40	1.29	1.40	
				1.38	1.34	1.34	
					1.31		
			P20	1.43	1.39	1.39	1.41
				1.48	1.4		
				1.39	1.41	1.40	
				1.40	1.38	1.43	
Emulsion CF	ACEMQL	25	D2	1.06	1.05	1.02	1.02
					1.01	1.03	
				1.08	0.98	1.01	
				0.98	0.99		
			P20	1.07	1.30	1.05	1.03
				0.94	0.98	1.01	
					1.05	0.98	
				1.01	1.01	1	
Emulsion CF	ACEMQL	15	D2		1.02	1.04	1.03
				1.01	0.99	1.04	
				1.05	1.01	1.01	
				1.03	1.04	1.03	
			P20	1.12	1.01	1.02	1.12
				1.26	1.19		
				1.10	1.21	1.03	
				1.09	1.28	1.04	
Emulsion CF	ACEMQL	10	D2	0.88	0.91	0.88	0.89
				0.90	0.94	0.86	
				0.87	0.89	0.87	
					0.88	0.89	
			P20	1.06	1.06	1.02	1.03
				0.99	1.06	1.05	
				1.03	1.04	1.01	
					1.01	0.97	

Cutting Condition			WP	Surface Roughness Readings (µm Ra)			Average for WP
Coolant	Cooling method	T. (°C)					
Emulsion CF	ACEMQL	5	D2	0.80	0.84	0.84	0.82
				0.84		0.82	
				0.79	0.80	0.80	
				0.83	0.86		
			P20	0.99	0.93	0.95	0.97
				0.98	0.98		
					1.08	0.97	
				1.01	0.92	0.92	

APPENDIX – D: Sample questionnaire used for the industrial survey

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Reference:

Survey of Work Material, Tool Material and Cutting Fluids used in Die and Mould Making Facilities

Please be kind enough to provide the following information about your organisation. Information gathered here are used only for academic research and will be not be disclosed to any other party. Presentation of the results will be done without disclosing identity of the participants. Thank you for your cooperation.

1. Organization name and address (*Optional*)

2. Please tick the types of dies and moulds most frequently made in the facility

1	Injection moulds (for plastics / rubber)	
2	Compression moulds	
3	Forming tools (Punching / Shearing / Stamping / etc.)	
4	Blow moulds	
5	Extruder dies	
6	Casting dies	
7	Other…	

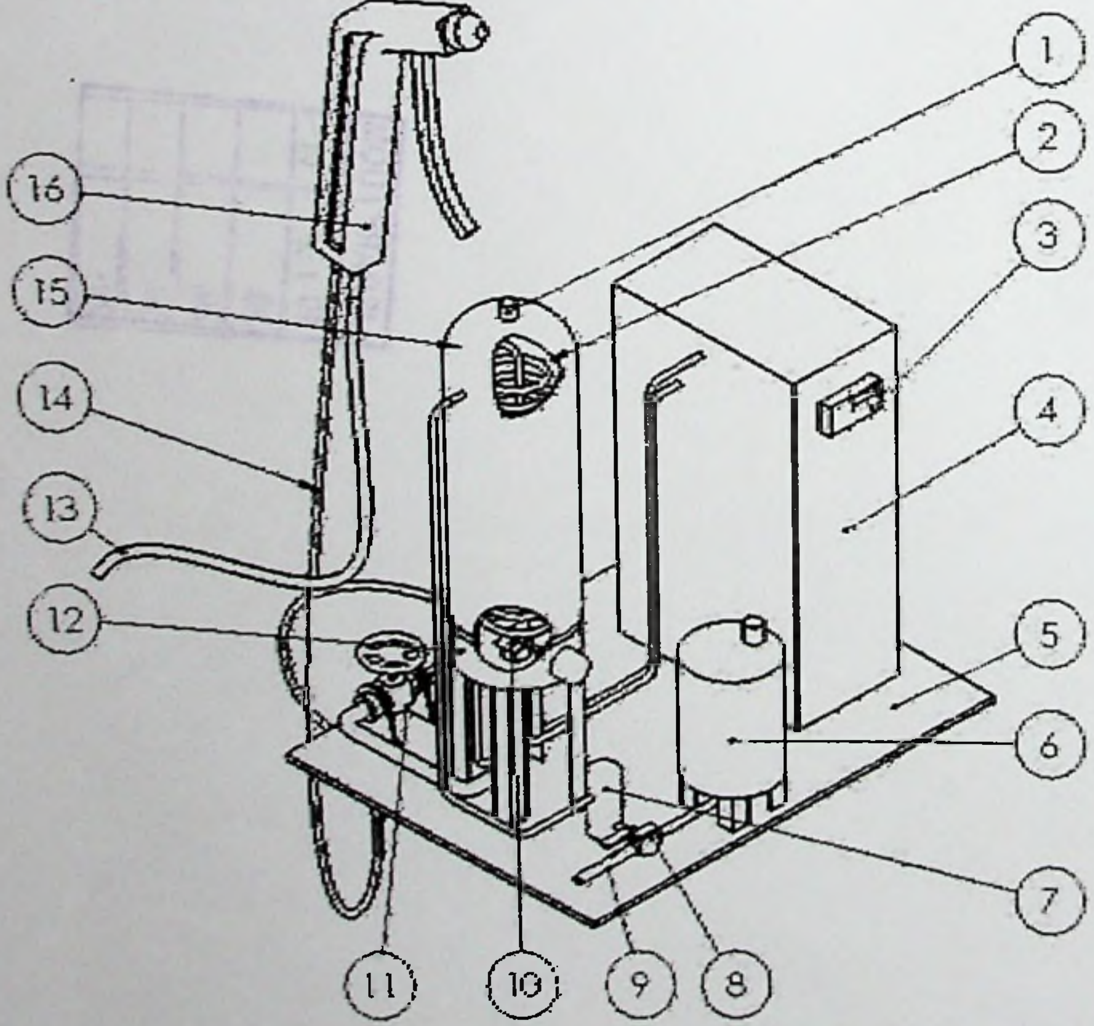
3. Please give information of the machine tools used in the facility

	Machine type	Control type (Manual / CNC)	Coolant used (Brand)	Max:Spindle speed used
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

4. Please specify the most common work material used in turning operations and the tool material (with brand name) used for the work material in order of usage

	Work-piece material	Tool/s used for the WP material
1		
2		
3		
4		
5		

APPENDIX – E: Assembly drawing of the ACEMQL unit



ITEM NO.	PART NUMBER	QTY.
1	Cooling chamber-wall	1
2	Evaporator coil	1
3	Temperature controller	1
4	Refrigeration unit	1
5	Base	1
6	Reservoir	1
7	Pump	1
8	Directional valve	1
9	External MWF inlet	1
10	Stirrer	1
11	Flow control valve	1
12	Cooling chamber-bottom	1
13	Pneumatic supply line	1
14	MWF supply line	1
15	Temperature display	1
16	Spray gun	1

Figure E.1: Assembly drawing