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"Viability of MQL in Turning Operation Of AS 1443 – 2004 M 1020MS Bright With Respect To Cutting Temperature, Surface Roughness and Cost of Lubrication"

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Abstract: *Lubrication is the process or technique used to reduce friction between surfaces coming in contact and relative to each other, by interposing a substance called a lubricant between them. Metalworking fluids (MWF) are known to provide many benefits to ensure that metal parts can be machined in a cost-effective manner. The positive features of metalworking fluids have long been established and include friction reduction, cooling, corrosion protection, welding protection from the tool to the workpiece and the washing away of metal chips. In the continuous quest for reducing the use of coolants in machining, only one process can offer a near-term solution for practical applications. This process uses a minimum quantity of lubrication and is referred to as* ***"MQL"****. In MQL, an air–oil mixture called an aerosol is fed into the machining zone. Compared to dry machining, Aerosols are generated using a process called atomization, which is the conversion of bulk liquid into a spray or mist (i.e., collection of tiny droplets), often by passing the liquid through a nozzle. MQL has the advantages of being inexpensive and simple retrofitting of the existing machines, same cutting tools used for flood MWF will work, easy to use and maintain equipment etc. However, these advantages do come at a cost. The most prohibitive part of switching to dry machining is the large capital expenditure required to start a dry machining operation. This paper aims at doing a systematic study and review of the available information about minimum quantity lubrication to evaluate its present status in the research and thereby draw some conclusion about its feasibility of application in the practical world.*

Keywords: *Aerosol, lubrication, Metal working fluids, MQL moving*

I. Introduction

1.1 History of Machining

Machining is a process in which a piece of raw material is cut into a desired final shape and size by a controlled material-removal process. Machining is a part of the manufacture of many metal products, but it can also be used on materials such as wood, plastic, ceramic, and composites. A person who specializes in machining is called a machinist. A room, building, or company where machining is done is called a machine shop or shop floor. Machining can be a business, a hobby, or both. The precise meaning of the term machining has evolved over the past one and a half centuries as technology has advanced. In the 18th century, the word machinist simply meant a person who built or repaired machines.

1.2 Cost involved in Machining

Manufacturing cost is the sum of costs of all resources consumed in the process of making a product. The manufacturing cost is classified into three categories: direct materials cost, direct labor cost and manufacturing overhead.

Direct materials cost: Direct materials are the raw materials that become a part of the finished product. Manufacturing adds value to raw materials by applying a chain of operations to maintain a deliverable product. There are many operations that can be applied to raw materials such as welding, cutting and painting.

Direct labor cost: The direct labor cost is the cost of workers who can be easily identified with the unit of production. Types of labor who are considered to be part of the direct labor cost are the assembly workers on an assembly line.

Manufacturing overhead: Manufacturing overhead is any manufacturing cost that is neither direct materials cost nor direct labor cost. Manufacturing overhead includes all charges that provide support to manufacturing.

Cost of Lubrication: Lubrication is the process or technique used to reduce friction between surfaces coming in contact and moving relative to each other, by interposing a substance called a lubricant between them. The lubricant can be a solid, or liquid such as oil, a liquid-liquid dispersion (a grease) or a gas.

The science of friction, lubrication and wear is called tribology. Adequate lubrication allows smooth continuous operation of equipment, reduces the rate of wear, and prevents excessive stresses or seizures at bearings. When lubrication breaks down, components can rub destructively against each other, causing heat, local welding, destructive damage and failure.

1.3 Machining with MQL Present Scenario

To understand why MQL machining works, a great body of the reported results on MQL has to be classified in a systemic fashion and analyzed using the fundamentals of metal cutting tribology. The lack of information on the experimental conditions, including the parameters of the aerosol, prevents any reasonable systematization of the work done. Unfortunately, many of these important parameters are not reported in many research documents and papers on MQL. As a result, a process or manufacturing engineer who wants to implement MQL is not equipped with sufficient recommendations to make proper choices of the equipment, parameters and regimes of MQL for a particular machining operation.

1.3.1 Introduction of Minimum Quantity Lubrication

In the continuous quest for reducing the use of coolants in machining, only one process can offer a near-term solution for practical applications. This process uses a minimum quantity of lubrication and is referred to as "MQL". In MQL, an air–oil mixture called an aerosol is fed into the machining zone. Compared to dry machining, MQL substantially enhances cutting performance in terms of increasing tool life and improving the quality of the machined parts. Small oil droplets carried by the air fly directly to the tool working zone, providing the needed cooling and lubricating actions. Aerosols are generated using a process called atomization, which is the conversion of bulk liquid into a spray or mist (i.e., collection of tiny droplets), often by passing the liquid through a nozzle. An atomizer is an atomization apparatus; carburetors, airbrushes, misters, and spray bottles are only a few examples of the atomizers used ubiquitously. In internal combustion engines, fine-grained fuel atomization is instrumental to efficient combustion. In short, MQL delivers a very small amount of coolant to a cutter's edge in the form of an oil mist or aerosol, as opposed to traditional techniques of flooding the workpiece and tool with a substantial volume of liquid coolant. Just a tiny bit of that aerosol is left on the chips, workpiece and machine during the cutting operation.

1.3.2 Classification of Minimum Quantity Lubrication

Unfortunately, there are no accepted classifications of MQL so it is very difficult for a practical engineer or plant manager to make the proper choice about the regimes of MQL and equipment needed. However the following classification can ease the purpose of study.

1.3.3 Classification by Aerosol Supply

The first level of MQL classification includes a way by which aerosol is supplied into the machining zone.

1) MQL 1: MQL with external aerosol supply. In MQL 1, the aerosol is supplied by an external nozzle placedin the machine similar to a nozzle for flood MWF supply.
2) MQL 2: MQL with internal (through-tool) aerosol supply. In MQL 2, the aerosol is supplied through the tool similar to the high-pressure method of internal MWFs supply.

   As the name implies, MQL with an external aerosol supply (MQL 1) includes the external nozzle that supplies the aerosol. There are two options in MQL 1, which are shown in Figure 1.

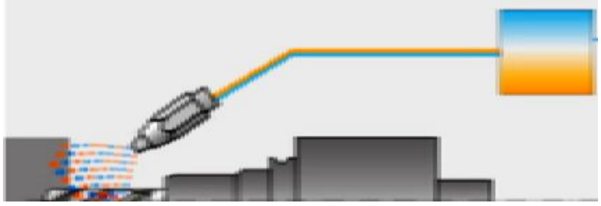

Figure 1.1 MQL with external aerosol supply

MQL 1 with an ejector nozzle: The oil and the compressed air are supplied to the ejector nozzle and the aerosol is formed just after the nozzle, as shown in Figure1. One of the possible designs of ejector nozzle is shown in Figure2. As can be seen, it has two air passages. The first one is external and creates the air envelope that served as the mixing chamber. The second one provides the atomizing air supply. The oil to be atomized is supplied through the central passage.MQL 1 with a conventional nozzle: The aerosol is prepared in an external atomizer and then supplied to a conventional nozzle, as shown in Figure1.1. The nozzle deign is similar to that used in flood MWF supply.

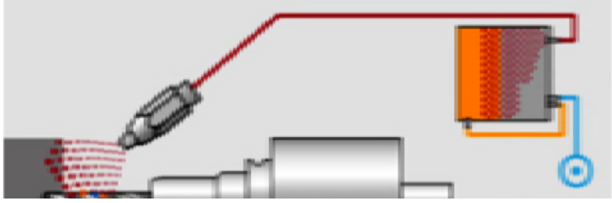

Figure 1.2 MQL with internal (through-tool) aerosol supply

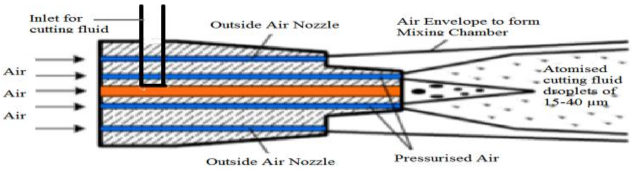

Figure 1.3 Nozzle design for MQL with external aerosol supply

MQL with external aerosol supply is probably the cheapest and simplest method. ThisNozzle unit works on an air pressure of 10-16 m/sec, which should be adjusted on the compressor. Attaching the fitting to the air supply, dropping the suction tube into an oil container, and locating the nozzle by means of the pipe through which cutting fluid passes, one can get MQL for a cost of Rs 1800/. The soft wire (used in medical field as inter-venous saline unit) in the nose can be bent to direct the fluid in the nozzleon to the work in the form of spray. It is designed for easy transfer from one machine to another

.

Figure 1.4 The soft wire (used in medical field as inter-venous saline unit)

However, adjustments are not that simple. If no special precautions are taken, the unit generates a dense mist that covers everything in the shop, including the operator’s lungs. To prevent this from happening and to gain the full control on the parameters of aerosol, one needs to have (design or buy) a hydraulic unit similar to that shown in Figure 1.4.

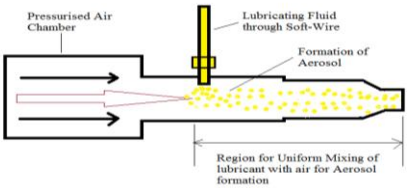

Figure 1.5: Aerosol control unit

When such a unit is used, the parameters of the aerosol can be adjusted in a wide range in terms of droplet size and oil flow rate by setting appropriate air and oil flow rates and by adjusting the pressure in the oil reservoir. Moreover, such a device prevents oil spills as it shuts down the oil supply line when the air supply is not available.

MQL 1 with a conventional nozzle is probably the simplest method. An external atomizer required is an off-the-shelf product, such as that shown in Figure 1.5.

1.4MQL 1 has the following advantages:

- Inexpensive and simple retrofitting of the existing machines
- The same cutting tools used for flood MWF will work

- Easy to use and maintain equipment
- The equipment can be moved from one machine to another
- Relative flexibility of MQL 1 with a conventional nozzle as the position of nozzle can be adjusted for the convenience of operator. As such, the parameters of the aerosol do not depend on the particular nozzle location.
- The equipment can be moved from one machine to another.
- Various standard and special nozzle designs are available with MQL 1 with a conventional nozzle to suite most common metal machining operations and tool designs. It is proven to be particularly effective in turning, face milling and sawing

1.5 MQL 1 has the following disadvantages:

- Both MQL 1; with an ejector nozzle and with a conventional nozzle do not work well with drills and boring tools as an aerosol cannot penetrate into the hole being machined
- A critical aspect for MQL 1 with an ejector nozzle and an important aspect for MQL 1 with a conventional nozzle is the location of the nozzle relative to the working part of the tool. For both methods, this location must be fixed, i.e., should not change as the tool moves. Note that this issue is not that important in flood MWF supply where gravity and the energy of MWF flow cover a much wider range of possible nozzle locations
- The parameters of the aerosol should be adjusted for each particular metal machining operation and the work material. This makes MQL 1 less attractive option in a job-shop environment

1.6 Need and Significance of the work

The United Auto Workers petitioned the Occupational Safety and Health Administration (OSHA) to lower the permissible exposure limit for metalworking fluids from 5.0 mg/m3 to 0.5 mg/m3. In response, OSHA established the Metalworking Fluid Standards Advisory Committee (MWFSAC) in 1997 to develop standards or guidelines related to metalworking fluids. In its final report in 1999, MWFSAC recommended that the exposure limit be 0.5 mg/m3 and that medical surveillance, exposure monitoring, system management, workplace monitoring and employee training are necessary to monitor worker exposure to metalworking fluids. In the current, competitive manufacturing environment, end-users of metalworking fluids are looking to reduce costs and improve productivity. The costs of maintaining and eventually disposing of metalworking fluids, combined with the aforementioned health and safety concerns, have led to a heightened interest in either eliminating metalworking fluid altogether or limiting the amount of metalworking fluid applied. The certain risks that are involved with the use of coolants may be enumerated as follows

1) Generation of dioxin
2) Harm to the human body
3) Wear of machine tool
4) Increase of maintenance cost
5) Danger of fire

Minimum quantity lubrication which is a very new method delivers the required minimum quantity of lubricant mixed with air and performs machining through a continuous supply of this air/oil mixture to the tool tip. It makes it possible to reduce the amount of coolant being used to nearly zero thereby resulting in minimizing most of the above mentioned risks involved with the use of coolants. Hence there seems to be a necessity to explore this method of machining.

1.7 Objectives of the study

The objectives of this study can be briefly stated as under

- This study of general aspects of minimum quantity lubrication is undertaken to try and understand the underlying possibilities of this relatively new concept
- This report will also aim at studying and understanding the effects of minimum quantity lubrication on some of the machining parameters such as surface finish and temperature.

II. Literature Review

2.1 Introduction

To understand why Minimum quantity lubrication machining works, a great body of the reported results on MQL has to be classified in a systemic fashion and analyzed using the fundamentals of metal cutting process. The lack of information on the experimental conditions, including the parameters of the aerosol, prevents any reasonable systematization of the work done. Unfortunately, many of these important parameters are not reported in many research documents and papers on MQL. As a result, a process or manufacturing engineer who wants to implement MQL is not equipped with sufficient recommendations to make proper choices of the equipment, parameters and regimes of MQL for a particular machining operation. Although professional magazines have published a number of articles on MQL, these articles do not present complete and systematic information on MQL even at the application level, limiting their scope to rather promotional aspects.

2.2 Some Studies on MQL

Hosokawa, Nozaki R, and A Ueda T, [1] found that temperature reduction in oil-mist turning is approximately 5%, while in oil-mist end milling it is 10–15% and in oil-mist drilling it is 20–25% compared to the temperature in dry cutting.

Chien and Wu [2] evaluated Minimum Quantity lubrication of three different steel materials. They found that the machining performance is affected by the lubrication type and its flow rate, the nozzle design, the distance between nozzle and tool tip, and the workpiece material. All these parameters are found to be dependent on the work material and process conditions. They concluded that only when the appropriate oil quantity and appropriate distance between the nozzle and tool tip are selected properly does MQL provides the optimum process condition.

Nikhil Ranjan Dhar, Islam S and Kamruzzaman M [3]studied the effect of Near Dry Machining in tuning of 4340 steel using external nozzle and aerosol supply to the tool. Interestingly, the authors found that the tool life is the same for dry and wet machining, which is in direct contradiction with common shop practice. They also found that the temperature at the tool–chip interface reduced by 5–10% (depending upon the particular combination of the cutting speed and feed) in NDM compared to wet machining. As a result, tool life and finish of the machined surface improved by 15–20%.

Nakamura T, Itoigawa F, Yoshimura H and Niwa K[4] found that, in machining of aluminium, the cutting force is lower and the surface finish is better with OoW NDM compared with dry, traditional NDM and wet machining.

Stephenson DA and Filipovic A [5] did not find any difference in tool life in gun-drilling and cross-hole drilling of crankshafts between wet machining and MQL. They are of the opinion that the difference between machining parameters of flooded lubrication and Minimum Quantity of Lubrication is negligible.

Shinozuka J, Kamata Y and Obikawa T [6] evaluated the performance of Near Dry Machining in high-speed grooving of a 0.45%C carbon steel with a carbide tool coated with TiC/TiCN/TiN triple coating layers. Studying tool life in grooving, they found that a vegetable oil supplied at constant rate of 7 ml/h reduced the corner and flank wears more effectively than water-soluble oil at high cutting speeds of 4 and 5 m/s.

Khan MMA and Dhar NR [7] found that NDM with vegetable oil reduced the cutting forces by about 5–15%. The axial force decreased more predominantly than the power force. They attributed this reduction as well as the improved tool life and finish of the machined surface to reduction of the cutting zone temperature as the major reason for the improved performance of machining operations.

Kuan-Ming Li K-M, Liang SY [8] found the cutting forces in machining 1045 steel to be lower in NDM compared with dry cutting. They also attributed this reduction to the cutting temperature difference.

III. System Development

3.1 Cutting Temperature in Machining with Minimum Quantity Lubrication:

The research on cutting temperature in metal cutting began as early as 1906. It was found that the cutting temperature was important to tool life. An empirical equation to estimate the tool life in terms of the cutting speed (consequently the tool temperature) was developed and subsequently widely used. Since that time, the steady state cutting temperature for dry machining has been studied by many researchers. Among them, Kuan Ming Lisummarized and modified the work of previous researches to estimate the temperature distribution for the tool in metal cutting.

The cutting temperature at the tool tip can be calculated according to the heat distribution on the tool-chip interface. The temperature change in the workpiece is caused by the primary heat source, the rubbing heat source, and heat the loss due to cooling. The proposed model is verified by experimental data of turning medium carbon steel AS 1443 – 2004 M 1020(MS BRIGHT) under minimum quantity lubrication. The temperatures are measured by an embedded thermocouple underneath the tool insert for comparison with model predictions.

3.2Temperature for Sharp Tools under Near Dry Condition:

The temperature distribution on the tool-chip interface for sharp tool edges in dry machining can be calculated with an analytical model, as proposed by Kuan Ming Li and Steven Liang [8]. It is believed that the temperature rise in dry machining is caused by the primary heat source at the shear plane and the secondary heat source at the tool-chip interface. In near dry machining, three heat sources/losses are considered: the primary heat source due to shear deformation, the secondary heat source due to friction, and the heat loss due to air-oil mixture cooling. The following sections describe how the heat loss due to convection on the tool flank face and workpiece is calculated based on a stationary heat source model (for the tool) and a moving-band heat source model (for the workpiece). The temperature distribution on the tool-chip interface is then estimated by the superposition of temperature changes due to different heat sources and heat losses.

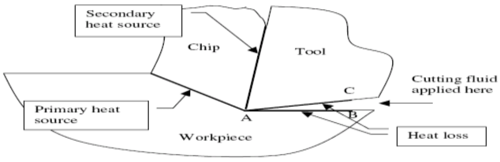

Figure 3.1: Heat sources and heat losses for the 2D model in near dry turning

3.2.1.1 Temperature Rise on the Tool Chip Interface in Chip

Temperature rise in the chip is attributed to both the primary heat source and the secondary heat source. The effect of the primary heat source is considered as this heat source moving in a continuous chip flow. The back side of the chip is assumed to be adiabatic. Then, the primary heat source and the imaginary heat source are symmetric with respect to the back side of the chip. The schematic of the imaginary chip and the heat sources is shown in Figure 3.3. The temperature rise due to the primary heat source is expressed as

$$\Delta T_{ch-s} = \frac{q_s}{2\pi k_{ch}} \int_{l_i=0}^{L} e^{\frac{-(X-x_i)V_{ch}}{2a_{ch}}} \left\{ K_0\left(\frac{V_{ch}}{2a_{ch}} \sqrt{(X-x_i)^2 + (Z-z_i)^2} \right) + K_0\left(\frac{V_{ch}}{2a_{ch}} \sqrt{(X-x_i)^2 + (Z-(-2t_{ch}-z_i))^2} \right) \right\} dl_i$$

$$\text{where} \quad x_i = L - l_i \sin(\phi - \alpha), \quad z_i = l_i \cos(\phi - \alpha), \quad L = \frac{t_0}{\sin\phi}$$

The above equation is valid only in the region of the chip physically removed, not the imaginary chip as depicted by the dash lines since there is not any material in the imaginary region.

Again, the above equation is valid only in the region of the chip removed. Considering both the primary heat source and the secondary heat source, the temperature rise in the chip is

$$\Delta T_{ch-s} + \Delta T_{ch-f} \, .$$

The heat loss intensity is calculated according to forced convection model as

$$q_{hl} = \overline{h}(T_{flank} - T_0)$$

Since the flow of the applied air-oil mixture is parallel to the tool flank face and the machined workpiece, the forced convection effect can be considered as a fluid flow passing through parallel flat surfaces. The average heat transfer coefficient in the above equation can be estimated by the Nusselt number as following

$$\overline{N}_u = \frac{\overline{h} L_{eff}}{k_{air}} = 0.664 \, \mathrm{Pr}^{1/3} \, \mathrm{Re}^{1/2}$$

3.2.1.3 Temperature Distribution on the Tool-Chip Interface

The temperature rise on the tool-chip interface is considered the same as that in the chip and in the tool. The heat partition function is solved by the following relationship.

$$\Delta T_{ch-s} + \Delta T_{ch-f} + T_0 \quad = \quad \Delta T_{t-f} - \Delta T_{t-hl} + T_0$$

If a total of n points are of interest on the tool-chip interface, the same number of equations can be solved for the heat partition factors. Subsequently, the temperature distribution on the tool-chip interface can be obtained.

3.2.2.3 Temperature Rise in the Workpiece

The temperature rise in the workpiece is caused by the primary heat source, the rubbing heat source, and the heat loss. The heat sources and the heat loss are considered as moving heat bands with respect to any fixed point in the workpiece. The temperature rise in workpiece was estimated by the moving heat bands models with proper coordinate systems. The imaginary part of the primary heat source is plotted in Figure 3.7. The heat source is assumed to move in a semi-infinite material with imaginary material. The effect of the primary heat source is expressed as

$$\Delta T_{wk-s} = \frac{q_s}{2\pi k_{wk}} \int_{l_i=0}^{L} e^{\frac{-(X_2-x_i)V_c}{2a_{wk}}} \left\{ K_0\left(\frac{V_c}{2a_{wk}} \sqrt{(X_2-x_i)^2+(Z_2-z_i)^2} \right) + K_0\left(\frac{V_c}{2a_{wk}} \sqrt{(X_2-x_i)^2+(Z_2-(-2t_o-z_i))^2} \right) \right\} dl_i$$

where $x_i = L_{VB} + l_i \cos\phi$, $z_i = l_i \sin\phi$.

3.3 Surface Finish in machining with Minimum Quantity Lubrication

Since machining is often the manufacturing process that determines the final geometry and dimensions of the part, it's also determines the part's surface texture. Surface roughness of a machined surface depends on: (a) geometrical factors, (b) work material factors, and (c) vibrations and machine tool factors. The two most important factors affecting the surface finish are tool geometry (nose radius) and the feed (Figure **5.1**). The effect of nose radius and feed can be combined in an equation to predict the ideal average roughness for a surface produced by a single-point tool. The equation applies to operations like turning, shaping, and planning:

$$\mathbf{R_i = \frac{f^2}{32 \times R}}$$

Where Ri is theoretical arithmetic average surface roughness (in or mm), f is feed (in or mm), and R is nose radius on the tool point (in or mm).

Ideal surface roughness (Ri) represents the best possible surface finish that can be obtained with a given tool shape and feed, and can only be approached if built-up edge (BUE) formation, chatter, inaccuracies in the machine tool movement, etc., are eliminated. Quantitatively, it is useful to express the roughness in terms of a single parameter, i.e. the arithmetical mean value.

In most machining operations, ideal surface finish can not be achieved because of factors related to the work material and it's interaction with the tool. An empirical ratio (R_{ai}) can be developed to covert the ideal roughness value into an estimate of the actual surface roughness. This ratio takes into account BUE, tearing, and other factors. Actual surface roughness can be predicted by the following equation:

$$\mathbf{R_a = R_{ai}\, x\, R_i}$$

Where R_a is the estimated value of actual roughness; R_{ai} is the ratio of actual to ideal surface finish; and R_i ideal roughness value calculated.

Surface roughness plays an important role in determining how a real object will interact with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces. Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion.

3.4 Cost analysis of Machining with respect to Lubrication

The historical, widespread use of coolants as MWF's has overshadowed MQL and kept it as a marginal technology. Sadly, not many machinists know or truly understand the concepts behind MQL and therefore never get to enjoy its many benefits. In an industry where production efficiency is crucial, the unknowns of a 'new' technology pose the potential threat of complications and downtime. The fear of the unknown may be the greatest challenge to MQL, and the fact that a large percentage of metalworking equipment comes already equipped with flood coolant systems is surely no help either.

$$\mathbf{L_c = Q_l \times Cost\ of\ Lubricant/Litre}$$

Where L_c is lubrication cost and Q_l is quantity of lubricant.

Repeated exposure to many coolants can have real consequences for the humans involved as well. Some coolants have been shown to cause dermatitis and to be carcinogenic with long-term exposure to coolant vapor. Studies have shown that the cumulative cost of coolants/MWFs can equal as high as **15%** of the total cost to produce a part.

IV. Performance Analysis

4.1 Verification of Analytical Output by Experimental Method

In the tests that were conducted, the validation of cutting temperatures in MQL was verified by measuring the temperatures with an embedded thermocouple located under the tool when cutting AS 1443 – 2004 M 1020(MS BRIGHT) with uncoated carbide tool inserts on a lathe under various cutting conditions. The cutting conditions are selected in the ranges of cutting speed = 45.75-137.25 m/min, feed = 0.0508-0.1016 mm/rev and depth of cut = 0.508-1.016 mm. The workpiece is 31.75 mm in diameter and 76.2 mm long. The air fluid mixture is supplied at 12.5ml/hr at a pressure of 275.8 kPa. The conditions that were observed during the tests can drafted into tabular form as follows

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4.1.1 Design of Experiment

Design of Experiments (DOE) is a method to identify the important factors in a process. In engineering settings, there are usually multiple factors involved and it is typically important to consider them together in case they interact (influence each other). This is done using a full factorial DOE. Here, a three level factorial DOE was used. This means three levels of each factor will be studied at once. If there are kfactors that we need to evaluate in a process we need to run the experiment 3^ktimes. Each factor will have three levels.

The three-level design is written as a 3^kfactorial design. It means that k factors are considered, each at 3 levels. These are (usually) referred to as low, intermediate and high levels. These levels are numerically expressed as 0, 1, and 2. One could have considered the digits -1, 0, and +1, but this may be confusing with respect to the 2-level designs since 0 is reserved for center points. Therefore, we will use the 0, 1, 2 scheme. The reason that the three-level designs were proposed is to model possible curvature in the response function and to handle the case of nominal factors at 3 levels. A third level for a continuous factor facilitates investigation of a quadratic relationship between the response and each of the factors.

These treatments may be displayed as follows

The design can be represented pictorially by

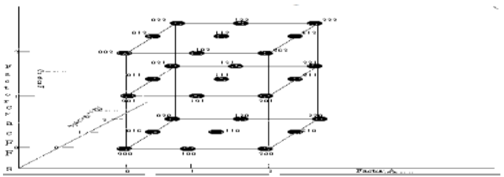


Figure 4.1A 3^3 Design Schematic

For the present experimental conditions three factors that were considered are cutting speed, feed and depth of cut. And for each of these factors three levels were taken into consideration. Based on the full factorial theory for three factors and three levels we can say that 3^3 =27 number of tests are to be conducted. These are drafted in tabular form as follows.

Table 4.2: Test cutting conditions & readings temperature, values for surface roughness and cost of lubricant.

				Temperature (^{0}C)			
Test No	**Speed (m/min)**	**Feed (mm/rev)**	**Depth of cut (mm)**	**Flooded**		**MQL**	
				Analytical	**Experimental**	**Analytical**	**Experimental**
1	45.75	0.0508	0.508	270	250	235	270
2	45.75	0.0762	0.508	430	443	374	430
3	45.75	0.1016	0.508	394	405	343	394
4	45.75	0.0508	1.016	267	248	238	267
5	45.75	0.0762	1.016	420	440	374	420
6	45.75	0.1016	1.016	396	400	352	396
7	45.75	0.0508	0.762	265	255	236	265
8	45.75	0.0762	0.762	425	439	378	425
9	45.75	0.1016	0.762	400	410	356	400
10	91.5	0.0508	0.508	585	598	521	585
11	91.5	0.0762	0.508	600	550	534	600
12	91.5	0.1016	0.508	580	570	516	580
13	91.5	0.0508	1.016	590	600	525	590
14	91.5	0.0762	1.016	575	500	512	575
15	91.5	0.1016	1.016	575	565	512	575
16	91.5	0.0508	0.762	570	590	519	570
17	91.5	0.0762	0.762	610	520	555	610

18	91.5	0.1016	0.762	580	570	528	580
19	137.25	0.0508	0.508	550	730	501	550
20	137.25	0.0762	0.508	550	590	501	550
21	137.25	0.1016	0.508	780	750	710	780
22	137.25	0.0508	1.016	550	730	501	550
23	137.25	0.0762	1.016	550	590	501	550
24	137.25	0.1016	1.016	780	750	725	780
25	137.25	0.0508	0.762	550	730	512	550
26	137.25	0.0762	0.762	550	590	512	550
27	137.25	0.1016	0.762	780	750	725	780

Table 4.2: Test cutting conditions & values for surface roughness and cost of lubricant.

				Surface roughness Ra, µm		**Lubrication cost in Rupees**	
Test No	**Speed (m/min)**	**Feed (mm/rev)**	**Depth of cut (mm)**	**Flooded**	**MQL**	**Flooded**	**MQL**
				Practical	**Practical**	**Practical**	**Practical**
1	45.75	0.0508	0.508	2.75	3.1	216	45
2	45.75	0.0762	0.508	2.6	3	172	26
3	45.75	0.1016	0.508	3.2	3.5	136	18
4	45.75	0.0508	1.016	3.25	3.8	224	56
5	45.75	0.0762	1.016	3.5	4	178	29
6	45.75	0.1016	1.016	3.3	3.9	148	16
7	45.75	0.0508	0.762	2.6	3.1	228	50
8	45.75	0.0762	0.762	2.7	3.3	192	32
9	45.75	0.1016	0.762	3.2	3.6	156	24
10	91.5	0.0508	0.508	2.9	3.2	216	45
11	91.5	0.0762	0.508	2.8	3.3	172	26
12	91.5	0.1016	0.508	3.6	4	136	18
13	91.5	0.0508	1.016	3.5	4.3	224	56
14	91.5	0.0762	1.016	3.6	4	178	29
15	91.5	0.1016	1.016	3.5	4.1	148	16
16	91.5	0.0508	0.762	2.9	3.4	228	50
17	91.5	0.0762	0.762	3.1	3.5	192	32
18	91.5	0.1016	0.762	3.5	3.9	156	24
19	137.25	0.0508	0.508	3.2	3.6	216	45
20	137.25	0.0762	0.508	3	3.8	172	26
21	137.25	0.1016	0.508	3.5	4.2	136	18
22	137.25	0.0508	1.016	3.4	4.1	224	56
23	137.25	0.0762	1.016	3.5	4	178	29
24	137.25	0.1016	1.016	3.6	4.2	148	16
25	137.25	0.0508	0.762	2.9	3.5	228	50
26	137.25	0.0762	0.762	2.8	3.4	192	32
27	137.25	0.1016	0.762	3.3	3.9	156	24

The estimated parameters according to the measured cutting forces for sharp tool and for worn tools are listed in Table 4.2. When investigating the near dry lubrication effect on the cutting temperatures, the values of rubbing force on the tool-workpiece interface F_{cw} is used.

The model-predicted temperatures and the measured temperatures under the tool insert for different cutting conditions and the values for surface roughness are shown in table 4.2.

4.4 Effects of cutting parameters on temperature in NDM

The effects of cutting parameters on the cutting temperature in near dry turning process are shown in Figures 4.2, 4.3, and 4.4. It is shown that the cutting speed is the dominant factor among the cutting conditions, followed by the feed, and then the depth. It is interesting that the effect of the depth of cut on tool-workpiece temperature for worn tool has no obvious trend

.

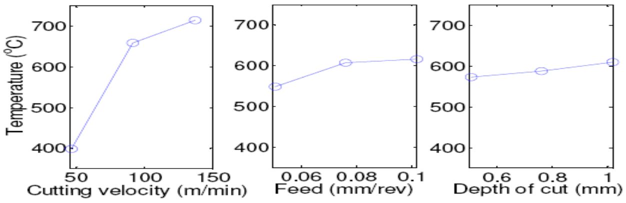


Figure 4.2: Tool-chip interface temperature trend for sharp tool with respect to cutting conditions

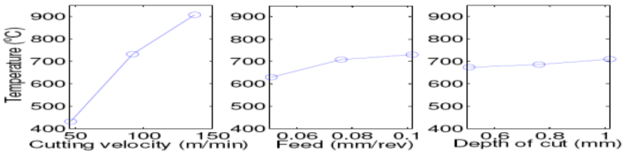


Figure 4.3: Tool-chip interface temperature trend for worn tool with respect to cutting conditions

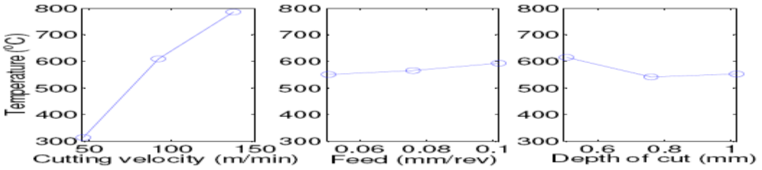


Figure 4.4: Tool-workpiece interface temperature trend for worn tool with respect to cutting conditions

The understanding of temperature distributions in machining under near dry situations is extremely important to the analysis of tool wear progressions and shop floor air quality. With cutting forces and the material properties as inputs, the average tool-chip interface temperature and the average tool-workpiece temperature are obtained [4]. In addition, the lubricating effect on cutting temperatures in near dry machining is considered by the change of cutting forces which lead to different heat intensities in the cutting zone. For the temperature rise in the chip on the tool-chip interface, the effects of the shearing heat source on the shear plane and the frictional heat source on the tool-chip interface are modeled as moving heat sources. Moreover, the reduction in the cutting temperatures is small by considering the lubricating effect as the reduction in cutting forces, and consequently the cooling effect on the tool flank wear face is insignificant when the differences in cutting forces between dry and near dry turning are small.

4.5 Cutting Temperature in NDM for AISI 9310

M. M. Rahman, M M A Khan and N R Dhar [6] focused on the effect of minimal quantity lubricant on chip-tool interface temperature under different cutting velocity and feed rate in turning of AISI 9310 steel. Chip-tool interface temperatures were measured for three different cooling types such as dry, wet and MQL conditions.

Experiments were carried out by plain turning a 100 mm diameter and 710 mm long rod of AISI-9310 steel of common use in a lathe at different cutting velocities and feeds under dry, wet and MQL by vegetable oil conditions to study the role of MQL on the machinability characteristics of AISI 9310 steel alloy in respect of cutting temperature. The experimental conditions are listed in Table 4.2. The ranges of the cutting velocity (Vc) and feed rate (So) were selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut was kept fixed to only 1.0 mm, which adequately served the purpose

.

Table 4.3 Experimental conditions for AISI 9310 steel

Machine tool	**Lathe Machine, 15 hp**	
Work specimens		
Material	:AISI 9310 steel (C-0.12%, Mn-0.55%, P-0.025%, Si-0.25%, Ni-3.4%, S-0.025%, Cr-1.3%, Mo- 0.14%)	
Hardness (BHN)	:257	
Size	:φ100 × 710 mm	
Cutting insert:	:Uncoated carbide, TTS, SNMG 120408 (P-30 grade) Composition: WC, TaC, TJC, Co Grain size: 1.4 μm	
Tool holder	:PSBNR 2525M12	
Working tool geometry	:Inclination angle	: -6°
	Orthogonal rake angle	: -6°
	Orthogonal clearance angle	: 6°
	Auxiliary cutting edge angle	: 15°
	Principal cutting edge angle	: 75°
	Nose radius	: 0. 8 mm
Process parameters		
Cutting velocity, V_c	:223, 246, 348 and 483 m/min	
Feed rate, S_o	:0.10, 0.13, 0.16 and 0.18 mm/rev	
Depth of cut, t	:1.0 mm	
Cutting Fluid	:Food-grade Vegetable Oil; Viscosity: 84 cP at 20°C and Flash Point: 340°C (open cup)	
MQL supply	:Air: 6 bar, Flow rate: 100 ml/h (through external nozzle).	
Environment	:Dry, Wet and Minimum Quantity Lubrication (MQL)	

Figures 4.5 and 4.6 show the effect of minimum quantity lubrication on average chip-tool interface temperature under different cutting velocity and feed rate as compared to dry and wet conditions. However, it is clear from the aforementioned figures that with the increases in Vc and So, average chiptool interface temperature increases as usual due to increase in energy input. The roles of variation of process parameters on percentage reduction of average interface temperature due to MQL have not been uniform. This may be attributed to variation in the chip forms particularly chip-tool contact length (CN) which for a given tool widely vary with the mechanical properties and behaviour of the work material under the cutting conditions. Post

cooling of the chips by MQL jet is also likely to influence θavg to some extent depending upon the chip form and thermal conductivity of the work materials.

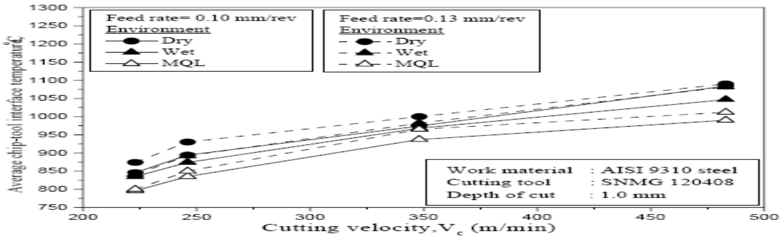


Figure 4.5: Variation in θavg with that of Vc and So in turning steel by SNMG insert under dry, wet and MQL cooling conditions at 0.10 and 0.13 mm/rev

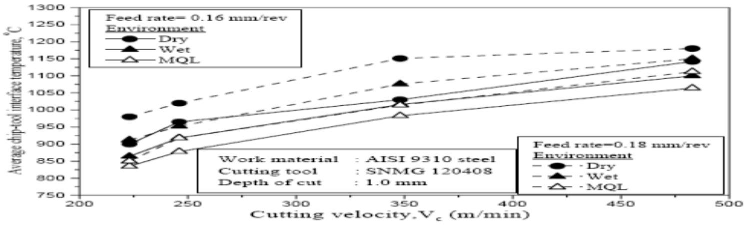


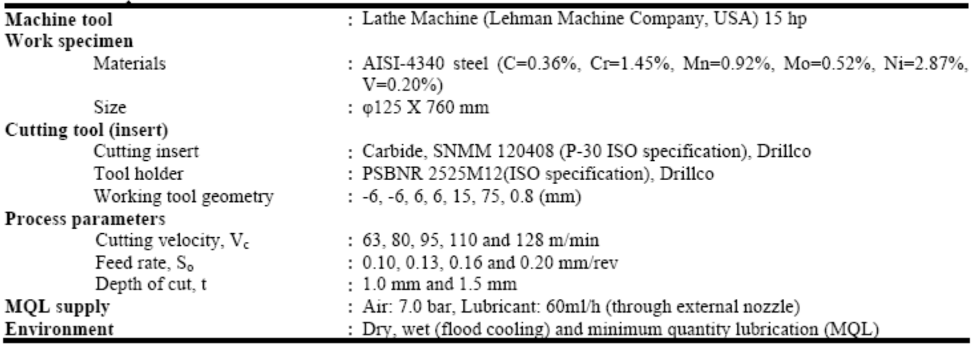
Figure 4.6: Variation in θavg with that of Vc and So in turning steel by SNMG insert under dry, wet and MQL cooling conditions at 0.16 and 0.18 mm/rev

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

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

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

Table 4.4 Experimental conditions for AISI 9310 steel



Machine tool	: Lathe Machine (Lehman Machine Company, USA) 15 hp
Work specimen	
Materials	: AISI-4340 steel (C=0.36%, Cr=1.45%, Mn=0.92%, Mo=0.52%, Ni=2.87%, V=0.20%)
Size	: φ125 X 760 mm
Cutting tool (insert)	
Cutting insert	: Carbide, SNMM 120408 (P-30 ISO specification), Drillco
Tool holder	: PSBNR 2525M12(ISO specification), Drillco
Working tool geometry	: -6, -6, 6, 6, 15, 75, 0.8 (mm)
Process parameters	
Cutting velocity, V_c	: 63, 80, 95, 110 and 128 m/min
Feed rate, S_o	: 0.10, 0.13, 0.16 and 0.20 mm/rev
Depth of cut, t	: 1.0 mm and 1.5 mm
MQL supply	: Air: 7.0 bar, Lubricant: 60ml/h (through external nozzle)
Environment	: Dry, wet (flood cooling) and minimum quantity lubrication (MQL)

The machining temperature at the cutting zone is an important index of machinability and needs to be controlled as far as possible. MQL was expected to provide some favorable effects mainly through reduction in cutting temperature. The effect of MQL on average chip-tool interface temperature (θavg) at different Vc and So under both dry and MQL conditions has been shown in Fig.4.6. It is evident from Fig.4.6 that during machining at lower Vc when the chip-tool contact is partially elastic, where the chip leaves the tool, MQL is dragged in that elastic contact zone in small quantity by capillary effect and is likely to enable more effective cooling. With the increase in Vc the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip-tool interface. MQL cooling effect also improved to some extent with the decrease in feed particularly at lower cutting velocity. Possibly, the thinner chips, specially at lower chip velocity, are slightly pushed up by the high pressure MQL jet coming from the opposite direction and enables it to come closer to the hot chiptool contact zone to remove heat more effectively. Further, at high velocity, the coolant may not get enough time to remove the heat accumulated at the cutting zone resulting in less reduction in temperature under MQL condition at high cutting velocity. However, it was observed that the MQL jet in its

present way of application enabled reduction of the average cutting temperature by about 5 to 10% depending upon the levels of the process parameters, Vc and So. Even such apparently small reduction in the cutting temperature is expected to have some favorable influence on other machinability indices.
Based on the results of the experimental investigation it was concluded that the cutting performance of MQL machining is better than that of dry and conventional machining with flood cutting fluid supply because MQL provides the benefits mainly by reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges.

4.7 Time saving in MQL

Apart from proving beneficial with regards to cutting temperature and subsequent machining parameters, near dry machining also helps to reduce the machining time and ultimately results in cost saving also. The reduction in machining time can be gauged from the following tabulated results.

V. Conclusions

Based on the study carried out it can presumed that MQL will deliver on the two factors of cutting temperature and surface roughness. From a total cost of ownership perspective, which considers machine cost, downtime, maintenance, floor space, electricity usage, coolant management and related factors, MQL will yield an improvement versus comparable wet operations. As for environmental impact, MQL can be a key factor in any plant's efforts in delivering no manufacturing by-products to landfill

.

Future Scope: There are also numerous other beneficial results that can be realized with the implementation of near dry machining, which can be enumerated as follows.Sensors, switches and electronics last much longer. Automation, a key component of any plant's machining processes, relies on switches, servos and other electronic elements that don't particularly like wet environments. In MQL, the plant may see a remarkable reduction in nuisance faults because there is no coolant that can find its way into electronic components. This ultimately leads to improved system uptime, which is vital for any high-production manufacturer. In addition, conveyors delivering parts in and out of cells will no longer need coolant-collecting pans underneath them, because there's no coolant to drip off of the MQL-machined parts being transferred. In wet operations, coolant left in conveyor catch pans for an extended period of time can become stagnant and malodorous.

Applications of MQL: As discussed above, the cutting tools should be designed for NDM. Not only should the aerosol-supply channels be suitable, but also the tool geometry, tool materials and design of the tool body (back tapers, reliefs, undercuts and supporting elements) should be optimized for NDM. Additional procedures in tool setting and maintenance as well as additional equipment for aerosol verification must be implemented and followed.

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