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Viability of Minimum Quantity Lubrication in turning operation on MS Brite

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Abstract— **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.**

Index Terms— **Aerosol, lubrication, Metal working fluids, MQL**

I. INTRODUCTION

Metalworking fluids (MWF) are known to provide many benefits to ensure that metal parts can be machined in a cost-effective manner. But metalworking fluids have undergone intense regulatory scrutiny during the last 15 years. There have been recent requirements to reduce the cutting fluids in mass production factories because of the high cost and harmfulness of the coolants, because of which in the current, competitive manufacturing environment, end-users of metalworking fluids are looking to reduce costs and improve productivity.

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.

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II. CLASSIFICATION OF MINIMUM QUANTITY LUBRICATION

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 placed in 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.

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.

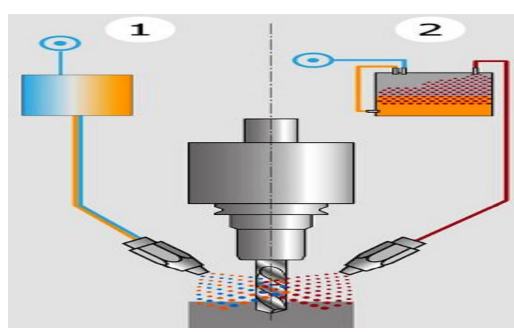

Figure 1.1 The two principles of MQL 1

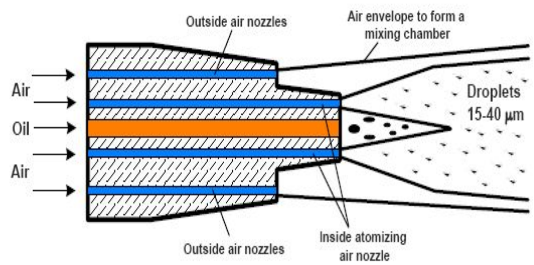

Figure 1.2 Nozzle design for MQL 1

MQL 1 is probably the cheapest and simplest method and 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

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

As the name implies, MQL with internal aerosol supply (MQL 2) includes internal passages for aerosol supply. There are two options in MQL 2: MQL 2 with an external atomizer and MQL 2 with an internal atomizer located in the spindle of the machine.

In MQL 2 with an external atomizer, the aerosol is prepared in an external atomizer and then supplied trough the spindle and the internal channels made in the tool. When MQL 2 with an external atomizer is used on machining centres or manufacturing cells, the aerosol supply unit has to react to the frequent tool changes that nowadays take only 1 or 2 s, setting the proper aerosol parameters for each given tool/operation. If the aerosol unit is shut down every time a tool change takes place then it requires some time to fill the whole system with aerosol again. The aerosol is produced continuously and supplied to the directional control valve, which allows aerosol into the spindle as soon as a tool change is over.

MQL 2 with an external atomizer has the following advantages:
- Lowest initial cost
- The possibility of keeping two cooling system on the machine: flood and MQL
- Relatively simple installation and control
- Accurate control of the aerosol parameters so that they can be easily adjusted by the machine controller for a given tool or even operation with the same tool

MQL 2 with an external atomizer has the following drawbacks:
- Spindle rotation creates a centrifugal force field that coats the wall of the aerosol delivery channel with oil that must be removed periodically. For a high-volume production manufacturing factory (plant, shop, line, cell), this downtime may be intolerable and costly. This additional cost can easily offset the savings on MQL.
- Special care should be taken of the position of the flexible line that connects the external aerosol unit with the spindle.

III. 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. 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 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.

IV. 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 paper 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.

V. Organization of the study

Dry machining has its advantages and associated drawbacks. The advantages of dry machining are obvious: cleaner parts, no waste generation, reduced cost of machining, reduced cost of chip recycling (no residual oil), *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. Machines and tools designed for MWFs cannot be readily adapted for dry cutting.

In MQL, an atomizer is used which is an ejector in which the energy of compressed gas, usually air taken from the plant supply, is used to atomize oil. Oil is then conveyed by the air in a low-pressure distribution system to the machining zone. As the compressed air flows through the Venturi path, the narrow throat around the discharge nozzle creates a Venturi effect in the mixing chamber, *i.e.*, a zone where the static pressure is below the atmospheric pressure (often referred to as a partial vacuum) [14, 10]. This partial vacuum draws the oil up from the oil reservoir where the oil is maintained under a constant hydraulic head. The air rushing through the mixing chamber atomizes the oil stream into an aerosol of micron-sized particles. The design of the atomizer is critical in MQL as it determines the concentration of the aerosol and the size of droplets. Unfortunately, this is one of the most neglected aspects in casual application of MQL.

VI. LITERATURE REVIEW

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. 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. Around the middle of the 19th century, during the Machine Age, *machining* referred to the "traditional" machining processes, such as turning, boring, drilling, milling, broaching, sawing, shapi ng, planing, reaming, and tapping. In these "traditional" or "conventional" machining processes, machine tools, such as lathes, milling machines, drill presses, or others, are used with a sharp cutting tool to remove material to achieve a desired geometry.

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.

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.

Review of some Other Studies on MQL

Wu and Chien evaluated MQL of three different steel materials [1]. 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.

Ueda T, Nozaki R, and Hosokawa A [2] 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.

Khan MMA and Dhar NR [3] found that MQL 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 [4] found the cutting forces in machining 1045 steel to be lower in MQL compared with dry cutting. They also attributed this reduction to the cutting temperature difference.

Dhar NR, Islam S and Kamruzzaman M studied the effect of MQL in tuning of 4340 steel using external nozzle and aerosol supply to the tool [5]. They 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 MQL compared to wet machining. As a result, tool life and finish of the machined surface improved by 15–20%. 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.

Filipovic A and Stephenson DA [6] did not find any difference in tool life in gundrilling and cross-hole drilling of crankshafts between wet machining and MQL.
Yoshimura H, Itoigawa F, Nakamura T and Niwa K [7] found that, in machining of aluminium, the cutting force is lower and the surface finish is better with OoW MQL compared with dry, traditional MQL and wet machining.
Obikawa T, Kamata Y and Shinozuka J [8] evaluated the performance of MQL 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.

VII. SYSTEM DEVELOPMENT

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. Although there have been 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.
Considering this very fact, 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.
Minimum quantity lubrication in machining refers to the use of cutting fluids of only a small amount, as an alternative to completely dry or flood cooling methods to address the environmental, economical, and mechanical process performance concerns. Many researches have suggested that MQL shows its potential competitiveness in terms of tool life, surface finish and cutting forces in turning, milling, drilling, reaming and taping. Most documented studies thus far concerning MQL are built upon experimental observations with individual and separate treatment of machining performance measures such as cutting force, cutting temperature, tool wear progress, chip formation, surface roughness, or air quality. Experimental measurement of surface finish, temperature and cost involved in MQL, and flood cooled turning cases will be considered to calibrate and validate the analytical predictive models.

Lubricant and Coolant cost

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.
The lubricant or coolant cost does not provide any direct value addition to the finished product. But machining is not possible without the use of coolant or lubrication. So it is a necessary evil. The use of minimum quantity lubrication can cut down the cost of lubrications as compared to flooded lubrication.

Cutting Temperature in 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 Li summarized and modified the work of previous researches to estimate the temperature distribution for a sharp tool in metal cutting. Temperature distribution on the tool-chip interface was attributed to the primary heat source (due to shear deformation in the shear zone) and secondary heat source (due to friction on the tool-chip interface) as specified in a moving oblique heat source model. For example, the heat generated by the friction on the tool-chip interface was considered as a moving heat source for any fixed point on the chip, while it was considered as a stationary heat source for any fixed point on the tool.

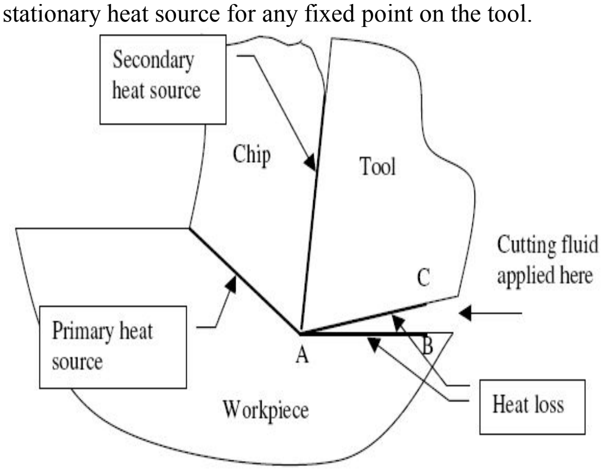

Figure 1.3: Heat sources and heat losses for the 2D model in near dry turning

The temperature in the chip is attributed to the primary heat source due to plastic shearing and the secondary heat source due to friction. The temperature in the tool is attributed to the secondary heat source, and the heat loss due to cooling on the tool flank face due to the air-oil mixture, while the rubbing heat source is also considered when the tool is worn. For a worn tool, the temperature on the interface between the tool flank face and the workpiece has to be estimated to calculate the heat partition factors on the tool-workpiece interface. This will be verified by experimental data of turning under near dry condition. The measured cutting forces are transferred to the equivalent cutting forces and thrust forces in orthogonal cutting according to the tool insert geometry. The obtained forces are the inputs to estimate the heat source intensities.

Surface finish in minimum quantity lubrication

Surface finish is one of the important parameters in machining. The value and quality of the product is decided by the surface finishing. The friction between tool and workpiece results in surface roughness. Lubrication reduces this surface roughness. In flooded lubrication a better surface finish is achieved. However it is important to analyse the comparison of surface finish with flooded lubrication and minimum quantity lubrication. The results of minimum quantity lubrication on surface finish will be studied and accepted only if the surface roughness is under acceptable tolerance limit.

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