The Experimental Evaluation of Environmentally Friendly Cutting Fluids in Micro-Milling

by

Yanqiao Zhang
BEng, Tianjin University, 2011,

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Abstract

In manufacturing, cutting fluids promote machining performance by removing heat, lubricating the cutting zone, flushing away chips, and preventing in process corrosion. To synthetize conventional metalworking fluids (MWFs), aside from choosing from a selection of base oils (straight oils, soluble oils, semisynthetic oils and synthetic oils), an array of additives are also typically added. In traditional cutting fluid applications, the cost of waste fluid treatment is enormous since at least two-thirds of used MWFs need to be disposed every year [1]. Moreover, the treatment is not always effective and disposal may lead to unexpected environmental contamination. The bacteria and chemical elements in the waste liquids may also introduce health and safety concerns.

For the milling process at the micro-scale, i.e., micro-milling, traditional flood cooling may not be suitable. Since the cutting zone between the tool flank and workpiece is in the order of micrometers, the liquid surface tension of flood coolant would impede effective cooling and lubrication of the cutting fluid especially at a high spindle speed for tools. So for micro-milling, some researchers have tried to use minimum quantity lubrication method to apply cutting fluids [2]. Other semi-dry methods like atomization method based on an ultrasonic atomizer [3] have also been tested. However, even though these systems are able to decrease the amount of cutting fluids, the atomization of conventional cutting fluids with harmful surfactants (especially water miscible MWFs) and additives inside would still pose problems related to health hazard and contamination. Thus, new systems and/or green cutting fluids that eliminate the use of undesired surfactants or
additives need to be developed. In this thesis, efforts to solve these problems for micro-milling operations are presented.

Firstly, canola oil is selected and used to be emulsified in distilled water through ultrasonic atomization without any surfactant. Then, the emulsified water and oil solution is applied as cutting fluid in micro-milling, and the cutting performance results are compared to those with dry machining and traditional cutting fluid – 5% TRIM aqueous solution. The experimental results show that smaller chip thickness, and burr amount are observed with canola oil-in-water emulsion compared to conventional MWF. Reduction of almost 30% in cutting forces has also been achieved.

Secondly, development of a new atomization-based cutting fluid system is introduced. Both cooling and lubricating capabilities of the cutting fluids are achieved using air-mixed water and oil mists, requiring no surfactants. Experiments are then conducted to evaluate the new system and the air-mixed jet of independently atomized water and oil sprays and compared to results with water only, oil only, and conventional cutting fluid (5% TRIM) conditions. The results reveal the mixture of water and oil leads to best performance in cooling and lubrication during micro-milling. The new system is proved to be effective in cooling and lubricating the cutting zone for both Al6061 and steel 1018. This atomization system is considered as a novel application method to apply totally green cutting fluids.

Finally, a novel environmentally friendly additive was added to conventional cutting fluids. In this thesis, lignin powder obtained from wood is considered as one kind of these “green” additives. It is firstly tried to be dissolved in 5% TRIM aqueous solutions in 8 different concentrations through injection and atomization methods. Then, those lignin containing cutting fluids are used to run micro-milling experiments and compared with 5% TRIM. Nine MWFs are all nebulized by a nebulizer to cool and lubricate the workpiece. The results show that the concentration of 0.015% lignin leads to the least cutting forces, tool wear and burrs. The obtained solution (f) with 0.15% lignin inside causes cutting forces that are just 50% in value of those with 5% TRIM. Considering lignin’s anti-oxidative characteristic and its performance in improving machining processes, it is a promising additive in MWFs.
Table of Contents

Supervisory Committee ................................................................. ii
Abstract .......................................................................................... iii
Table of Contents ........................................................................... v
List of Tables .................................................................................... vii
List of Figures ................................................................................... viii
Acknowledgments ............................................................................. xi
Chapter 1: Introduction .................................................................... 1
  1.1 Background and Motivation ....................................................... 1
  1.2 Research Objectives and Scopes ............................................... 3
  1.3 Thesis Outline ........................................................................... 4
Chapter 2: Literature Review ........................................................... 6
  2.1 Process Modeling in Micro-Endmilling .................................... 7
      2.1.1 Minimum Chip Thickness ($h_{\text{min}}$) Effect ..................... 7
      2.1.2 Cutting Force Model ....................................................... 9
  2.2 Cutting Fluid Application Systems ......................................... 12
      2.2.1 Flood Cooling (Wet Cooling) ....................................... 12
      2.2.2 Dry Machining ............................................................. 13
  2.3 Review of Different Kinds of Cutting Fluids ......................... 19
      2.3.1 Four Basic Types of Cutting Fluids ............................... 20
          2.3.1.1 Four Basic Types of MWFs .................................. 20
          2.3.1.2 Choice of Four Kinds of Cutting Fluids ............... 22
          2.3.1.3 Surfactants in Water Miscible Cutting Fluids ........ 24
      2.3.2 Conventional & Unconventional Cutting Fluids ........... 25
          2.3.2.1 Problems of Conventional Cutting Fluids ........... 25
          2.3.2.2 Unconventional (Sustainable) Cutting Fluids ....... 27
  2.4 Review of Different Kinds of Additives in Cutting Fluids .......... 35
      2.4.1 MWFs Additives .......................................................... 35
      2.4.2 Lignin as Additives in other Aspects ............................ 37
Chapter 3: Previously Developed Atomization-based Cutting Fluid System for Micro-
   Milling ........................................................................................... 41
  3.1 Ultrasonic Atomization System ............................................... 41
  3.2 Design Parameters of the Nozzle ............................................ 42
  3.3 Theory of Droplet Impingement Dynamics against Workpiece Surface ... 43
  3.4 Improvements based on Ultrasonic- Atomization System .......... 46
Chapter 4: Canola Oil in Water Emulsion as Cutting Fluids through Ultrasonic
   Atomization .................................................................................. 47
4.1 Canola Oil Emulsion in Water through Ultrasonic Atomization ........................................ 47
4.2 Experimental Setup and Cutting Conditions ........................................................................ 52
4.3 Performance of Canola Oil Emulsion in Water as MWF for Al6061 and Steel 1018 .......................................................... 54
  4.3.1 Experimental Results for Al6061 .................................................................................. 54
  4.3.2 Experimental Results for Steel 1018 .......................................................................... 60
  4.3.3 Conclusions and Discussion ...................................................................................... 65
Chapter 5: Mixed Jet of Independently Atomized Water and Oil Sprays as Cutting Fluids in Micro-milling .......................................................... 67
  5.1 Mixed Jet System including Ultrasonic Atomizer and Nebulizer .................................. 68
  5.2 Machining Setup and Cutting Conditions ....................................................................... 72
  5.3 Experimental Results for Al6061 .................................................................................... 73
    5.3.1 Results at the Feed Rate of 0.3 and 1.0µm/tooth ...................................................... 73
    5.3.2 Results at the High Feed Rate of 2.0µm/tooth ......................................................... 80
  5.4 Experimental Results for Steel 1018 .............................................................................. 81
  5.5 Conclusions and Discussion .......................................................................................... 86
Chapter 6: Lignin as Additive in Metalworking Fluids for Micro-Milling ........................................ 88
  6.1 Synthesis of Lignin Containing Cutting Fluid ................................................................. 88
    6.1.1 Injection and Atomization Methods ......................................................................... 90
    6.1.2 Lignin Containing Solutions .................................................................................. 92
  6.2 Experimental Setup and Cutting Conditions .................................................................. 94
  6.3 Performance of Lignin as Additive in Cutting Fluids in Micro-milling ......................... 95
    6.3.1 Experimental Results of Machining Al6061 with 396 µm End Mill ......................... 95
    6.3.2 Experimental Results of Machining Al6061 with 1.6 mm End Mill ...................... 99
    6.3.3 Experimental Results of Machining Steel 1018 with 1.6mm End Mill ............... 102
  6.4 Conclusions .................................................................................................................. 104
Chapter 7 Conclusion and Future Work .................................................................................. 106
  7.1 Conclusions .................................................................................................................. 106
  7.2 Future Work .................................................................................................................. 108
Bibliography .......................................................................................................................... 110
List of Tables

Table 1: Selection of MWFs for general workpiece and machining conditions.............. 23
Table 2: Weber number ranges for different impingement regimes.............................. 45
Table 3: Critical value of no-dimensional parameter for spread to splash regime transition. ........................................................................................................................................... 45
Table 4: Number of slots machined for steel before tool failure. .................................. 61
Table 5: Peak-to-valley forces of each slot................................................................. 81
Table 6: Total number of slots cut. .................................................................................. 84
Table 7: Generated 8 lignin-Trim aqueous solutions..................................................... 92
## List of Figures

Figure 2- 1: Schematic of minimum chip thickness effect .................................................. 8
Figure 2- 2: Schematic of the workpiece-tool interference model ....................................... 9
Figure 2- 3: Shearing and plowing mechanisms in endmilling cutting force model ............. 10
Figure 2- 4: Flood cooling system in machining .................................................................. 13
Figure 2- 5: Benefits of dry machining ................................................................................ 15
Figure 2- 6: Structure of the CFSytem ............................................................................... 26
Figure 2- 7: Lignin powder .................................................................................................. 38
Figure 2- 8: A possible lignin molecular structure ................................................................. 38
Figure 3- 1: The design of the atomization-based cutting fluid application system. [3] .. 42
Figure 3- 2: Four different nozzle geometries studied ......................................................... 42
Figure 3- 3: Experimental photographs of the spray with different nozzle geometries.... 43
Figure 3- 4: Droplet impingement regimes .......................................................................... 44
Figure 4- 1: A schematic of the experimental setup to test emulsification of vegetable oil in water.............................................................................................................................. 48
Figure 4- 2: A photograph of the experimental setup ............................................................ 49
Figure 4- 3: A photograph of canola oil added to water within atomization chamber .... 50
Figure 4- 4: A photograph of the collected solutions at different oil percentages in the atomization chamber.............................................................................................................................. 50
Figure 4- 5: A photograph of oil droplets observed under a microscope: (a) ultrasonically atomized oil droplets and (b) oil droplets within conventional MWF (TRIM®) at 5% concentration (scale bar = 50 µm). ................................................................. 51
Figure 4- 6: A photograph of the collected solution and solution form the atomization chamber at 20% oil. ................................................................................................................................. 52
Figure 4- 7: Possible regimes of emulsification through ultrasonic atomization ............... 52
Figure 4- 8: Photographs of Alio micro-machine system ..................................................... 53
Figure 4- 9: Experimental setup for micro-milling operations ............................................. 54
Figure 4-10: Raw force figure.............................................................................................. 55
Figure 4-11: Peak-to-valley forces with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0µm/tooth ......................................................................................................................... 57
Figure 4-12: Tool wear photographs at different MWF conditions after milling 25 slots. ........................................................................................................................................................................ 58
Figure 4-13: SEM photographs of generated chips with dry, TRIM 5%, and canola oil-in-water emulsion (scale bar = 50 µm). ................................................................................................................. 59
Figure 4-14: SEM photographs of chip thickness at the feed rate of 1.0 µm/flute with dry, TRIM 5%, and canola oil-in-water emulsion (scale bar = 5 µm). .......................................................................... 59
Figure 4-15: Photographs of slots’ burrs on the top surfaces ............................................. 60
Figure 4- 16: Average resultant cutting forces over the number of slots machined before tool failure with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0 μm/tooth................................................................. 62
Figure 4- 17: Tool wear photographs at different MWF conditions after milling 2 slots. 63
Figure 4- 18: SEM photographs of generated chips with dry, 5% TRIM and canola oil-in-water emulsion (scale bar = 400μm).................................................................. 64
Figure 4- 19: SEM photographs of chip thickness with different cutting fluid conditions at the feed rate of 1.0μm/flute (scale bar = 10μm). ............................................... 64
Figure 4- 20: Photographs of burrs formed on slot top surfaces after machining two slots at the feed rates of 0.3 and 1.0 μm/tooth. ................................................................. 65
Figure 5- 1: A schematic overview of the system that applies a mixture of oil and water droplets as a spray jet................................................................. 68
Figure 5- 2: The experimental setup and working principle of ultrasonic atomization device................................................................. 69
Figure 5- 3: A photograph of nebulizer and the schematic of the structure inside........... 70
Figure 5- 4: a photograph of the developed system................................................... 72
Figure 5- 5: Cutting fluid application system with nebulizer........................................ 73
Figure 5- 6: Peak-to-valley forces with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0 μm/tooth................................................................. 75
Figure 5- 7: Average peak-to-valley forces with different cutting fluid conditions at the feed rates of 0.3 and 1.0 μm/tooth................................................................. 76
Figure 5- 8: Tool wear photographs at different MWF conditions after milling 25 slots. 77
Figure 5- 9: SEM photographs of generated chips (scale bar = 500 μm). ...................... 78
Figure 5- 10: SEM photographs of chip thickness at the feed rate of 0.3 and1.0 μm/tooth (scale bar = 10 μm). ................................................................. 79
Figure 5- 11: Photographs of burrs formed on 25th slots’ top surfaces.......................... 80
Figure 5- 12: Lengths of all machined slots at different MWF conditions at the feed rate of 2.0μm/tooth................................................................. 81
Figure 5- 13: Resultant cutting forces with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0 μm/tooth................................................................. 83
Figure 5- 14: Tool wear photographs at different MWF conditions after milling 2 slots. 85
Figure 5- 15: Photographs of burrs formed on slot top surfaces.................................... 86
Figure 6- 1: Auto-Sonicator................................................................. 89
Figure 6- 2: Lignin powder with 5% TRIM through sonication in the bottle.................... 89
Figure 6- 3: Injection method................................................................. 91
Figure 6- 4: Atomization method.............................................................................. 91
Figure 6- 5: Eight lignin containing solutions............................................................. 93
Figure 6- 6: Lignin particles in generated solutions (scale 900μm ×1200μm).................. 94
Figure 6- 7: Average resultant forces with different lignin added cutting fluids............ 97
Figure 6-8: Tool wear photographs under different MWF conditions after milling 25 slots of Al6061 at the feed rate of 0.3µm/tooth.

Figure 6-9: Photographs of machined surfaces with different cutting fluids.

Figure 6-10: Average resultant cutting forces of machining Al6061 with 1.6 mm diameter end mill.

Figure 6-11: Tool wear photographs under different MWF conditions after milling 25 slots of Al6061 at the feed rate of 1.0 µm/tooth with 1.6 mm diameter tool.

Figure 6-12: Photographs of machined surfaces with 1.6 mm end mill under different fluid conditions.

Figure 6-13: Peak-to-valley values of resultant forces with steel 1018 as work material.

Figure 6-14: Peak-to-valley of resultant forces averaged over five slots under different fluid conditions.

Figure 6-15: Photographs of machined slots and burrs with steel 1018 under different fluid conditions.
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Chapter 1: Introduction

1.1 Background and Motivation

In recent decades, the negative impacts of conventional cutting fluids are becoming more and more prominent. Traditional metalworking fluids (MWFs) are effective in cooling, lubrication and carrying away chips during machining operations such as drilling, turning and grinding. And flood cooling is the most used method of MWFs. In this type of application, cutting fluids are sprayed out through nozzles to the workpiece and the quantity of cutting fluids is substantial. It is reported that over 7.5 billion liters of cutting fluids were used by North American manufacturers in 2002 [4]. It’s pretty costly to treat waste fluid and the disposal may lead to unexpected environmental pollution since most of the MWFs are petroleum or mineral based oils. Those normally used surfactants to emulsify water with oil and additives in conventional cutting fluids also contain organic sulfur, chlorine, nitrite elements that are harmful to the human body and environment. Moreover, bacteria and fungi may breed in some soluble oil emulsions that are deleterious to human body. The US National Institute for Occupational Safety and Health (NIOSH) estimates that 1.2 million workers are exposed to MWFs annually and reports health-related issues such as dermatitis and respiratory disease due to exposure to MWFs [5].

Many researchers are trying to solve those problems through new discoveries and technologies. Recently, considering the large amount of waste liquids from manufacturing, manufacturers have applied dry machining as well as minimum quantity lubricant (MQL) strategies involving low-volume sprays of oil delivered in compressed air. Dry machining without any metalworking fluids may solve the contamination
problems but the high temperature of the cutting zone would result in fast worn tools and rough machined surface. Thus, creative ways to cool down the workpiece should be discovered when dry machining is applied. The MQL approach can also eliminate large volumes of aqueous waste, thereby reducing environmental burdens [6]. Boubekri and Shaikh [7] have figured out that MQL application in machining shows better results in certain operations including drilling, a cleaner environment and to be a more cost-effective machining technology. Another example is that Barczak et al. [8] conducted a study of plane surface grinding under MQL conditions comparing with traditional flood cooling. They found that low friction conditions, a reasonable specific material removal rate and better workpiece quality can be achieved under MQL conditions. Although the findings above, MQL cannot be universally applied since it does not provide sufficient cooling for many operations [9]. Also, very hard materials and high cutting speed may not be suitable for MQL.

To solve the use of petroleum-based cutting fluids and additives, efforts have been made to use vegetable-based fluids. For example, a development of environmentally adapted lubricants (EALs) using vegetable-based lubricants instead of the petroleum-based is made. EALs have high biodegradability and low toxicity with performance equal to or better than conventional MWFs [10]. However, EAL-based MWFs can harbor bacteria as well as their byproducts and still contain surfactants, biocides, and defoamers [11].

Recently, for micro-milling operations, since flood cooling is not appropriate due to the liquid surface tension, an atomization-based MWF application has been introduced by Jun et al. [12]. The atomization-based system has been demonstrated to be quite effective
in micro-milling operations. However, they still used conventional cutting fluids, which contain harmful surfactants and additives. The atomization-based method usually generates mist that consists of fine droplets smaller than 10 µm in diameter and can be harmful to respiratory systems. Thus, there is a strong need for elimination of harmful surfactants and additives when the atomization-based cutting fluid application systems are used.

This thesis focuses on improvement of the atomization-based systems such that the problems related to health hazard and contamination can be addressed. Thus, methods to eliminate the use of surfactants and additives are investigated while maintaining the cooling and lubricating capabilities of the atomization-based cutting fluid system. Also use of a new non-toxic additive is investigated.

1.2 Research Objectives and Scopes

In general, three main aspects are considered for improvement: cutting fluids, cutting fluid application method, and additives in cutting fluids. Thus, the following three main objectives are achieved in this thesis:

- Development of vegetable oil-in-water emulsion through ultrasonic atomization without any surfactant to be used as cutting fluids in micro-milling;
- Development of a novel atomization MWFs application system that uses a mixed jet of independently atomized distilled water and canola oil;
- Feasibility study of using lignin, a natural element abundant in woods, as an additive in cutting fluids for micro-milling operations.

Although the presented methods in this thesis can be applied to different machining processes, the scope of the experimental evaluation of the methods is limited to micro-
milling operations. Also, the atomization-based cutting fluid system is used for all evaluation experiments although the knowledge obtained in this thesis can be applied to other methods such as conventional MQL approaches.

1.3 Thesis Outline

The aim of this thesis is to provide three novel methods to solve conventional cutting fluids and MWFs application systems’ problems for micro-milling. Chapter 2 will offer a review of micro-end milling theory, cutting fluids’ current situation including surfactants and additives inside and the existing relevant research for sustainable MWFs and their application systems.

In Chapter 3, the atomization-based cutting fluid system previously developed is summarized. Then, experiments related to the nozzle geometries and spray velocities of the atomization system to study formation of a focused spray jet are described. The droplet impingement dynamics against workpiece surface is described, which is important for the use of the atomization-based system. In the subsequent chapters, improvements made to the atomization-based system as described before are presented.

In Chapter 4, vegetable oil-in-water emulsion is achieved using ultrasonic atomization without using any surfactant. The emulsified oil-in-water solution is applied as metalworking fluid in micro-milling to compare with dry machining and conventional cutting fluid – 5% TRIM aqueous solution. The experimental results in forces values, tool wear, slots’ burrs and chips morphology are then discussed.

In Chapter 5, an independently atomized and air-mixed water and oil jet system for micro-milling is presented. Cutting performance results with water only, canola oil only, and 5% TRIM are compared to those with separately atomized water and oil mixture as
MWFs in micro-milling. The effectiveness of this novel atomization-based system is evaluated for different workpiece materials and feed rates.

In Chapter 6, lignin powder obtained from wood is considered as one kind of the “green” additives, it is added to 5% TRIM aqueous solutions in 8 different concentrations through injection and atomization methods. Then, those lignin containing cutting fluids are applied to micro-milling experiments and the cutting performances are compared with the results when only 5% TRIM cutting fluid is used. Performances are compared in terms of resultant forces, tool wear and burr formations.

Finally, Chapter 7 summarizes the research work and outlines the future work.
Chapter 2: Literature Review

In this chapter, the background knowledge and relevant research are reviewed.

Firstly, process modeling in micro-endmilling including minimum chip thickness ($h_{cmin}$) effect and cutting force model are carefully studied. Owing to the cutting forces and tool wear produced in machining processes, suitable cutting fluids through appropriate application systems are required to cool and lubricate the cutting zone.

According to the problems to dispose substantial amount of cutting fluids, description and recent work of dry machining and MQL technologies are reviewed compared with flood cooling. For specific micro-milling, flood cooling is not appropriate since the liquid surface tension may inhibit cutting fluids going into the cutting zone to effect. So MQL or atomization system have been tried to replace flood cooling in micro-milling as well.

Although MQL or atomization method can decrease the amount of metalworking fluids during manufacturing, the droplets or moisture of conventional cutting fluids atomized by them are harmful to the environment and human body when MWF mist is inhaled. Therefore, environmentally friendly cutting fluids with nontoxic surfactants and green additives inside are required. Thus, the classification of cutting fluids is reviewed in this section. And sustainable and environmental friendly MWFs including vegetable oil-based cutting fluids are intensively introduced. Last is the description of normally used additives in MWFs. Lignin powder obtained from wood is considered as a kind of green additive but it has never been tired in cutting fluids. So it’s applications as additive in other fields are review in this section as well. The literature review provides a lot of information for the experiments in later chapters.
2.1 Process Modeling in Micro-Endmilling

To analyse the experimental results correctly, it is essential to understand the process modeling in micro-endmilling. In micro-endmilling, there are several special mechanisms such as minimum chip thickness \((h_{cmin})\) effect, elastic recovery effect and plowing mechanism. Because of the minimum chip thickness \((h_{cmin})\) and plowing force component, the tool behaves totally different in micro-endmilling which results in district dynamic response to the micro-endmill. Thus, work regarding minimum chip thickness \((h_{cmin})\) effect and modeling of plowing force components is presented in this section.

2.1.1 Minimum Chip Thickness \((h_{cmin})\) Effect

The schematic explaining the principle of the minimum chip thickness \((h_{cmin})\) effect is shown in Figure 2-1. In case (a) and (b), the uncut chip thickness \((h_c)\) is less than the minimum chip thickness \((h_{cmin})\), so the area just deforms under the edge of the tool and there is no chips coming out. Only if the uncut chip thickness \((h_c)\) is greater than the minimum chip thickness \((h_{cmin})\) as in case (c), the chips start to form. Yuan et al. [13] has investigated the minimum chip thickness \((h_{cmin})\) effect with two mills with different edge radii of 0.3 and 0.6 \(\mu m\). He found that the critical value of \(h_{cmin}\) is approximately 30 \% of the tool edge radius. Besides, the minimum chip thickness \((h_{cmin})\) is found to have different values depending on the materials like aluminum and copper [13, 14]. It was figured out that Copper has lower minimum chip thickness \((h_{cmin})\) value in half than the aluminum.
Figure 2-1: Schematic of minimum chip thickness effect.

Vogler et al. [15, 16] once attempted to incorporate the minimum chip thickness effect in machining model. They found that the workpiece elastically deforms without any chip formation in the condition of the chip thickness $(h_c)$ less than the minimum chip thickness $(h_{cmin})$. Then, the deformed material will fully recover after the tool pass. According to the law of elasticity, deformation forces are proportional to the volume of the interface between the workpiece and the tool flank. The workpiece-tool interference model was developed by Wu [17] as shown in Figure 2-2. Wu noticed the minimum chip thickness effect increased the cutting forces and lowered surface quality, especially at the low feed rates. Liu et al. [18] then developed the force model by including micro-endmilling vibrations. He explained the instability was due to feed rates and the volume of the material recovering elastically.
It has been discussed that only elastic deformation occurs in case of plowing/rubbing when the chip thickness is less than the minimum chip thickness. However, in most of the cases in real manufacturing, chips and burrs formed on the machined surface suggest that the tool workpiece interaction is more likely to be elastic-plastic. More complicated slip-line plasticity models are required considering elastic-plastic deformation and elastic recovery.

2.1.2 Cutting Force Model

According to minimum chip thickness \( (h_{cmin}) \) effect, two mechanisms can be separated in endmilling cutting force model. Figure 2-3 shows the sectional drawing in vertical view during endmilling processes. The dashed area is the chip formation area. Practically, this area is a curved slice. When uncut chip thickness \( h_c \) is larger than \( h_{cmin} \), chips are cut out and only shearing mechanism works in this area. On the contrary, when \( h_c \) is smaller than \( h_{cmin} \), there are no chips coming out. In this condition, plowing mechanism effects in this area, which means a part of this workpiece surface plastically deforms and the other part obeys the elastic deformation, recovering after the tool path.
Figure 2-3: Shearing and plowing mechanisms in endmilling cutting force model.

Referring to cutting forces, the shearing mechanism is the most common method to obtain the forces’ values. As introduced in Figure 2-3, Albrecht [19] theorized the plowing mechanism was the second most dominant mechanism that affects the machining forces after the shearing mechanism. It is desired to have a micro-endmilling force model that includes these effects.

Jun et al. [20] pointed out that when the edge radius is large relative to the feed rate value, the overall material removal process in micro-endmilling is influenced by three types of mechanisms. When the uncut chip thickness $t_c$ is smaller than a certain critical value $t_{ce}$ (minimum chip thickness), only elastic deformation happens, and the deformed material will fully recover to its original position. As $t_c$ increases beyond $t_{ce}$, the deformation of the workpiece becomes mixed elastic-plastic mechanism. In this case, a constant percentage of the workpiece material follows elastic recovery while the other material undergoes plastic deformation. When $t_c$ increases to the value of minimum chip thickness $t_{cmin}$, the deformed material will be removed as a chip and the elastic recovery rate decreases to zero. Thus, in micro-endmilling, a comprehensive method to calculate the dynamic chip thickness needs to include the effects of not only the cutting parameters
and dynamic vibrations but also the elastic recovery from the previous tooth path. There is no perfect mechanism of cutting force model for micro-endmilling until now even though researchers are trying to found more improved mechanisms.

The discrete simulation of cutting forces in end milling in Yusuf Altintas’ article [21] is still the most common used method in calculating cutting forces. The accuracy of the cutting force prediction strongly depends on the selected digital integration interval. The brief calculating process is below.

For each digital integration interval, the basic parameters are the integration height $\Delta \alpha$, feed per tooth $c$, inclination angle from the tip of tool to the position of the cutting height $\Phi$, and four cutting constants: $K_{tc}, K_{rc}, K_{te}, K_{re}$. The chip thickness at one certain point is obtained from the equation below:

$$ h = c \sin \Phi $$

Then the differential tangential and radial forces are:

$$ \Delta F_t = \Delta \alpha (K_{tc}h + K_{te}) $$

$$ \Delta F_r = \Delta \alpha (K_{rc}h + K_{re}) $$

And the differential feed and normal forces are:

$$ \Delta F_x = -\Delta F_t \cos \Phi - \Delta F_r \sin \Phi $$

$$ \Delta F_y = \Delta F_t \sin \Phi - \Delta F_r \cos \Phi $$

Summing the differential feed and normal forces together separately:

$$ F_x = \sum \Delta F_x $$

$$ F_y = \sum \Delta F_y $$
Finally the resultant force value at this immersion angle $\Phi$ can be achieved.

$$F = \sqrt{Fx^2 + Fy^2}$$ \hfill (2.8)

In real end milling processes’ analysis, programming is made use of to calculate the accurate values of cutting forces. Normally the inputs are cutting conditions, tool geometry, cutting constants, integration angle and integration height.

Through the introduction of force modeling, it indicates that when cutting parameters are given, cutting fluids are required to cool and lubricate the cutting zone in order to decrease the cutting forces. And the relatively low cutting forces would result in longer tool usage and better surface finish. In the next section, cutting fluids will be discussed in detail.

### 2.2 Cutting Fluid Application Systems

#### 2.2.1 Flood Cooling (Wet Cooling)

In manufacturing industry, the common methods to apply cutting fluids include flooding, misting, spraying, dripping and brushing. Among them, flood cooling is the most universal way. Flood cooling with nozzles or jets has been used as a standard method for coolant application for more than a century. The general machining condition of flood cooling is shown in Figure 2-4. The cutting fluids are sprayed out through nozzles or jets to the workpiece and the quantity of cutting fluids is pretty large. As referred before, the disposal of the huge quantity of waste metalworking fluids brings about big problems to environment and human health. The strict work safety and environmental legislation to treat the waste liquids in turn mean more economic problems for manufacturing companies. Surveys carried out in the German automotive industry [22] show that the deployment of cutting fluids accounts for 7-17% in total workpiece-
related manufacturing costs, which is several times higher than tool costs [23–27]. Due to these problems, novel MWFs application systems need to be discovered to save the amount of waste liquids.

Figure 2-4: Flood cooling system in machining.

Except for those above, there are still several fundamental requirements that should be considered. The closer nozzle position to the cutting zone, suitable nozzle design and critical areas of fluid delivery are essential. Besides, the cutting fluid ejecting speed is best to be at 100% to 120% of the tool velocity.

In micro-milling, since the cutting tools are normally of the magnitudes of 10³, 10² or even 10μm, the application of flood cooling may not be so effective due to liquid surface tension especially at a very high spindle speed. The spray of metalworking fluids is relatively difficult to go into the cutting zone to work.

2.2.2 Dry Machining

To reduce the used amount of cutting fluids in manufacturing, dry and semi-dry
machining are tried to be popularized by researchers in recent years. According to Weinert et al. [28], the main benefits of dry machining are presented in Figure 2-5. Before reviewing developments of dry cutting, an introduction of the fundamentals of technological aspects should be made. Since coolant functions are not available in dry machining, there is more friction and adhesion in the interface between workpiece and tool. Thus, the temperature and thermal load for tools and workpieces are higher than wet cooling. This may lead to more serious tool wear, ribbon and snarled chips, higher cutting forces which are undesirable in real machining. On the contrary, dry cutting may have positive effects like a reduction in thermal shock. Sreejith and Ngoi [29] point out that since some of the benefits of cutting fluids are not available in dry machining, dry machining is acceptable only if the part quality and machining time achieved in wet cutting are equalled or surpassed. In dry machining, appropriate measures should be taken to compensate for the primary functions of cutting fluids such as cooling, lubrication and chips’ removal. In Sreejith and Ngoi’s research, they suggest an indirect contact of coolants as one approach towards dry machining which can take the heat of the cutting zone and tools.

- An under-cooling system in which the coolants can flow through channels under the insert, then go out to the environment.
- Internal cooling by a vaporisation system, where a vaporisable liquid is inside the shank of the tool and vaporised on the underside surface of the insert.
- Cryogenic system with a stream of cryogenic liquid is routed through a conduit inside the tool.
- A thermoelectric cooling system applying a module of couples of thermoelectric
material elements.

Three other primary solutions are using appropriate materials for tools and workpiece, and doing coating on the cutting tools. The tool requirements include the development of refractory-type tool materials, the use of ultra-hard tool materials like diamond and CBN and the application of coatings on tools. Those selections may withstand high temperatures, reduce cutting energy or even provide a lubricating effect for decreasing friction. For tool coating technologies, Jayaram et al. [30] have tried to improve the properties of tool coating materials by reducing the spatial scale of the material system to nanometer dimensions. Their studies indicate that nano-coatings may significantly improve the hardness, toughness and modulus of the tool so that they are able to behave better in friction, wear and lubrication.

![Figure 2-5: Benefits of dry machining.](image)

Klocke et al. [22] have summarized the performances of dry machining in cutting cast
iron, steel and aluminum materials. The dry machining on cast iron has already been tried by G. Spur and U. Lachmund using ceramic cutting materials and CBN at high feed rates and surface speeds. They find that CBN tools have the highest thermal conductivity when compared with other ceramic type of tools so that they are pretty suited for dry machining on cast iron. Aluminium and its alloys have relatively high thermal conductivity so the workpiece can absorb much heat from machining and cause deformation. Thus, when cutting those materials, tools need to be coated without cutting fluids. In addition, for interrupted cutting, dry machining is a better choice rather than wet machining.

Above all, dry machining is only feasible when all the operations can be done dry. More skills and technologies are requested in dry machining to compensate the defects for the absence of coolants.

2.2.3 Minimum Quantity Lubrication (MQL) System

Among semi-dry machining, minimum quantity lubrication system is the most popular skill. In recent years, many developments and creative ideas about it have been generated. Now we will introduce MQL and those novel discoveries about it.

The concept of MQL was proposed a decade ago as a mean for addressing the problems of environmental contamination and potential hazards related to airborne cutting fluid particles. The MQL technique refers to misting or atomizing a very small amount of cutting fluid, normally in a flow rate of 50 to 500 ml/hour, in an air flow directed to the cutting zone \[31\]. Typically, the lubricants are sprayed through external supply system with one or more nozzles. Tests indicate that the amount of MWFs in MQL is nearly 3 to 4 orders of magnitude lower than that in conventional system including flood cooling. Taking advantage of this technology, a little fluid can make a
significant difference. In MQL, except for cutting performances, secondary characteristics are also important including safety properties, biodegradability, and oxidation.

Filipovic and Stephenson [32] summarize in their paper that external spray and through-tool are the two basic types of MQL delivery systems. In the external spray system, a cutting fluid reservoir is usually assembled besides the machine and the nozzles directed to the cutting zone are connected to the reservoir through tubes. This kind of system of MQL is economical and portable for most of machining operations. For through-tool system, there are two configurations available according to the way to create air-oil moisture. The first configuration is external mixing of oil and air and piping the mixture through the spindle or tool to the cutting zone. The other method is internal mixing oil and air. The most common structure of it is two parallel tubes’ routing through the spindle to bring them to an external mixing device besides the tool holder where the mist can be created. The first method is simple and inexpensive. Nevertheless, the second way has less dropouts and dispersion and can deliver mist with larger droplets’ sizes. The internal system offers more effective cooling and lubrication for workpiece than the external spray.

MQL produces small droplets that can massively go into the cutting zone in micro-milling, which performs much better than flood cooling. And the recent MQL applications in unique milling operations are introduced below. In June 2009, a study [33] was conducted by Heisel and Schaal to investigate the influence of burr formation using MQL in up-, down- and face-milling. The main results suggest that variation in cutting speed has no influence on burr formation. However, varying feed per tooth increases the
burr value in dry machining and MQL. The supply of the fluid through an external nozzle is proved to be disadvantageous. Similar work [34] has been done to investigate the effects of MQL in high-speed end milling of AISI D2 cold worked die steel. The tool performances of Ti0.75Al0.25N and Ti0.69Al0.23Si0.08N coated carbides end-mills are compared with flood cooling, dry and MQL conditions. The findings indicate the MQL shows maximum cutting length with minimum flank wear followed by dry cutting and wet cutting. Ti0.69Al0.23Si0.08N coating was better than Ti0.75Al0.25N coating. In addition, Liao and Lin [35] have made experiments to watch the mechanism of MQL in high-speed milling of hardened steel comparing with dry cutting. The results show that resultant forces and surface roughness with MQL are less than dry machining. Tool is maintained better in MQL under all cutting speeds. SASAHARA et al. [36] have applied MQL to the helical feed milling hole-making process on aluminum alloy in 2008. The experiments show that the shape error is decreased, a burr formation is decreased, machining temperature becomes low and the cutting force becomes small comparing with drilling process with flood coolant. Besides, Bruni and d’ Apolito et al. [37] have tested their surface roughness modeling in finish face milling under MQL and dry cutting conditions. In their experiments, they consider different cutting speeds and lubrication cooling conditions (dry, wet and MQL), in finish face milling of AISI 420 B stainless steel. They discover that MQL lubrication cooling technique provides very low surface roughness than dry and wet machining. Minimum quantity lubrication seems to be a prospective way to apply metalworking fluids in the future. Moreover, Khan et al. [38] have tried to present the effects of MQL using vegetable oil-based cutting fluid in turning on low alloy steel AISI 9310 with comparison to completely dry and wet cutting. Their
performances are tested in chip-tool interface temperature, chip formation, surface roughness and tool wear. It is seen from the experimental results that MQL with vegetable oil as MWF behaves much superior to reduce cutting zone temperature, enable favorable chip formation, enhance tool life and surface finish. Furthermore, MQL may maintain clean and dry working area, and avoid health hazards owning to heat, fumes, smoke, gases, etc. at the same time. Compared with wet cooling, the small droplets that are broken into through MQL can easily go into the cutting zone between the workpiece interface and highly rotating tool to play the role in cooling as well as lubricating. Thus, combining the research review above, it presents that MQL is suitable for micro-milling to some extent.

Despite of its advantages in many cases, MQL still has some limitations. Firstly, MQL applications generate mist that should be effectively controlled especially when oil-based metalworking fluids are atomized. Secondly, additional testing is required for more types of materials. For example, aluminum machining includes sensitivity to surface finish due to a tendency of the material to create a built-up edge on the tool. Besides, MQL has been proved to work well in short-term tests in a range of operations. But long-term performance and robustness are still unanswered. Finally, in the pretty high-speed cutting condition, the application of MQL is inappropriate, which, can be justified in Chapter 4 on cutting Al6061 blocks. So much more work should be done in this field.

2.3 Review of Different Kinds of Cutting Fluids

Cutting fluids are used to improve the efficiency of metal cutting operations in terms of increasing tool life or improving surface finish. They may also reduce cutting forces, and thus the power required may be less. Increased tool life may also be expressed as closer
dimensional control of the finished workpiece, resulting from slower rate of tool wear.

Cookson [39] has already classified cutting fluids into four basic types in his research early in 1977 based on MWFs’ physical & chemical properties and compositions. In this section, his work is firstly is reviewed. Then the pollution and safety problems of conventional MWFs are presented. Due to those problems, MWFs are then sorted into conventional and sustainable cutting fluids including vegetable oil-based MWFs. The advantages and disadvantages of them are carefully discussed.

2.3.1 Four Basic Types of Cutting Fluids

2.3.1.1 Four Basic Types of MWFs

From the simple introduction of cutting fluids, we can know cutting fluids have beneficial effects on manufacturing. And the normally used cutting fluids may be assorted as follows.

① Water Miscible

Soluble oils are emulsions or suspensions of oil droplets in water maintained by the existence of emulsifying agents. This type of cutting fluids is the most used MWF in manufacturing. The common soluble-oil cutting fluids have large droplets which can reflect almost all incident light. Therefore they appear opaque or milky. Usually a range of available soluble oils are: general emulsified oil based on a mineral oil with emulsifiers like petroleum sulphonates, rosin, amine soaps and anti-foam agents; translucent or clear emulsions with a small content of oil and big amounts of emulsifier; super-fatted emulsions with the attendance of animal or vegetable fats to increase lubricating properties; extreme-pressure emulsions including sulphur, phosphorus or chlorine additives.
2 Synthetic Fluids

Synthetic fluids have been developed in recent years to replace soluble oils. They are formed with unconventional materials which may be petroleum-derived organic chemicals of the polyglycol type. The additives in them have the tendency to form colloidal aggregates among the surface-active molecules, which are smaller than emulsion droplets and so the fluids are clear. Synthetic fluids have lubrication functions which also can be improved by incorporating chlorine, sulphur and phosphorus additives to give extreme pressure qualities.

3 Semi-synthetics

In order to improve a synthetic fluid’s performance, some oil in the form of an emulsion can be added, to the concentration of 10-15% of the base fluid. These fluids are called semi-synthetics. The oil droplets sizes are small, thus the fluids seem translucent. Extreme-pressure additives can be added more readily than in synthetic fluid so that the lubricating performance of semi-synthetics is superior to the entire synthetic fluids.

4 Neat Cutting Oils

Neat cutting oils are cutting fluids that are pure oils, of petroleum, animal or vegetable origin, solely or in combination, with or without the participation of additives. They are used undiluted, which means there’s no water attendance. Several basic types of neat cutting oils are straight mineral oils, sulphured fatty-mineral oils, blends of fatty and mineral oils, sulphureted fatty-mineral oils, chlorinated oils and sulpha-chlorinated oils. However, since detailed formulations differ with each other and there are amounts of additives, the basic types of neat cutting oils cannot include all the possibilities which are available commercially.
2.3.1.2 Choice of Four Kinds of Cutting Fluids

Four kinds of MWFs talked above have different characteristics. So how to choose them in a certain machining condition needs to be considered. The right way to make a decision is also presented by Cookson [39].

Water-miscible fluids are for 80% of all machining operations. Since they give a combination of cooling and lubrication, soluble-oil cutting fluids are suitable for the majority of cutting operations – turning, grinding, milling etc. Moreover, they are more economical than neat oils since water reduces the cost, and the working conditions are better with cleaner workpiece, a reduction in oil mist and decrease in fire hazard. Synthetic water-miscible fluids have some obvious advantages over emulsified water-miscible fluids. They have detergent properties and are easy to mix. Besides, synthetic fluids have improved stability and freedom from bacterial growth leading to a long working life. The inclusion of certain oils in the cutting fluids, making them semi-synthetic fluids, avoids the difficulties with the lubrication of machined workpiece and the evaporation problems are not so serious. Neat oils are effective when both good lubrication and cooling effects are required. The economic tool life and a finished surface can also be obtained with neat oils, especially when high speed steel tools are used. They also have strong points whenever the combination of a slower cutting speed and low surface roughness is demanded.

The most significant criteria for selecting cutting fluid is the type of machining operation, workpiece material and the machining parameters of cutting speed, feed rate and depth of cut. The choices of cutting fluids considering materials and machining operations are presented in Table 1. From this table, milling is better to be conducted with
soluble oil, semi-synthetic or synthetic fluids as cutting fluids. Besides, neat cutting oils may also be expected. Thus, those kinds of MWFs (distilled water, 5% TRIM, canola oil and water-in-oil emulsion) used in this thesis are all appropriate for micro-milling. Except for operations and materials, machining conditions are also essential in choosing proper MWFs. The major factor is the cutting speed. Normally, the lubricating characteristics of MWFs are most important at lower cutting feed while the cooling properties are more significant at higher speeds. According to this, neat oils cannot perform adequately at cutting feeds above 75 m/min. But there is also exception. For instance, in grinding operation where the maintenance of wheel is of the prime requirement, neat oils are essential to reduce the wheel wear as much as possible.

Table 1: Selection of MWFs for general workpiece and machining conditions

<table>
<thead>
<tr>
<th>Machining operation</th>
<th>Workpiece material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grind</td>
<td>Clear-type soluble oil, semi-synthetic or chemical grinding fluid</td>
</tr>
<tr>
<td>Turn</td>
<td>General-purpose soluble oil, semi-synthetic or synthetic fluid</td>
</tr>
<tr>
<td>Milling</td>
<td>General-purpose, or fatty, soluble oil, semi-synthetic or synthetic fluid</td>
</tr>
<tr>
<td>Drill</td>
<td>Fatty or extreme pressure, soluble oil, semi-synthetic or synthetic fluid</td>
</tr>
<tr>
<td>Gear shaping</td>
<td>Extreme pressure soluble oil, semi-synthetic or synthetic fluid</td>
</tr>
<tr>
<td>Hobbing</td>
<td>Extreme pressure soluble oil, semi-synthetic or synthetic fluid (neat cutting oils may be preferable)</td>
</tr>
<tr>
<td>Broaching</td>
<td>Extreme pressure soluble oil, semi-synthetic or synthetic fluid (neat cutting oils may be preferable)</td>
</tr>
<tr>
<td>Tapping</td>
<td>Extreme pressure soluble oil, semi-</td>
</tr>
</tbody>
</table>
In Cookson’s work, he just provides us a tendentious way to choose cutting fluids. In real manufacturing, there are still many factors that should be taken into account to finally decide which kind of MWFs is suitable for a certain case.

### 2.3.1.3 Surfactants in Water Miscible Cutting Fluids

As introduced before, water miscible (soluble oil) cutting fluids are for 80% of all machining operations. In water miscible MWFs, surfactants are essential to lower the surface tension between water and oil so that the droplets of them can be attached to synthesize the emulsion. Normally applied surfactants can be classified into four types (examples attached behind):

- **Anionic**: sulfate, sulfonate, phosphate esters and carboxylates;
- **Cationic head groups**: cetylpyridinium chloride (CPC), benzalkonium chloride (BAC), Benzethonium chloride (BZT) and Dimethyldioctadecylammonium bromide (DODAB);
- **Zwitterionic surfactants**
- **Nonionic surfactants**

From the classification, general surfactants in soluble oils contain sulfonates, carboxylates, chlorides and ethoxylates. Many of them are toxic to animals, ecosystems, and human beings, and may increase the diffusion of other environmental pollutions [40]. For instance, two main surfactants applied in 2000 were alkylphenol ethoxylates (APE) and linear alkylbenzene sulfonates (LAS). They broke down in the aerobic conditions and are finally found in sewage treatment plants and soil [41]. Therefore, bio-surfactants or water miscible cutting fluids without surfactants can be attempted. Bio-surfactants such
as Emulsan, sophorolipids [42] and Rhamnolipid [43] are all prospective cases. In the work of this thesis, two methods of eliminating the use of surfactants will be developed instead of using bio-surfactants.

2.3.2 Conventional & Unconventional Cutting Fluids

2.3.2.1 Problems of Conventional Cutting Fluids

The conventional cutting fluids have many safety and pollution problems. These problems have bad effects on machine operators’ health and the environment. Based on the four types of conventional cutting fluids in last section, this problem will be discussed in detail in the following.

The primary issue is the disposal of spend fluids. On the face of it, synthetic and semi-synthetic fluids may be easier to be disposed of than oil-based fluids, because they contain little or no oil but, in reality, not all synthetics are biodegradable. Discharge of the metalworking fluids would cause serious water and soil contaminations. The treat of those waste liquids requires heavy investment. In addition, the hands and faces of machine operators are exposed to cutting oils’ mist and fumes. What’s more serious is that some soluble oil emulsions can provide a breeding ground for bacteria and fungi. The infected systems may develop considerable quantities of slimes, gums and sludge. Also, the corrosion problems caused by MWFs would leads to coarse surface and short-lasting workpiece. Here, a specific example is taken. Evans [44] has suggested that some synthetic fluids might cause cancer. According to him, many synthetic fluids consist principally of sodium nitrite and triethanolamine. Usually triethanolamine contains diethanolamine, which can react with sodium nitrite to form the carcinogen N-nitrosodiethanolamine. A further possible hazard with these cutting fluids has been
indicated by Evans. A large proportion of the metalworking fluid mist inhaled by the operators will be blocked by the cilia instead of entering the lungs. Since most people swallow phlegm, the polluted fluid will reach the stomach. The acid condition in the stomach catalyzes reactions between nitrites and the amines usually found in a normal diet: then a spectrum of carcinogenic nitrosamines could be formed. Meciarova and Stanovsky [45] introduce in their paper a novel technology called ‘CFSystem’ to select suitable cutting fluids based on the extent of health and environmental hazards. CFSystem is a software tool and the structure of it is shown below.

![Figure 2-6: Structure of the CFSystem](image)

This tool enables the calculation of the overall score to measure health/environmental performance for a given MWF. However, just using this kind of technology to choose an appropriate cutting fluid is not a permanent solution. The best way is to figure out sustainable, as say “green”, cutting fluids.
2.3.2.2 Unconventional (Sustainable) Cutting Fluids

Conventional cutting fluids are introduced a lot above. Now the developments on sustainable cutting fluids in recent decades will be introduced. Among those novel cutting fluids, vegetable oil is used in my own research. Thus the characteristics of it will be discussed elaborately.

A. An Overview of Sustainable Cutting Fluids

According to Crichton [46], the ideas behind sustainable cutting fluids is that they are obtained from natural renewable resources and are made of in such a way to as to finally break down after use for simple disposal. Horner [47] has put forward some normal base fluids and additives of unconventional cutting fluids in his paper. The base fluids are:

- **Triglycerides**: natural fatty stuffs like linseed oil, canola oil, sperm oil and palm oil are triglyceride mixtures of saturated and unsaturated fatty acids. Triglycerides are much more biodegradable than mineral or petroleum based oils. Besides, they display much better tribological characteristics like shear stability, wear protection and low coefficient friction. However, the limitations of triglycerides are their inadequate low-temperature behaviour, poor oxidation as well as hydrolytic stabilities. Thus, corresponding additives should be added to improve these aspects.

- **Synthetic esters**: This kind of base oils covers a series of pure chemical compounds. The main group of synthetic esters is polyolesters like trimethylolpropane esters and glycerine trioleates. Synthetic esters are primarily formulated by petrochemical or biochemical alcohols with fatty acids derived from natural substances. This type of base oils has good hydrolytic stability, perfect oxidation stability and biodegradability.
- Polyglycols: Polyethylene glycols are able to be rapidly biodegraded up to a molecular weight of 600. Polyglycols are normally water-miscible, which would cause contamination into the ground or water in some leaking cases. Due to this, non-water soluble polyalkylene glycols are attempted as alternatives.

- Polyalphaolefins: Polyalphalefins are low viscous and easily biodegradable.

- Fatty alcohols: They are used more in operations where cooling is the primary requirement. Fatty alcohols are proven to be more suitable in Minimum Quantity Lubrication (MQL) than traditional flood cooling. Positive examples of fatty alcohols include manufacturing on cast iron, steel and aluminium.

Synthetic and vegetable oil-based esters provide the best choice in forming environmental friendly lubricants. Sustainable vegetable oil based metalworking fluids belong to the first type of base oil – triglycerides. Except for the base oils, appropriate additives are also needed in synthesis of sustainable cutting fluids. There are indicated below:

- EP/AW additives: The typical examples are sulphurized fatty substances which can offer wear-reducing properties if added to esters.

- Corrosion protection additives: Calcium sulphonates, succinimides and derivates are the basic cases.

- Antioxidants

- Pourpoint depressants: They are only necessary when natural base oils are used and haven’t been chemically modified. However, since some natural products’ pourpoint is over 0°C, they can be used in winter without the addition of pourpoint depressants.
These four kinds of additives for unconventional cutting fluids are just a small part of the whole additive filed. More additives in manufacturing coolants will be introduced in next section in Chapter 2.

Nagendramma and Kaul [48] also make an overview of development of ecofriendly biodegradable lubricants. The most common available biodegradable lubricants in their review are listed below.

- Highly unsaturated or high oleic vegetable oils (HOVOs)
- Low viscosity polyalphaolefins (PAOs)
- Polyalkylene glycols (PAGs)
- Dibasic acid esters (DEs)
- Polyol esters (PEs)

Their classification of sustainable cutting fluids is similar with D. Horner’s opinion. Unconventional MWFs may bring lots of benefits to the environment and human body.

**B. Advantages & Disadvantages of Vegetable Oil**

According to the introduction above, the application of vegetable oils as cutting fluids is a typical case of sustainable MWFs. Vegetable oil based lubricants base on renewable sources, such as corn, soy beans and canola which are abound in earth and will decrease the cost for the MWFs. They have less potential toxicity and can degrade more easily in the soil. Biodegradable lubricants and hydraulic fluids based on them are widely available in North America. Genetic engineering technologies bring vegetable oils with better lubricating properties. These include genetically modified corn and soybean oils with high oleic content that enhances oxidation stability [49]. The superiorities of vegetable oil based lubricants over mineral oils are tested by researchers in recent years.
Shashidhara and Jayaram have reported a comprehensive review on use of vegetable-based oil as cutting fluids and concluded that vegetable oils are found to be promising alternative for mineral based oils [50]. The two researchers then do the experimental determination of cutting power for drilling and turning on AA 6061-T6 using vegetable oil as cutting fluid [51]. This time, pogamma pinnata and Jatropha curcas oils are used in turning AA 6061 comparing with a commercially available branded mineral oil. Also, drilling is conducted to determine the material removal rate (MRR) with these three oils. A noticeable decrease in cutting forces is observed with Jatropha curcas oil than mineral oil. And both of the two vegetable oils have better MRR compared to the petroleum oil.

In Chiffre and Belluco’s research [52], a comparison is made of those methods for cutting fluid performance evaluation that involves metal cutting operations. An analysis of repeatability, resolution and cost is carried out, based on results from comprehensive experimental investigations in turning, drilling, milling, reaming, and tapping. Different workpiece materials, such as carbon steels, stainless steels, and aluminium alloys, as well as different kinds of cutting fluids, including water based products, straight mineral oils, and vegetable oil based formulations, are considered. Those performances are compared in different aspects: tool life, cutting forces, and workpiece surface finish. In their results, vegetable oil is proved to be able to prolong tool life, reduce cutting forces than water based products and straight mineral oils [53-56]. Lawal [57, 58] conducts application of vegetable oil-based cutting fluids in machining ferrous as well as non-ferrous metals. His work shows that vegetable oil-based metalworking fluids can be an environmental friendly mode of machining with the similar performances obtained under mineral oil-based cutting fluids. Belluco and Chiffre [59, 60] have evaluated the performance of
vegetable-based oils in drilling, reaming and tapping stainless steel – AISI 316L. For reaming and tapping experiments, they measured surface integrity and part accuracy after machining with vegetable oils and a widely diffused commercial mineral oil as MWFs. And cutting fluids based on vegetable oils present comparable or even better results than mineral oils. For drilling on AISI 316L, they tested five vegetable-based cutting fluids at the different levels of additivation comparing with mineral-based oil. The experiments indicate that all vegetable oil-based fluids have better expressions than mineral oil. The best one is obtained with a vegetable oil cutting fluid yielding 177% increase in tool life and 7% decrease in thrust force. An interesting project has been done by Ozcelik et al. on the optimization of surface roughness in drilling AISI 304 steel blocks using vegetable-based cutting oils derived from sunflower oil [61]. The researchers used two different vegetable fluids developed from refined sunflower oil and another two conventional MWFs – semi-synthetic and mineral types to do drilling on AISI 304 with HSSE tools. The test of surface roughness suggests that sunflower oils are better than the commercial cutting fluids in reducing roughness. Except for sunflower oil, canola, soybean, and rapeseed oil have all been currently emerging as an environmentally viable alternative.

Vegetable oils are investigated as a potential source of environmental friendly lubricants, due to a combination of biodegradability, renewability, a high flash point and excellent lubrication performance of them. However, some facts like low oxidation and thermal stability, poor low-temperature properties and narrow range of available viscosities limit their application range as industrial lubricants. Vegetable oils have advantages and disadvantages. Autoxidation is one of those disadvantages. In the oxidation process, some oxidation compounds such as volatile, high molecular weight
and free fatty acid can be generated. Those compounds will bring negative effects to tool wear and machinability. So measures should be taken to decrease oxidation of vegetable oil [62]. Special breeding programs or genetic modification can increase their stability by reducing the level of unsaturated fatty acid in vegetable oils [63, 64]. In addition, stability can be improved by chemical changes of the oil structure by blending, hydrogenation and epoxidation technologies [65, 66, and 67]. Wagner [68] has presented a detailed review of the methods to modify vegetable oil characteristics. The stability of the formulations can also be developed through addition of antioxidant additives inside.

When vegetable oil is used in water solution as cutting fluid, a question comes out. Since oil cannot be dissolved in water, the problem of how to mix them together should be solved. Usually, the emulsions of vegetable oils are completed using ionic and non-ionic surfactants and agents as discussed in section 2.3.1.3. Oil modification is achieved through ozonation and sulfurization reactions. The viscosities of the modified oil are apparently higher than the original oil. Those emulsions normally show good stability and anticorrosion properties. In particular, modified soybean oil required comparatively increased amounts of surfactant than the regular oil to obtain a stable emulsion [69]. In recent decades, several novel methods to emulsify water and vegetable oil together are discovered by researcher, one of them – ultrasonic atomization emulsion technology without any surfactants will be discussed in Chapter 4.

C. Other Kinds of Unconventional Cutting Fluids

Except for vegetable oil, there are other types of untraditional cutting fluids. Here three examples are introduced.
In Abdalla and Baines’s research [1], they try to develop methods for the formulation of novel sustainable neat-oil metalworking fluids. The performances in cost, low temperature properties, kinetic viscosity (KV) and oxidative stability of the final formulations are evaluated for the stainless steel and aerospace-grade titanium alloy materials. Four different formulations of neat-oil MWFs are conducted and suitable benchmark fluids are identified for each material. In further work, they cite that the machining operations (tapping and milling), oxidation stability, tool compatibility, misting and volatile emissions potential of the final formulations will be benchmarked against conventional fluids. Fukutani et al [70] figure out in their work a novel water-soluble cutting fluid containing hydrogen carbonate ion, bromide ion, carbonic acid ion and fluoride ion if necessary and another new water-soluble cutting fluid including additives such as rust-preventive agents to be a substitute for traditional cutting oils. Those kinds of new water-soluble MWFs increase the useful life of a cutting tool and improve the operation efficiency. Moreover, waste fluids of the present invention do not include environmentally-hazardous substances. Therefore, it does not exert a harmful influence on the environment. What’s interesting is that some researchers have thought about surprising method to cool and lubricate the workpiece instead of conventional coolants. For instance, Paul and Dhar [71] try to set up liquid nitrogen jet to cool the cutting area. They have investigated in the role of cryogenic cooling of it on tool wear and surface finish in turning of AISI 1060 steel. The results have been compared with dry machining and machining with soluble oil as coolant. The experimental results of their work justify substantial benefit of cryogenic cooling by liquid nitrogen jet on tool life and surface finish, which attributes to significant reduction in cutting zone temperature.
D. Defects of Unconventional Cutting Fluids

In Crichton’s [46] summary of sustainable cutting fluids, he reports that recently biodegradable lubricants have been pushed as the clean alternatives to replace traditional petroleum and chemical based products, but this ‘green’ solution may have its own problems. The fact behind biodegradable lubricants is that they are derived from natural renewable sources (usually vegetable-based) and are able to be depredated eventually after easy disposal. Nevertheless, in real machining situations, cross contamination between them and other fluids involved in the machining process such as gearbox oils, hydraulic oils and mill oils may happen. Since biodegradable coolants can quickly be polluted by these fugitive oils in machine, so-called sustainable cutting fluids are difficult to work as expected. They cannot be disposed of in sewage treatment plants or released to the environment directly any longer. So the disposal cannot be less expensive as required. In recent years, researchers are trying to develop other bio-balanced or bio-stable substitutes which can be recycled instead of being disposed in landfill. But the developments and skills in this direction are still immature. Regard of this problem, there is no doubt that using sustainable MWFs in manufacturing brings much less contamination and harm.

From all above about cutting fluids in this section, we can see the clear classification of cutting fluids. Besides, researchers have developed many unconventional cutting fluids as substitutes for the traditional ones which can be harmful to environment and human body. The two kinds of classification of cutting fluids can do help for us to know the organization and situation of cutting fluid field in recent years.
2.4 Review of Different Kinds of Additives in Cutting Fluids

To synthetize MWFs, aside from choosing from a selection of base fluid materials (straight oils, soluble oils, semisynthetic oils and synthetic oils) and concentration, an array of additives should also be added. As suggested in the part of background and motivation, the second way to improve cutting fluids’ condition is to take advantages of “green” additives to replace the traditional ones. In this section, the normal types of additives in MWFs are introduced and then the creative selection of lignin powder as MWFs additive will be discussed.

2.4.1 MWFs Additives

Gresham [72] has taken a comprehensive study of the most common used additives in MWFs. Here his ideas are introduced to make a clear and simple classification of additives. Additives are chemical components or blends used at a certain specific treat rate to provide one or more functions in the MWFs. Usually, the treat rates of additives are from 1% to 35% in cutting fluids. There are many types of additives and the most common types are elaborated below.

Boundary lubricity additives can adsorb on the metal surface to form a film, reducing metal-to-metal contact so that the lubricity of the fluids is enhanced. These additives are compatible with mineral oil or water. Lard oil and canola oil are the examples for this kind of additives.

Extreme pressure additives may reacts with the metal surface, forming a metal salt layer or a physical barrier between the tool and the workpiece under sever machining conditions. The layer prevents friction, wear and damage. Examples are sulfurized lard oils, chlorinated paraffins and overbased calcium sulfonates. However, since this type of
additives has different activation temperatures, they must be applied in suitable conditions.

Corrosion inhibitors prevent the corrosion in the workpiece and cutting tools as their name. They effect by forming a coating on the metal surface or by neutralizing corrosive contaminants in the fluids. Examples are alkanolamides, aminoborates and aminocarboxylates.

Reserve alkalinity additives maintain the pH value in a suitable range by neutralizing acidic contaminations. Those additives can also react with other components to stabilize the cutting fluids. Examples are triethanolamine, aminomethylpropanol and 2-ethanol.

Metal deactivators protect the fluids from staining nonferrous alloys (especially copper and brass) and reduce corrosion. They act by forming a coating on the workpiece surface. Examples are mercaptobenzothiazole, tolyltriazole and benzotriazole.

Emulsifiers help to stabilize oil-water emulsion metalworking fluids by reducing interfacial tension. Examples are sodium petroleum sulfonate and alkanolamine salts of fatty acids. Similarly, couplers assist in stabilizing water-soluble cutting fluids to prevent separation of components. Examples are propylene glycol, glycol ethers and non-ionic alkoxylates.

Chelating agents (water softeners or conditioners) decrease the destabilizing effect of hard water on metalworking fluid emulsions. In addition, chelating agents bind calcium and magnesium salts to stop them reacting with anionic emulsifiers such as fatty acid salts of alkanolamines. An instance is ethylenediaminetetraacetic acid.

Antimist additives are specific in minimizing the amount of lubricant that disperses into the air during manufacturing. The typical cases are ethylene, propylene copolymers
and polyisobutenes for oil-based systems and polyethylene oxides for water-based systems.

The last kind of normal additives is dyes, which give the cutting fluids a specific color requested by customers. Their main value is indicate the product exist in water-diluted fluids. Nevertheless, some dyes are unstable and may change color. What’s worse is that some of them would pass waste treatment systems resulting in pollution.

Since there are a number of additives available, it is essential to keep everything under control. Arbitrary use of additives under various machining conditions is pretty significant.

2.4.2 Lignin as Additives in other Aspects

The traditional additives in cutting fluids such as extreme pressure additives, corrosion inhibitors, reserve alkalinity boosters, emulsifiers and chelating agents can do help in lubricity, wear reducing, stabilizing fluids and resistance to oxidation during machining [73]. Nevertheless, those additives contain organic sulfur, chlorine, nitrite elements and base of petroleum that are harmful to the human body and environment [23]. Efforts have been made to solve this problem. For example, vegetable oil and esters [74] are tried to replace the conventional additives. Vegetable-based additives have a polar group that interfaces with metal and a tail that is compatible with mineral oil or water. Examples are corn oil and canola oil. They are biodegradable, environmental friendly and innocuous. Nevertheless, more “green” additives need to be discovered and developed.

In this thesis, lignin powder as shown in Figure 2-7 is considered as a possible additive in cutting fluids. Lignin is a complex chemical compound derived from wood. It is normally aromatic and hydrophobic in nature. But the degree of polymerisation is
difficult to be measured because it is fragmented during extraction and there are various types of substructures in the molecule [75]. Figure 2-8 shows a possible molecular structure of it.

![Lignin powder](image)

**Figure 2- 7: Lignin powder.**

![Possible lignin molecular structure](image)

**Figure 2- 8: A possible lignin molecular structure [75].**

Lignin is one of the most abundant organic polymers on Earth, employing 25% of non-
fossil organic carbon [76]. Thus, the application of it in industry is totally economic. Lignin is an integral part of the secondary cell walls of plants and its regeneration [77] as well as biodegradability in soil [78] has been proven by researchers, which mean that it is environmentally friendly.

Due to its plentiful resource, low cost and advantages, lignin has already been applied as additives in many areas.

- **Concrete**: Low levels of lignin or modified lignin may yield high performance concrete strength aid, reduce damage of building external wall induced by moisture and acid rain and good concrete grinding aid.

- **Antioxidant**: Lignin can act as free radical scavengers. Its natural antioxidant properties provide employment in cosmetic and topical formulations.

- **Asphalt**: Adding 0.3% lignin fibers, an asphalt mixture’s water stability can be improved.

- **Chemicals**: Phenols prepared by incorporating lignin react with a H-supplying solvent at elevated temperature/pressure. And lignin depolymerisation offers routes to resorsinols, quinones, cresols, catechols, guaiacols and vanillin.

- **Battery**: Lignin improves performance of energy storage devices. Lignin forms a thin film on the graphite powder surface that protects the graphite powder from reducing H overvoltage and does not influence conditions of the graphite powder.

- **Heat**: Non-petroleum based wax using lignin and 1, 3-propanediol and artificial fire log using cellulosic materials are derived from a renewable resource with improved flame properties. If Indulin AT lignin is added to wood pellets, it will produce better quality pellets and has higher fuel value.
Agriculture: Lignin is applied either directly or chemically modified, as a binder or dispersant agent for pesticides/herbicides, emulsifier. It also behaves as a heavy metal sequestrate. Besides, lignin nutrient medium has been used as an additive for recovering vegetation on bare mountain and road slope.

Except for the applications above, lignin has also been utilized in carbon fiber, plastics/polymers, dust control, paper, fuel and dispersants. Some cases for lignin applications as additive are listed. Mahato has analyzed the role of lignin additives in pasted lead electrodes early in 1977 [79]. Lignin additive is also used on negative electrode of lead-acid battery in the form of lignosulfonate to extend the battery life in Hirai et al.’s work [80]. The fact that adding sodium lignosulphonate in cement can improve the workability of concrete in engineering has been proved by Yousuf and Mollah in 2006 [81]. Besides, since lignin is found to have inhibiting effect towards hydrocarbons oxidation [82], it is also applied in polypropylene/coir composites in Morandim-Giannetti and Agnelli’s research [83]. However, lignin has never been attempted as additive in MWFs.

However, lignin has never been attempted as additive in MWFs. It is prospective to examine lignin’s performance as an additive in cutting fluids because of its pollution-free and anti-oxidation characteristics and broad source. But other required properties like lubricity and cooling in machining still need to be justified. In this thesis, lignin is tried to dissolve in 5% TRIM and then tested in micro-milling experiments. The machining results will illustrate the feasibility of lignin as additives in MWFs which is carefully discussed in Chapter 6.
Chapter 3: Previously Developed Atomization-based Cutting Fluid System for Micro-Milling

3.1 Ultrasonic Atomization System

Besides Minimum Quantity Lubrication technologies, atomization methods to apply cutting fluids may also be considered as an effective substitute for flood cooling in micro-milling. The metalworking fluids will be atomized into small droplets and those droplets will be transported and sprayed out by high pressure air to the cutting zone to effect. Normally there are three atomization methods:

- **Pressure nozzle atomization**: Fluid at high pressure is injected into a low-pressure environment through a nozzle and the droplet sizes are usually 2-200μm.

- **Gas-assisted atomization**: Fluid is introduced into a high speed gas or air that causes the fluid breaking into droplets. The droplets’ size in this condition is about 2-120μm.

- **Ultrasonic atomization**: Fluid surface is broken by vibration into quasi-monodisperse droplets. And the droplet sizes depend on the vibration frequency.

In the Laboratory for Advanced Multi-scale Manufacturing (LAMM) at the University of Victoria, Rukosuyev et al. [3] have already designed and developed an atomization system using the ultrasonic atomization method. Cutting fluids added into reservoir inflows into an ultrasonic atomizer. A piezo at the bottom of atomizer will vibrate at 1.75 MHz when switched on. Through vibration, the MWFs are atomized into droplets. Then those droplets are then focused into the cutting zone by using a spray jet, as in Figure 3-1. Moisture from the atomizer goes through a relatively thick tube at low velocity. Meanwhile there is a small tube inside the nozzle with high air pressure. When the moisture arrives at the jet at the end of tube, the air pressure will transport the cutting fluid droplets directly to the cutting zone at high velocity.
3.2 Design Parameters of the Nozzle

When the atomized droplets of cutting fluids are transported with a low velocity air pressure to the end of the tube, the suitable nozzle geometry and air spray velocities should be selected to make sure the spray jet is focused and strong enough to lubricate and cool the cutting zone. Rukosuyev and Seo [3] have also made tests about this. Figure 3-4 shows 4 different nozzle geometries including the position of the center gas tube.

Consider the mist velocity of low gas pressure \((V_m)\) from the atomizer and the spray velocity of high air pressure \((V_s)\) from the center tube in the nozzle, the experimental photos for the four different nozzles are presented in Figure 3-5 below. From the photos
we can see that nozzle (a) has the most advantageous geometry and will be made to install to the ultrasonic atomization system.

<table>
<thead>
<tr>
<th>$V_{in}$ = 1 m/s</th>
<th>$V_{in}$ = 3 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_a = 12$ m/s</td>
<td>$V_a = 12$ m/s</td>
</tr>
<tr>
<td>$V_s = 18$ m/s</td>
<td>$V_s = 18$ m/s</td>
</tr>
</tbody>
</table>

![Experimental photographs of the spray with different nozzle geometries.](image)

In addition, Rukosuyev and Seo’s work [3] also indicates that lower mist velocity and higher spray velocity would lead to most focused spray jet.

### 3.3 Theory of Droplet Impingement Dynamics against Workpiece Surface

After the droplets of MWFs are sprayed out by high speed air from nozzles, those droplets will impact the workpiece surface. And the condition of droplet impingement against workpiece surface is essential since it is the key to fulfill all requirements of a metalworking fluid: sufficient cooling, lubrication and chip flushing. Those factors cause decreased cutting forces and vibrations, less tool wear, fewer burrs and better surface finish [84][85]. Normally four different impingement regimes exist as in Figure 3-6. The first regime is the sticking regime. Sticking occurs if droplets adhere to the workpiece surface in a nearly spherical shape. This often happens when the impact energy is very low and the surface temperature is below the temperature required for pure sticking. The
second regime, rebounding regime appears if droplets bounce off the surface. The third regime, spreading, is the only one desired for application of MWF to the cutting zone since droplets spreading on the workpiece surface and tool interface can provide enough cooling and lubrication. The fourth regime is splashing and often occurs when the incoming droplets break into many secondary droplets. This is also unexpected because of the lack of fluid penetration into the cutting zone. Thus, in order to make sure the cutting fluids could work effectively, parameters should be controlled to let the spreading regime exist only during the machining.

Figure 3- 4: Droplet impingement regimes.

The parameters influencing droplet impingement mechanisms include droplet diameter \((d_o)\), normal velocity component of the incident drop \((w_o)\), fluid viscosity \((\mu)\), density \((\rho)\), and surface tension \((\sigma)\). Two numbers are evaluated:

\[
W_e = \frac{\rho w_o^2 d_0}{\sigma}, \quad O_h = \frac{\mu}{\sqrt{d_0 \delta \rho}}
\]  

(3.1)

Here, \(W_e\) is the Weber number and \(O_h\) is the Ohnesorge number. The value of Weber number and its corresponding impingement regime are presented in Table 2.
Table 2: Weber number ranges for different impingement regimes

<table>
<thead>
<tr>
<th>Weber Number, $W_e$</th>
<th>Impingement Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_e &lt; 5$</td>
<td>Sticking</td>
</tr>
<tr>
<td>$5 &lt; W_e &lt; 10$</td>
<td>Rebounding</td>
</tr>
<tr>
<td>$W_e &gt; 10$</td>
<td>Spreading</td>
</tr>
</tbody>
</table>

From above we can see that to approach spreading regime, Weber number should be firstly larger than 10. Then the transition criterion from spreading to splashing is calculated through another number. Mundo et al. [86] has conducted droplet impact tests on two different kinds of stainless steel surfaces with different roughness values and developed a no-dimensional parameter $K_m$. $K_m$ is decided through the following equation:

$$K_m = \left( \frac{\rho d_0}{\delta} \right)^{\frac{3}{4}} W_e^\frac{5}{4} = \left( \frac{\rho}{\mu} \right)^{\frac{2}{5}} W_e^\frac{5}{8}$$

(3.2)

$$K_{mc} = 57.7$$

(3.3)

$K_{mc}$ is a critical value which can be compared with $K_m$. By comparing them, the final regime is determined as in Table 3.

Table 3: Critical value of no-dimensional parameter for spread to splash regime transition.

<table>
<thead>
<tr>
<th>Spreading Condition</th>
<th>Splashing Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_m &lt; K_{mc} = 57.7$</td>
<td>$K_m &gt; K_{mc} = 57.7$</td>
</tr>
</tbody>
</table>

In real manufacturing, the droplet size and fluid properties are given, so the normal velocity of the incoming droplets need to be controlled to make sure that they are delivered to the cutting zone within the spreading regime. According to this effect, the spray jet velocities of the atomization system can be independently controlled to make
sure that the impingement regime of cutting fluids for experiments in this thesis is to just be spreading on the workpiece surface.

3.4 Improvements based on Ultrasonic- Atomization System

As discussed in Introduction, this ultrasonic atomization system still needs improvement because conventional cutting fluids are still used. The atomized mist of the conventional cutting fluids containing surfactants and additives may be harmful to humans if inhaled. For example, Tawakoli et al. [87] have pointed in their study of the influence of oil mist sizes on MQL grinding process that the normal sizes of oil mist through MQL are in the range of 200-500 μm in diameter. Also, in Duchosal et al.’s work [88] of investigation on oil mist characterization used in MQL milling process, they referred the regular cutting fluid mist droplets are around 100 to 600 μm in diameter. Those droplets will cause malaise if inhaled. So a way to solve the problems of this application system in micro-milling is to change the atomized traditional cutting fluids and additives inside. In detail, in this thesis two methods – eliminating toxic surfactants in water miscible MWFs and replacing conventional additives with green ones are conducted. To eliminate surfactants, canola oil-in-water emulsion without surfactants is achieved in Chapter 4, and a mixed jet of independently atomized water and canola oil sprays in Chapter 5 is presented. In addition, lignin as such kind of green additive will be tried in cutting fluids in Chapter 6. Thus, in the content of the following chapters, two methods of eliminating surfactants and a novel additive – lignin are introduced in detail.
Chapter 4: Canola Oil in Water Emulsion as Cutting Fluids through Ultrasonic Atomization

Large amount of work is reported on development of vegetable oil based cutting fluids and vegetable based oils as MWFs. Since vegetable oil cannot be dissolved in water directly, a series of surfactants are applied to promote the emulsion process of oil and water. Nevertheless, normal surfactants have chemical elements that are harmful to environment and health. In this chapter, canola oil is selected and an ultrasonic atomization system is introduced as a creative way to emulsify water and canola oil without any surfactants. Then the emulsified canola oil in water is used as cutting fluid in micro-milling operation through ultrasonic atomization method. Lower resultant cutting forces, thinner chip thickness, less tool wear and slots’ burrs are observed with it when compared to conventional MWF (5% TRIM) through same application system. The results show advantages of canola oil over conventional cutting fluid and show the feasibility of this ultrasonic atomization system in emulsion of vegetable oil and water without surfactants. The detailed steps are discussed below. The work to make canola oil-in-water emulsion and the micro-milling experiments on Al6061 are conducted by Burton and Goo [89] in 2011. My work is to applying the emulsion on milling steel 1018 as cutting fluid.

4.1 Canola Oil Emulsion in Water through Ultrasonic Atomization

The working theory of ultrasonic or acoustic emulsification is breaking up the oil droplets to smaller oil droplets and preventing small droplets from coalescence at the same time, so that more stable emulsification will be generated [90-92]. Kamogawa et al. [92] has irradiated oleic oil in water solution and obtained oil droplet size as small as 100
nm in diameter using 200 kHz frequency. Normally, a frequency as high as 100 kHz can be used in stabilizing the emulsification.

Emulsification through ultrasonic atomization is considered in this chapter instead of irradiation. Figure 4-1 shows a schematic of the setup to atomize canola oil and water mixture in ultrasonic atomizer which vibrates at 1.75 MHz. The photograph of experimental setup is presented in Figure 4-2. In the experiments, a range of 1-30% of canola oil has been mixed with water and those mixtures are tested. As the mixture is atomized, the atomized moisture with droplets is carried to the nozzle through carrier air as indicated in Figure 4-1. To examine the atomized droplets, those droplets are transported by high speed air to form a spray jet at the nozzle and finally collected in a beaker.

Figure 4-1: A schematic of the experimental setup to test emulsification of vegetable oil in water.
Figure 4-2: A photograph of the experimental setup.

Figure 4-3 suggests the view inside the atomization chamber when canola oil is mixed with water at 1% in volume. Before atomizing, canola oil floats on water. However, from the solution collected after ultrasonic atomization, stable emulsification of oil in water can be observed. Figure 4-4 indicates a photograph of all collected solutions after four days. The emulsification is very stable. Since those solutions are kept in test tubes, and there is still no separation line of oil from water observed by eye after two years. Those ultrasonically atomized solutions are achieved with different percentages of oil volume initially added to the atomization chamber as shown in Figure 4-4. What is interesting is that, regardless of the percentage of oil added into water by volume, the atomized solutions seem to have the same amount of oil emulsified in water at room temperature. The concentration of canola oil in all mixtures is found to be 0.15% in volume using a refractometer (Extech RF-12). Thus, this result implies that the performance will be consistent. After several days later, water evaporation may change the percentage of oil amount in water but still cannot change of the performance of the atomized solutions.
Figure 4-3: A photograph of canola oil added to water within atomization chamber.

Figure 4-4: A photograph of the collected solutions at different oil percentages in the atomization chamber.

Figure 4-5 presents the oil droplets observed under an optical microscope. The average droplet size is measure through scale bar to be around 2.1μm. For comparison, traditional metalworking fluid (5% TRIM) is also watched. The size of oil droplets in 5% TRIM solution is similar to that of canola oil droplets emulsified within water as shown in Figure 4-5.
Figure 4- 5: A photograph of oil droplets observed under a microscope: (a) ultrasonically atomized oil droplets and (b) oil droplets within conventional MWF (TRIM®) at 5% concentration (scale bar = 50 μm).

The experimental results in this section indicate that stable emulsification of canola oil in water can be obtained through ultrasonic atomization method. It is probably that basic emulsification is achieved due to ultrasonic vibration inside the atomizer. Nevertheless, when 20% canola oil is added into the chamber, a fraction gets emulsified and the rest is separated as shown in Figure 4-6. Even so, stable emulsified solution still can be obtained when atomized. This may because that only the emulsified oil-in-water part is atomized into moisture in Figure 4-7a, and the rest oil and water will still exist with the separation line in the atomizer, or pretty thin film wraps every atomized droplet in Figure 4-7b. After the droplets are collected in beaker, the oil film becomes small oil droplets in the solution, leading to stable emulsification. Deeper research and analysis needs to be conducted to decide the accurate process of emulsification through ultrasonic atomization.
Figure 4-6: A photograph of the collected solution and solution form the atomization chamber at 20% oil.

Figure 4-7: Possible regimes of emulsification through ultrasonic atomization.

4.2 Experimental Setup and Cutting Conditions

To perform all the micro milling tests, the custom built micro-machine tool (Alio Industries) with a spindle (NSK E800Z) at maximum 80,000 rev/min (RPM) is used, as shown in Figure 4-8. This machine is a CNC (Computerized Numerical Control) system. The controller directs the tool paths through G-code typed into the controlling software. In order to measure cutting forces during manufacturing, a Kistler MiniDyn 9256C1 dynamometer is connected to a data acquisition board (NI PCI-6133) under the workpiece through an electric cable. A force-measuring software collects and records the
force signals for X, Y and Z directions from the dynamometer. Then through programs in Matlab, any kinds of cutting forces can be calculated. This Alio micro-machine system is the foundation of all the micro-milling experiments in the thesis.

Figure 4- 8: Photographs of Alio micro-machine system.

The schematic of cutting fluid application system has already been depicted in Figure 3-1 in Chapter 3. This previous ultrasonic atomization method can be used here since the obtained cutting fluid – emulsion of oil in water is pure sustainable MWF. Figure 4-9 shows the machine and cutting fluid system setup. Two-flute flat end mills of 396μm in diameter are used to cut slots on Aluminum and steel blocks. For Al6061 which has a surface speed of 75 m/min, 60,000 rpm is selected as the spindle speed and 150μm is the depth of cut. 25 slots are machined for each new tool on one block. For carbon steel that has the surface speed of 60 m/min, 50,000 rpm is the corresponding spindle speed and the depth of cut is changed to 50μm. In this condition, as many as slots are tried to be cut on
steel blocks. For both of the two materials, two feed-per-tooth (FPT) values of 0.3 and 1.0μm/tooth are chosen. The experiments are carried out with dry machining and two kinds of metalworking – canola oil emulsion in water obtained above and 5% TRIM solution. After machining, their performances in resultant forces, tool wears, chip morphology and slot burrs are compared. Cutting forces generated during milling are measured and collected by the dynamometer. Tool wears and slots’ burrs are observed using an optical microscope (Olympus BXFM) and chip morphology is watched and measured with a scanning electron microscopy (SEM, Hitachi S4700).

Figure 4-9: Experimental setup for micro-milling operations.

4.3 Performance of Canola Oil Emulsion in Water as MWF for Al6061 and Steel 1018

4.3.1 Experimental Results for Al6061

A. Machining Forces
In this section, cutting forces measured during milling are evaluated and compared. Figure 4-10 shows the raw force data of one experimental slot at the feed rate of 0.3μm/tooth. The sampling rate of recording forces is 20,000 points/sec. Since the forces’ data is recorded before and after cutting the slot both, part ① and part ② should be trimmed firstly. Then the average force value for this slot can be calculated in Matlab. The average forces for all the slots can be obtained, and so on. If the peak-to-valley forces are considered, the number of sampling points for one revolution (one rotation of the spindle as well as tool) should be calculated. Then the maximum and minimum values of resultant forces are selected and getting the difference of them. Finally, the average peak-to-valley force of one slot can be obtained from averaging all the revolutions.

Figure 4-10: Raw force figure.

Figure 4-11 shows the peak-to-valley values of the resultant cutting forces for all the slots at the feed rate of (a) 0.3 and (b) 1.0μm/tooth. As expected, dry cutting leads to the highest cutting forces. And substantial force variations can be observed in this condition. This may because of formation of built-up-edge or clogging of chips in the cutting zone.
When compared to conventional 5% TRIM solution, lower peak-to-valley forces are obtained with the canola oil in water emulsion as cutting fluid. This indicates that with the application with canola oil, better lubricating effects are achieved. One thing should be noticed that 5% TRIM solution contains surfactants and additives, so the lubricity of the conventional cutting fluid is affected by these.

From Figure 4-11, at the feed rate of 1.0 μm/flute, around 30% decrease in peak-to-valley cutting forces’ values is achieved with canola oil and water emulsion as the MWF compared to 5% TRIM. When compared to dry machining, the values of forces with oil and water emulsion are less than a half. This suggests the superiority of canola oil and the feasibility of it in water emulsion achieved through ultrasonic atomization method in micro-milling operation.
Figure 4-11: Peak-to-valley forces with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0 μm/tooth.

B. Tool Wears

Figure 4-12 provides the tool wear photographs taken under an optical microscope to compare the cutting edge conditions of the tools after 25 slots are milled. It is as expected that more tool wear is observed with dry cutting and it seems to have slightly more tool wear with 5% TRIM as MWF. Besides, at the feed rate of 1.0 μm/flute, hardly any wear exists along the cutting edges with emulsion of oil and water while much more wear is
seen with the use of conventional cutting fluid of 5% TRIM. The performance in tool wear proves better lubricity of the canola oil-in-water emulsion over 5% TRIM solution.

Figure 4-12: Tool wear photographs at different MWF conditions after milling 25 slots.

C. Chip Morphology

After machining, chips generated during the cutting processes are carefully collected and examined to justify the chip morphology and thickness. Figure 4-13 presents the SEM images of chips morphology obtained at the feed rates of 0.3 and 1.0μm/tooth with different cutting fluid conditions. From the figure we can see that those chips collected with dry cutting are much larger and continuous than other two conditions, which may due to improved cooling functions with the use of atomized MWFs [12]. Chips generated with canola oil-in-water emulsion and 5% TRIM are similar in size and shape. Figure 4-14 shows measured thickness of the chips in three MWF conditions at the feed rate of 1.0μm/flute. The chips with emulsion of oil and water are thinnest while those chips in dry cutting are the thickest. The thinnest chips with canola oil-in-water emulsion provide indirect validation of the effective lubricity since thinner chips are brought about by higher shear angle, which is resulted in decrease in the friction forces.
**D. Burr Formation**

The performance of top burrs along slots is analyzed to study the roles of MWFs in producing the quantitative amount of burrs on the top surface. Figure 4-15 exhibits the images of burrs generated on the top surfaces for the 1st and 25th slots. Top burrs formed...
on the 1\textsuperscript{st} slot in dry machining are significantly larger and more than the conditions with cutting fluids. In canola oil-in-water condition, there is hardly any burr along the edges being watched. And some burrs exist in the 1\textsuperscript{st} slot with 5\% TRIM as metalworking fluid. On the 25\textsuperscript{th} slots, both dry cutting and conventional cutting fluid result in a lot of burrs while the amount of burrs is much less with canola oil-in-water emulsion. The result agrees with the peak-to-valley forces’ measurement and chip thickness observations.

![Figure 4- 15: Photographs of slots’ burrs on the top surfaces.](image)

\subsection*{4.3.2 Experimental Results for Steel 1018}

\textbf{A. Machining Forces}

Table 4 shows a number of slots machined for steel before tool failure at two different feed rates. As shown, the oil-in-water emulsion achieved by ultrasonic
atomization lead to more number of slots machined before tool failure. Note that at low feed rates, due to excessive ploughing and large forces, tool failed only after machining 3, 4, and 5 slots under the conditions of dry, 5% TRIM, and oil-in-water emulsion, respectively. Figure 4-16 shows the average values of the resultant milling forces for machining 3 slots at the feed rate of 0.3 µm/tooth and 7 slots at 1.0 µm/tooth. The number of slots was taken for calculating averages values so that the same number of slots is taken for all three conditions. Because the tool failed subsequently under the dry cutting condition while the tools survived in other conditions, these were the maximum number of slots possible. As shown in Figure 4-16, lower cutting forces are observed with the canola oil-in-water emulsion at both feed rates, compared to conventional cutting fluids (5% TRIM). This explains why the tool was able to machine more slots with canola oil-in-emulsion.

Table 4: Number of slots machined for steel before tool failure.

<table>
<thead>
<tr>
<th>Feed rate [µm/tooth]</th>
<th>Cutting Fluids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
</tr>
<tr>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>1.0</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 4-16: Average resultant cutting forces over the number of slots machined before tool failure with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0 µm/tooth.

**B. Tool Wears**

Figure 4-17 shows optical microscope images taken to observe the cutting edge of the tool after machining two slots. As expected, significantly more wear is observed with dry cutting. Also, cutting edges are almost worn out at the feed rate of 0.3 µm/tooth, due to excessive ploughing and rubbing. There seems to be slightly less wear with canola oil-in-water emulsion than 5% TRIM at both feed rates. These results are in agreement with the number of slots machined before tool failure given in Table 4 and cutting force results in Figure 4-16.
Figure 4- 17: Tool wear photographs at different MWF conditions after milling 2 slots.

C. Chip Morphology

Chips generated during machining were carefully collected and examined to verify the chip morphology and thickness. Figure 4-18 shows the SEM images of the chips generated at the feed rates of 0.3 and 1.0 µm/tooth with dry cutting, 5% TRIM, and canola oil-in-water emulsion. Similar to the aluminum chips, chips generated with both canola oil-in-water emulsion and 5% TRIM are smaller and discontinuous than those with dry cutting. It seems that chips generated with canola oil-in-water emulsion are slightly shorter than those with 5% TRIM. The chip thickness at the feed rate of 1.0 µm/tooth is shown in Figure 4-19. As shown, the chip thickness is thinnest with canola oil-in-water emulsion while it is the thickest with dry cutting. This agrees with the aluminum cutting results, and this indirectly shows that better cooling and lubricity was provided with oil-in-water emulsion.
Figure 4-18: SEM photographs of generated chips with dry, 5% TRIM and canola oil-in-water emulsion (scale bar = 400µm).

Figure 4-19: SEM photographs of chip thickness with different cutting fluid conditions at the feed rate of 1.0µm/flute (scale bar = 10µm).

D. Burr Formation

Figure 4-20 shows photographs of burrs generated on top of the second slot after machining. The amount of generated burrs with dry cutting is significantly larger, especially at the low feed rate. It shows that the amount of burrs decreased substantially with the use of oil-in-water emulsion. Increasing the feed rate to 1.0 µm/flute decreased formation of top burrs significantly. Increase in the mount of burrs at the low feed rate is likely due to increased rubbing and ploughing associated with small uncut chip thickness.
closed to the minimum chip thickness. Consistent with results given above, results with canola oil-in-water seem to be the best among the tree conditions examined. This shows significant improvement in cutting fluid application because, although the use of surfactants and additives are eliminated, the cutting results are similar to or better than when conventional cutting fluids are used.

Figure 4-20: Photographs of burrs formed on slot top surfaces after machining two slots at the feed rates of 0.3 and 1.0 μm/tooth.

4.3.3 Conclusions and Discussion

The following conclusions can be drawn from the work of this chapter:

- Stable emulsification of vegetable oil (canola) in water can be achieved through ultrasonic atomization without use of any surfactant.

- Vegetable oil in water emulsion with the same concentration (0.15% by volume) is obtained regardless of ratio of oil and water within the atomization chamber when ultrasonic atomization is used to generate the oil-in-water emulsion.

- Reduction in peak-to-valley values of the resultant cutting force is achieved for both materials examined (Al6061 and Steel 1018) with the use of the canola oil-in-emulsion compared to the conventional MWF (5% TRIM).
• Thinner chip thickness and less burr amount with the use of canola oil-in-water emulsion indicate that better lubrication is achieved compared to conventional MWF (5% TRIM).

• The results of this chapter show potential for vegetable oil-in-water emulsion obtained through ultrasonic atomization as an effective and environmentally friendly MWF without the use of surfactants.
Chapter 5: Mixed Jet of Independently Atomized Water and Oil Sprays as Cutting Fluids in Micro-milling

In last chapter, through ultrasonic atomization 0.15% concentration of canola oil in water emulsion without any surfactants is obtained. However, sometimes a larger ratio of oil in water is required to enhance lubrication effect during machining. So in this chapter, a novel application system including an ultrasonic atomizer and a nebulizer is applied to achieve a mixed jet of independently atomized water and oil sprays as cutting fluids in micro-milling. Then this independently atomized water and oil mixture is directly applied in micro-milling experiments. Nebulized 5% TRIM, distilled water and canola oil are also used as metalworking fluids. Distilled water instead of tap water is used in my work for better controlled experiments because minerals contained in the tap water may influence the experimental results.

After the experiments, the performance of them in cutting forces, tool wear, slots’ burrs and chip thickness is compared and discussed to obtain the conclusion of feasibility of this new mixing system. One thing that should be paid attention is that by controlling the mist velocity of low gas pressure ($V_m$) from the atomizer and the spray velocity of high air pressure ($V_s$) from the center tube in the nozzle, the ratio of canola oil and water in the mixture can be changed as requested, which is advantageous to the emulsion in Chapter 4.
5.1 Mixed Jet System including Ultrasonic Atomizer and Nebulizer

Figure 5-1: A schematic overview of the system that applies a mixture of oil and water droplets as a spray jet.

Figure 5-1 shows a schematic overview of the system that applies a mixture of oil and water droplets as a spray jet. The concept of this system involves separate atomization of oil and water, mixing of the oil and water droplets in the air, and applying the mixture as a spray jet to the cutting zone. This mixed jet system requires two atomization installations. An ultrasonic atomization device [93] designed and developed by our group and a Collison nebulizer (CN24, BGI Inc.) are available for the setup. The working theory of them is introduced below.

The schematic of working principle of this ultrasonic atomization device designed by Rukosuyev and Goo [93] is attached in Figure 5-2. Two chambers form the main body of this system. In machining, the cutting fluid is added into the sump and goes into the bottom of the atomization chamber on the right. There is a piezo vibrating at 1.75 MHz at the bottom when switched on. The power of vibration (amplitudes) can be changed as requirement. When vibrated, the liquid in the atomization chamber forms a peak. Since
the entrance position of air pressure carried into this chamber is at the almost same height with the peak, the liquid at the peak is broken up into droplets by the air. Then the air pressure transports the moisture of cutting fluid through a tube to the cutting zone.

Figure 5-2: The experimental setup and working principle of ultrasonic atomization device.

Except for the ultrasonic atomizer, a Collison nebulizer (CN24, BGI Inc.) can also be used to nebulize MWFs as shown in Figure 5-3. From the schematic of the structure inside, the fast flowing air results in a pressure $P$ which is smaller than the atmosphere press $P_0$. So the cutting fluid goes up through a tubule according to venturi effect. Then the liquid is scattered by the air pressure at the top of this tubule into droplets. The heavy droplets will impact the chamber wall and flow back to the bottom while those light ones will be directed by the air pressure through a tube to the cutting zone. This atomization method is just one example of the pressure atomization method summarized in Chapter 3.
Figure 5- 3: A photograph of nebulizer and the schematic of the structure inside.

Since vegetable-based oils do not atomize using ultrasonic vibration due to high viscosity, pressure atomization method through the nebulizer is used to atomize vegetable-based oils. While water droplets of 2-8 µm diameters are generated using the ultrasonic atomizer. As shown in Figure 5-1, as water and oil droplets are generated independently, they are carried by the carrier gas to the mixing chamber. In the mixing chamber, water and oil droplets get mixed in the air as they swirl around within the chamber. Then, the mixed droplets are carried into the nozzle. There is a tube at the center of the nozzle for the center gas to focus the droplets at the nozzle tip and create the spray jet. The nozzle tip is designed so that the droplets go through initial focusing. The nozzle tip is also detachable so that different sizes of nozzle tip can be used. The diameter of the tube for the center gas determines the spray jet diameter, and the tube can be interchanged with different diameter tubes. The center gas controls the spray jet velocity and thus the velocity control is very easy for achieving desired impingement dynamics of the droplets onto the cutting zone as well as effective flush-away of the chips.

As water and oil are atomized separately, mass flow rate of each can be controlled independently leading to precise control of the ratio of the amount of water and oil
delivered to the cutting zone. Unlike other MQL methods, the system in Figure 5-1 produces three major elements (water, oil, and jet) independently to satisfy the three roles of MWFs, that is, to cool, lubricate, and flush away chips. (1) Water droplets are very effective in cooling the cutting zone through evaporative cooling. (2) Oil droplets provide sufficient lubrication in the cutting zone. (3) The spray jet supplies enough energy for droplets to penetrate into the cutting zone to cool and lubricate and simultaneously flush away the chips from the cutting zone. As the system can control the amount of each element independently, the appropriate mass flow rates and velocity can be tailored to the materials, tools and machining conditions. In addition, because water and oil droplets are not emulsified, there is no need for surfactants or emulsifiers. Also, because only the minimum quantity of vegetable-based oil and water are used, recycling and disposal of the fluids are not necessary, eliminating the need for additives such as biocides, and defoamers.

A photograph of the system set up on a micro-milling machine is shown in Figure 5-4. As mentioned above, the ultrasonic atomizer in-house is to atomize water. The nebulizer is procured and used to atomize oil. In this chapter, canola oil is still selected because it has been known to be effective for lubrication during cutting. The nozzle was developed in-house as well and mounted to be directed towards the cutting zone. A photograph of the spray jet from the nozzle is also shown in Figure 5-4, which clearly shows the focused jet.
5.2 Machining Setup and Cutting Conditions

To test the independently atomized water and oil mixture’s performance in micro-milling, three other cutting fluids – canola oil, distilled water and 5% TRIM are separately atomized using the nebulizer to compare.

Figure 5-5 shows the setup for the atomization system with only the nebulizer. The cutting fluids are atomized into moisture in the nebulizer and then delivered to the chamber through a tube. In the end of another tube connected to the chamber, a nozzle is directed to the cutting zone so that the cutting fluid’s spray can cool and wet the workpiece successfully. This system is used for nebulizing of pure distilled water, pure canola oil and 5% TRIM.
Figure 5- 5: Cutting fluid application system with nebulizer.

Now four different kinds of MWFs conditions (nebulized distilled water, canola oil, 5% TRIM and independently atomized water and oil mixture) are applied in machining. And two types of materials (Al6061 and steel 1018) are cut using two-flute flat end mills of 396 μm in diameter. For each new tool, 25 slots of 45 mm length are tried to be milled on the metal block surface in one corresponding condition.

5.3 Experimental Results for Al6061

For Al6061, since the surface speed is 75 m/min, three feed rates of 0.3, 1.0 and 2.0 μm/tooth are chosen and a spindle speed of 60,000 rpm is selected. For each new tool, 25 slots of 45mm length are tried to be cut at the depth of cut of 150 μm. The experimental results of 2.0μm/tooth are exhibited independently since the tools are broken in the first few slots with this feed rate. The performance of 0.3 and 1.0 μm/tooth is indicated firstly in the following.

5.3.1 Results at the Feed Rate of 0.3 and 1.0μm/tooth

A. Machining Forces
Figure 5-6 shows the peak-to-valley values of the resultant milling forces for each slot at the feed rates of (a) 0.3 and (b) 1.0 µm/tooth. As shown in the line chart, the force values with nebulized canola oil as coolant through atomization system are most stable and orderly. This may due to advantageous lubrication of canola oil to the tool. Water and oil gas mixture can achieve some lowest forces considering its double effects of water’s cooling and canola oil’s lubricating. The peak-to-valley forces obtained with nebulized distilled water are larger than those obtained with oil and mixture as MWFs. Atomization with 5% TRIM leads to the highest and fluctuating peak-to-valley resultant forces during milling.
Figure 5-6: Peak-to-valley forces with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0 µm/tooth.

It is hard to figure out any other useful information in the line charts above so the average values and the standard errors are calculated of 25 slots for each condition. The result is presented in the bar chart in Figure 5-7 below. It shows that the lowest average forces can be gotten in water and oil mixture condition while the standard errors are the smallest in canola oil MQL condition, which are accordant with the information in the line charts. Nebulized distilled water as cutting fluid leads to larger average peak-to-valley forces than canola oil and mixture conditions. 5% TRIM through atomization system is the worst. This may be because this particular cutting fluid, being a general purpose metalworking fluid, is not best suited for micro-milling operations. The results clearly show that performance is mostly improved when the mixture of water and canola oil is applied.
Figure 5-7: Average peak-to-valley forces with different cutting fluid conditions at the feed rates of 0.3 and 1.0 µm/tooth.

From the analyses above, two important conclusions can be made. Firstly, canola oil behaves perfect in lubricating the cutting zone. The attendance of canola oil in cutting fluids reduces the cutting friction substantially. Besides, water is the most significant reason in cooling the cutting zone. That’s why the mixture of water and oil can have the most desired forces. However, because of the mixture, the cutting fluid is not a kind of pure liquid, which may be the reason for the unstable forces’ values in this case.

**B. Tool Wears**

Tool wear photographs were taken using an optical microscope to observe the cutting edge of the tool after 25 slots were milled. In Figure 5-8, tools’ shape with canola oil as cutting fluid obviously maintains the best. Hardly any wear is seen in the tip at both two feed rates. This verifies that canola oil behaves best in lubrication. At the feed rate of 0.3µm/tooth, tools with water, oil and mixture as MWFs all have very little tool wear while bright abraded parts come out on the tools with 5% TRIM as coolant. At the feed rate of 1.0µm/tooth, the tool is seriously worn and even broken in the tip in distilled
water condition. 5% TRIM condition takes the second place. After milling 25 slots, the lubrication performance of different MWFs conditions is evident. Canola oil keeps the tool shape best. TRIM is also a kind of oil, which thus affects better than pure water in lubrication. This can explain why the tool wear is clearest in water condition. The comparison of tool wear indicates that tool wear is mostly related to lubricating effects of the cutting fluids.

Figure 5- 8: Tool wear photographs at different MWF conditions after milling 25 slots.

C. Chip Morphology

Chips generated during slot-milling were carefully collected and examined to verify the chip morphology and thickness. Figure 5-9 shows the SEM photos of the chips generated at the feed rates of 0.3 and 1.0 µm/tooth with distilled water, canola oil, water and oil gases’ mixture and 5% TRIM through atomization. The morphologies of the chips under four conditions are interesting and distinct from each other. In the images of distilled water, the chips are well-regulated and quadrate in shape. The chips are longer and larger in size at the higher feed rate of 1.0µm/tooth. In the images of canola oil,
because of the oil’s characteristics, the chips are curved and coarse. For the mixture of water and oil, the corresponding chips are like the compromise of the chips with water and oil together. They are more squared in shape than the chips with canola oil but the sizes are pretty similar with the latter. In the lubrication with 5% TRIM, the chips are longer and curved than with other cutting fluids.

Figure 5-9: SEM photographs of generated chips (scale bar = 500 µm).

The thickness of chips can also be measured under SEM. 10 Chips are selected and calculated the average thickness value for each condition. Those average values are also attached under the images in Figure 5-10. From the photos, the thickness of the chips with oil in cutting fluid is the smallest. Distilled water condition has thicker chips and 5% TRIM conditions have the thickest ones. The thin chip with canola oil provides indirect validation of the improved lubricity effect since thinner chips are caused by higher shear angle, which is due to decrease in the friction forces.
Figure 5-10: SEM photographs of chip thickness at the feed rate of 0.3 and 1.0 μm/tooth (scale bar = 10 μm).

D. Burr Formation

Top burrs are examined to study the effects of the MWF condition on the quantitative amount of burrs on the top surface. Figure 5-11 shows photographs of burrs generated on top of the machined slots (25th slots). With water and oil mixture as MWF, the slots’ edges are thinnest and most straight. There are hardly any burrs on the top surface as well in this condition. The distilled water takes second place. A big amount of burrs exist through the new nebulization system with 5% TRIM. From the images, it can be concluded that cooling effect plays a more important role in reducing the slots’ burrs.
5.3.2 Results at the High Feed Rate of 2.0μm/tooth

Here micro-milling experiments on Al6061 at the feed rate of 2.0μm/tooth are also added to justify the results above. After machining in 4 MWFs conditions, it discovers that the tools can only machine one slot at this feed rate and then the tools are broken. The lengths of the machined slots for each condition are written besides a sketch of Aluminum block in Figure 5-12. And the peak-to-valley forces of each slot are listed in Table 5. At this high feed rate, nebulized canola oil causes the longest slot and lowest cutting force, which may indicate that lubrication is the most significant factor for Al6061 at this feed rate.
Figure 5-12: Lengths of all machined slots at different MWF conditions at the feed rate of 2.0\(\mu\)m/tooth.

Table 5: Peak-to-valley forces of each slot.

<table>
<thead>
<tr>
<th>Cutting fluid condition</th>
<th>Peak-to-valley forces [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>3.3868</td>
</tr>
<tr>
<td>Canola oil</td>
<td>2.4892</td>
</tr>
<tr>
<td>Water&amp;oil mixture</td>
<td>2.905</td>
</tr>
<tr>
<td>5%TRIM MQL</td>
<td>4.7108</td>
</tr>
</tbody>
</table>

5.4 Experimental Results for Steel 1018

For steel 1018, two feed rates of 0.3 and 1.0\(\mu\)m/tooth are still used and a spindle speed of 50,000 rpm is selected since the surface speed is 60 m/min. For each new tool, as many as slots of 45mm length are tried to be cut at the depth of cut of 50 \(\mu\)m.

A. Machining Forces

When steel 1018 is used as workpiece, the results present some difference as shown in Figure 5-13. This time the average resultant forces are calculated in Matlab instead of peak-to-valley forces. It shows that the forces increase promptly in the early few slots.
Since steel is a relatively hard material, 396 μm flat end mills may break during the machining process. So the total number of slots cut before breaking of the tool occurred can be seen in Table 6. As expected, the highest forces are observed with 5% TRIM in nebulization and the tools are earliest broken under this condition, which agrees the Al6061 experiments. This may because TRIM has no effective lubricating characteristic and the attendance of TRIM obstructs water’s cooling role. Another thing that should be noticed is that pure water atomization reduces the cutting forces to a great extent in the first several slots. It seems that water have a profound effect on cutting forces in the beginning for steel material since the cooling effect of it can decrease heat and friction forces rapidly. Forces obtained with pure oil and mixture as cutting fluids are similar to each other. However, the separately atomized canola oil and water mixture cut the greatest number of slots before breaking. This means that tool life is most improved under this condition. Likely, a combination of the added lubrication from the oil and enhanced cooling from the water is responsible. As referred before, the water only condition does result in lower forces for the first 11 to 12 slots. What may be occurring is that the added oil in the mixture condition is repelling water from the cutting zone, reducing its ability to cool. As water finally begins to saturate the surface in the mixture condition, or when the heat becomes too much for the water to handle in the water only condition due to increased tool wear, the forces between the two conditions start to match, with the mixture condition only having slightly lower forces that lead to an increased number of machined slots. Besides, the reason for forces’ large values in feed rate of 0.3μm/tooth is that 0.3μm/tooth is inappropriate for steel. Too small feed rate would lead to rubbing as well as ploughing and increase cutting forces.
Figure 5-13: Resultant cutting forces with different cutting fluid conditions at the feed rates of (a) 0.3 and (b) 1.0 µm/tooth.
Table 6: Total number of slots cut.

<table>
<thead>
<tr>
<th>Cutting fluid condition</th>
<th>Feed Rate [μm/tooth]</th>
<th>Total Number of Slots Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.3</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>25</td>
</tr>
<tr>
<td>Canola oil</td>
<td>0.3</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>24</td>
</tr>
<tr>
<td>Water&amp;oil mixture</td>
<td>0.3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>34</td>
</tr>
<tr>
<td>5%TRIM MQL</td>
<td>0.3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>9</td>
</tr>
</tbody>
</table>

**B. Tool Wears**

Tool wear photographs are taken under microscope and then compared to each other and a new tool on the left. Since tools cannot cut 25 slots on steel, tool wear is observed after two slots are machined for each condition. The tool wear phenomenon is more obvious with steel as indicated in Figure 5-14. It is evident that the tools are sharpest and maintain the most complete shape with atomized mixture of water and oil as the MWF. Especially for the tool at 1.0μm/tooth, the tips still exist as on new tools. The water only condition is better than the oil only and 5% TRIM MQL cases, which is corresponding with the forces’ changes in the early few slots according to Figure 5-13.
Figure 5-14: Tool wear photographs at different MWF conditions after milling 2 slots.

C. Burr Formation

Top burrs are observed of the 1st and 2nd slots for all the conditions at the feed rate of 0.3µm/tooth as shown in Figure 5-15. The selection reason is that under the feed rate of 0.3µm/tooth, the burrs are more obvious than those in the feed rate of 1.0µm/tooth. It shows that the slots have the least burrs and the thinnest edges with water&oil mixture as MWFs. Nebulized canola oil leads to a little more burrs than the mixture. On the contrary, a big amount of burrs and coarse edges are observed on the 2nd slot with atomized 5% TRIM as cutting fluid. For distilled water, the size of burrs along slots is pretty big and those burrs are very bright, which may because of the lack of lubricating staff in cutting zone with water. The images present that in machining steel material, the characteristic of lubrication plays an unique role in reducing slot burrs’ sizes.
5.5 Conclusions and Discussion

The following conclusions can be drawn from the work of this chapter:

- The new atomization system can apply air-mixed water and oil sprays as one spray jet to the cutting zone, which substitutes the conventional oil-in-water emulsion since it requires no surfactant or emulsifiers. And the results of micro-milling experiments show that the cutting zone can be effectively cooled and lubricated.

- Among four different kinds of cutting fluids, the mixture of distilled water and canola oil behaves best in almost all aspects including reducing cutting forces, tool wear, and slots’ burrs. This may due to the combination of both cooling and lubricating characteristics of the mixture.

- The mixed jet of independently atomized water and oil sprays has a prominent advantage, which is, any ratio of oil and water droplets in mixture can be achieved by changing the mist velocity of low gas pressure ($V_m$) from the atomizer and the spray velocity of high air pressure ($V_s$) from the center tube in the nozzle. On the contrary, the volume concentration of oil-in-water emulsion in Chapter 4 is just constant to be 0.15%.

Figure 5-15: Photographs of burrs formed on slot top surfaces.
• Combining the emulsion through ultrasonic atomization in Chapter 4, these two chapters successfully provide methods to eliminate surfactants to emulsify water and oil in cutting fluid, which reduces the harm of surfactants to humans and environment.
Chapter 6: Lignin as Additive in Metalworking Fluids for Micro-Milling

The conventional additives in metalworking fluids (MWFs) have effects in improving the machining conditions. However, many additives can bring about environmental contamination and health problems. In this chapter, lignin obtained from wood is considered as a new “green” additive in MWFs. Lignin has been used as additives in other areas like pasted lead electrodes and polypropylene/coir composites but has never been applied in cutting fluids. It is prospective to examine lignin’s performance as an additive in cutting fluids because of its pollution-free and anti-oxidation characteristics and broad source. The feasibility of lignin as an additive in MWFs is investigated in this chapter. Two different methods have been developed to uniformly add or dissolve lignin in conventional MWFs as an additive. Then, micro-milling experiments were conducted to evaluate the performance of lignin added MWFs in terms of machining forces, tool wear, and burr formation. The results were compared to those with conventional MWFs without lignin. Two different tool diameters were considered for evaluation experiments. Then, the feasibility of lignin as an additive for MWFs is discussed.

The application of lignin as additive in MWFs is also a project with Lignol Energy Corporation. The powder of lignin is purchased from the company and then be tested in cutting fluids in the Laboratory for Advanced Multi-scale Manufacturing (LAMM) in University of Victoria.

6.1 Synthesis of Lignin Containing Cutting Fluid

The objective is to add lignin powder into 5% TRIM® (conventional cutting fluid) solution as an additive with uniform dispersion. Because lignin powder does not dissolve
in water, the sonication way to mix lignin with 5% TRIM is firstly considered. Figure 6-1 shows an Auto-Sonicator (Branson) in the lab. A small amount of lignin powder and 5% TRIM solution are added in a plastic bottle and put inside the sonicator. However, after about one hour’s sonic vibration, a lot of lignin powder still floats on the 5% TRIM solution or sticks on the bottle as presented in Figure 6-2. The mixture cannot be used as cutting fluid.

Figure 6-1: Auto-Sonicator.

Figure 6-2: Lignin powder with 5% TRIM through sonication in the bottle.
The sonication method is not effective so a proper dissolvent is required in order to make completely dissolved lignin solutions. Among effective solvents such as acids, alkalis and organic solvents, ethanol is selected because of its volatility and safety. Then two methods are used to mix the lignin-alcohol solution into 5% TRIM as cutting fluids.

6.1.1 Injection and Atomization Methods

A. Injection Method

Lignin powder was dissolved in in ethanol by heating under reflux at the boiling point of the alcohol (78°C) for 2 hours, after which completely dissolved lignin-alcohol solution is obtained. The mass of lignin powder was measured before injection, and the weight of alcohol solution before and after adding lignin was also measured in order to calculate the amount of lignin in the alcohol. Then a medical type hypodermic syringe was used to inject a specific volume of lignin-alcohol solution into TRIM concentrate as shown in Figure 6-3. It is hypothesized that lignin-alcohol solution break into droplets within TRIM concentrate as it exits the needle. Then, alcohol is evaporated out of the TRIM concentrate leaving lignin particles behind, and lignin-TRIM “solution” is obtained with small lignin particles dispersed in the concentrate. In each step, we kept track of the weight of the solution for precise calculation of lignin concentration within TRIM concentrate. For use as cutting fluids, water is added to the lignin-TRIM solution proportionally to achieve a given percentage cutting fluid. For example, 95% water is added to achieve 5% cutting fluid.
B. Atomization Method

In this method, the lignin-alcohol solution was atomized first using an air-assisted atomizer before being put into the TRIM concentrate. A BGI Collison nebulizer (same one as introduced in Chapter 3) was used to nebulize the lignin-alcohol solution into fine droplets of smaller than 10 µm diameter. Then, the atomized droplets were carried by air and pushed into the TRIM for some time. The duration of atomized droplets flowing through the TRIM concentrate determines the concentration of lignin within the TRIM concentrate. As air carrying the lignin droplets exits the solution, lignin particles remain in the concentrate with uniform dispersion. A schematic of the atomization method is shown in Figure 6-4. Once alcohol is evaporated out, lignin-TRIM solution is obtained.
6.1.2 Lignin Containing Solutions

Using each method described above, 5% TRIM cutting fluids with four different lignin concentrations have been synthesized. Concentrations of lignin in the cutting fluids for each method are given in Table 7, each solution is denoted from (a) to (h). Note that lignin concentrations with the injection method are generally higher than those with the atomization method. This is because mass flow rate with the atomization is quite small, and it would take a long time to further increase the lignin concentration with the atomization method. Photographs of each solution are also given in Figure 6-5, along with a photograph of 5% TRIM solution. As shown, the solution becomes darker with increasing lignin concentration. The solutions (a) and (f) have the similar color because they have similar concentrations.

Table 7: Generated 8 lignin-Trim aqueous solutions.

<table>
<thead>
<tr>
<th>Injection Method</th>
<th>Atomization Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0.014%</td>
</tr>
<tr>
<td>(b)</td>
<td>0.05%</td>
</tr>
<tr>
<td>(c)</td>
<td>0.18%</td>
</tr>
<tr>
<td>(d)</td>
<td>0.40%</td>
</tr>
<tr>
<td>(e)</td>
<td>0.007%</td>
</tr>
<tr>
<td>(f)</td>
<td>0.015%</td>
</tr>
<tr>
<td>(g)</td>
<td>0.035%</td>
</tr>
<tr>
<td>(h)</td>
<td>0.041%</td>
</tr>
</tbody>
</table>
Figure 6-5: Eight lignin containing solutions.

Figure 6-6 shows the lignin particles seen under an optical microscope at the same magnifications. The sizes of lignin particles range from 5 to 50 µm in diameter. As shown, depending on the dispersion method and the lignin concentration, lignin particle sizes are different and agglomeration can be seen as concentration is increased. Solutions (a) and (f) are generated using two different methods (injection and atomization, respectively) but have similar lignin concentrations. As can be seen, lignin particles in solution (f) are smaller and dispersion is more uniform than those in (a). It seems that the atomization method may result in smaller particle sizes and uniform dispersion. However, they are other factors that could have caused the particle size and dispersion such as dissolution uniformity of lignin in alcohol or the alcohol evaporation process (temperature and duration). A large agglomeration can be seen in solution (d). It seems that increasing the lignin concentration leads to higher chance of agglomeration of particles.
Lignin was provided by Lignol, who produces cellulosic ethanol and lignin as a byproduct. The performance of lignin containing cutting fluids is evaluated via micro-milling experiments. To perform the micro milling tests, the custom built micro-machine tool (Alio Industries) with a spindle (NSK E800Z) at maximum 80,000 rev/min (RPM) is used. Two-fluted and four-fluted flat end mills of 396 μm and 1.6 mm (Performance Micro Tools), respectively, were used for micro-milling operations. Considering the possibility of lignin powder’ deposit into the bottom of ultrasonic atomizer, lignin containing cutting fluids are all delivered to the cutting zone using the nebulization system as presented in Figure 4-2. Cutting forces generated during micro-milling were measured using a Kistler MiniDyn 9256C1 dynamometer. The measured signals of forces were acquired through a data acquisition board (NI PCI-6133). Tool wear, machined part
quality, and burr formations were evaluated using an optical microscope (Olympus BXFM).

The experiments were carried out with each of the 8 lignin added cutting fluids as well as conventional 5% TRIM cutting fluid. Aluminum 6061 was used as the work material. Two different diameters of end mill were considered: 396 μm to represent micro-milling and 1.6 mm to represent conventional milling. Full immersion slots were milled on both materials. 25 slots were machined with each tool, and tool wear of the tool was observed afterward. With 396 μm diameter end mills, feed rates of 0.3 and 1.0 μm/tooth and spindle speed of 60,000 rpm were selected. With 1.6 mm diameter end mills, feed rates of 1.0 and 3.0 μm/tooth were selected at the spindle speed of 15,000 rpm. For each new tool, total of 25 slots were milled. The length of each slot for 396 μm tools is 40mm while for 1.6 mm mills is 20mm. The axial depth of cut was 150 μm and 300 μm for 396 μm and 1.6 mm diameter end mills, respectively.

In order to examine the effect of lignin additive on different materials with relatively low machinability, steel 1018 was also considered as work materials. Steel 1018 was machined using 1.6 mm end mill to cut slots in a length of 20mm at the feed rate of 3.0 μm/tooth, the spindle speed of 12,000 rpm, and the axial depth of cut of 150 μm.

6.3 Performance of Lignin as Additive in Cutting Fluids in Micro-milling

6.3.1 Experimental Results of Machining Al6061 with 396 μm End Mill

Since 9 solutions (a, b, c, d, e, f, g, h and 5% TRIM solutions) are used as cutting fluids and two feed rates are considered, 18 machining experiments are conducted. The experimental results are shown below.
A. Machining Forces

The average resultant forces over machining 25 slots are shown in Figure 6-7 at the feed rates of 0.3 and 1.0 µm/tooth when different cutting fluids were used. The lignin concentration is indicated on top of the bars for each lignin added cutting fluid. The dissolution method is also displayed above the plot. It shows that with the injection method, cutting fluids with higher lignin concentrations led to higher forces than the conventional cutting fluid (5% TRIM). Considering that lignin added cutting fluids (b), (c), and (d) all have higher lignin concentration than the lignin added cutting fluids achieved using the atomization method, it seems that too high lignin concentration has adverse effect on the cutting performance. This may be due to the presence of large agglomerated lignin particles. The forces measured when lignin added fluids achieved with the atomization method are all lower than that when 5% TRIM is used. The lowest forces are achieved with the lignin added cutting fluid (f); almost 50% reduction is achieved at the feed rate of 0.3µm/tooth. Decreasing or increasing the lignin concentration from the concentration of (f) leads to increased forces. Comparing the results with (a) and (f), which have similar lignin concentrations, it seems that the atomization method results in better machining performance, likely due to better lignin particle dispersion. The results shown in Figure 6-7 indicate that lignin as an additive can improve the machining performance of the cutting fluid under the appropriate conditions.
Figure 6-7: Average resultant forces with different lignin added cutting fluids.

**B. Tool Wear**

Tool wear photographs were taken using an optical microscope to observe the cutting edge of the tool after twenty five slots were milled, and the photographs of tool wear at the feed rate of 0.3 µm/tooth are shown in Figure 6-8. Significant wears are observed with lignin added cutting fluids (c) and (d). This is expected because large forces are also observed with these fluids. There is also substantial wear with 5% TRIM. On the other hand, hardly any wear is observed with (f), which is consistent with the cutting force measurements. The fluid (a) has similar lignin concentrations as (f) but synthesized using the injection method. However, slightly more wear is observed with (a) compared to that with (f). This confirms that atomization method is better for synthesis of lignin added cutting fluids. Nevertheless, tool wear with (a) is small compared to that with most of fluids. It seems that lignin concentration around 0.015% is quite appropriate when lignin is used as an additive.
Figure 6-8: Tool wear photographs under different MWF conditions after milling 25 slots of Al6601 at the feed rate of 0.3µm/tooth.

C. Slots’ Burrs

Machined surfaces and top-burrs have been analyzed using an optical microscope as well. The photographs of the first and last slots machined when 5% TRIM, (a), (d), and (f) are used as cutting fluids are given in Figure 6-9. Consistent with the results above, significant amount of burrs can be observed with (d). The amount of burrs is also quite significant when 5% TRIM is used. However, only small amount of burrs is observed with (f) even after machining 25 slots at both feed rates.
Figure 6-9: Photographs of machined surfaces with different cutting fluids.

6.3.2 Experimental Results of Machining Al6061 with 1.6 mm End Mill

Experiments were also conducted using a larger diameter tool (1.6 mm). Note that higher feed rates (1.0 and 3.0 µm/tooth) were considered since the tool diameter is larger. All lignin added cutting fluids (a) to (h) were used to evaluate their cutting performance.

A. Machining Forces

The average machining forces during machining 25 slots of Al6061 with different cutting fluids are shown in Figure 6-10. The results are quite similar to those with 0.396 mm diameter end mill. The lignin concentration of 0.015% dissolved in conventional cutting fluids using the atomization method, i.e., fluid (f), results in the best performance; the measured cutting force is the lowest with this lignin added cutting fluid. It also shows that the average resultant forces at all other conditions are quite comparable to the results.
with 5% TRIM, and this shows that appropriate concentration of lignin is important for improved cutting fluid performance.

![Bar chart showing average resultant cutting forces of machining Al6061 with 1.6 mm diameter end mill.](image)

**Figure 6-10:** Average resultant cutting forces of machining Al6061 with 1.6 mm diameter end mill.

**B. Tool Wear**

Optical microscope photographs of the tool wear after cutting 25 slots of Al6061 at the feed rate of 1.0 µm/tooth are shown in Figure 6-11. Similar to the cutting force results, more wears are seen with 5% TRIM and (d). With the injection method, cutting forces were the lowest with (a), and the tool wear seems to be the smallest with (a) as well. With the atomization method, very little wear is observed with (f), which is consistent with previous results.
Figure 6-11: Tool wear photographs under different MWF conditions after milling 25 slots of Al6061 at the feed rate of 1.0 µm/tooth with 1.6 mm diameter tool.

C. Slots’ Burrs

Figure 6-12 shows machined surfaces and top-burrs of the 25th slot when 5% TRIM and lignin added fluids (a), (d), and (f) are used. Presence of some burrs can be observed with 5% TRIM especially at the feed rate of 3.0 µm/tooth. As expected, increased amount burrs is detected with the fluid (d). However, the amount of burrs is significantly decreased with the fluids (a) and (f). Hardly any burr is seen with the fluid (f). This result is consistent with cutting force and tool wear results. The burr results with other fluids also show the same trend.
6.3.3 Experimental Results of Machining Steel 1018 with 1.6mm End Mill

In order to examine the effect of lignin additive on a different material, a 1.6 mm diameter end mill was used to machine steel 1018 at the axial depth of cut of 150 µm. Four lignin added cutting fluids (a, b, f, and h) were selected for cutting experiments with steel 1018 because cutting performances are better at their lignin concentrations. In addition, two pairs (a–f and b–h) have similar lignin concentrations achieved using different dissolution methods. By comparing the results within each pair, the effect of the dissolution method can be also evaluated. Under each fluid condition, total of 15 slots were machined with a new tool.

Due to excessive wear when cutting steel 1018, cutting forces increased substantially after cutting each slot. Figure 6-13 shows comparison of peak-to-valley values of the resultant forces when 5% TRIM and fluid (f) were used. Increase in machining forces after cutting each slot is clearly seen. It also shows that the peak-to-valley values are similar with both fluids initially, but values with 5% TRIM increase more rapidly than those with the lignin added fluid (f).
Figure 6-13: Peak-to-valley values of resultant forces with steel 1018 as work material.

Figure 6-14 shows peak-to-valley values of resultant forces averaged over 5 slots when cutting fluids, (a), (b), (f), (h), and 5% TRIM are used. Consistent with previous results, the cutting fluid (f) performs the best. Also, it is clear that the atomization method to dissolve lignin in cutting fluids (f and h) is better than the injection method (a and b). Figure 6-15 shows photographs of first and last machined slots under different cutting fluid conditions. As shown, least amount of burrs are observed with (f) on both the first and last slots. Feed marks are more uniformly and clearly shown with (f) as well. It seems that the machined slot quality is the worst with (b) and 5% TRIM. This is also the same with cutting force measurements shown in Figure 6-14. This indicates that when added at appropriate concentration, lignin can be an effective additive to achieve improved cutting performance for steel 1018 as well.
Figure 6-14: Peak-to-valley of resultant forces averaged over five slots under different fluid conditions.

Figure 6-15: Photographs of machined slots and burrs with steel 1018 under different fluid conditions.

6.4 Conclusions

The following conclusions can be drawn from the work of this chapter:
- Two different methods (injection and atomization) have been developed to achieve addition of lignin as an additive into conventional cutting fluids.

- The experimental results show that the atomization method leads to better machining performance potentially owing to more uniformly dispersed lignin particle within conventional cutting fluids.

- When the added lignin concentration is too high (> 0.05%), adding lignin no longer has positive effect on machining performance.

- When added at appropriate concentration, lignin can be an effective additive to achieve improved cutting performance. It seems that concentration of around 0.015% is an appropriate value to use lignin as an additive.

- The results of this chapter show feasibility of lignin as a green additive in conventional cutting fluids.
Chapter 7 Conclusion and Future Work

7.1 Conclusions

In this thesis, three creative alternatives for conventional cutting fluids and application systems in micro-milling are discovered and identified cautiously. The content of Chapter 4, 5 and 6 carefully presents the certification process of: eliminating the use of surfactants through canola oil-in-water emulsion and a mixed jet of independently atomized water and oil sprays as cutting fluid, as well as the feasibility of lignin as green additive in cutting fluids. A lot of positive results have been approached and the conclusions of them have already attached at the end of each chapter. Here a summary is made to sum up of all the experiments in this thesis.

For emulsion of canola oil and water as cutting fluid in Chapter 4, not only the effective characteristics of vegetable oil-based emulsion in micro-milling have been proved, but the ultrasonic atomization way to emulsify oil and water without any surfactants has been figured out as a good idea. Besides, the lubrication effect of canola oil-in-water emulsion is unsurpassable compared to traditional MWFs. Thus, a kind of simple but clean cutting fluid, water and vegetable oil emulsion without any surfactants is achieved in the field of sustainable cutting fluids. The only limitation of the obtained emulsion is that the concentration of oil in water is 0.15% in volume, which cannot be changed.

For the examination of mixed jet of independently atomized water and oil sprays in Chapter 5, the best behavior of oil and water mixture through this system has been justified in this chapter. And the two most significant effects of MWFs in manufacturing, cooling and lubrication, are analyzed about their priority in causing different machining
performances. That is, cooling is more important in decreasing forces while lubricating is the primary factor in maintaining tools and surface’ smoothness. Finally, the superiority of the new atomization system has been proved being able to cool and lubricate the cutting zone effectively for both Al6061 and steel 1018. Considering the outcome in Chapter 4, this chapter offers another way to apply water-oil mixture without toxic surfactants as cutting fluid. In addition, the ratio of oil and water through this system can be adjusted as required.

For the machining experiments of lignin as additive in metalworking fluids in Chapter 6, lignin powder from the nature has been used as additive in cutting fluids for the first time. And the participation of it indeed develops the performance of 5% TRIM solution much. Especially the concentration of 0.015% lignin plays an outstanding role to decrease the cutting forces, tool wear and slot burrs. The performance in lubricating and cooling cutting zone is even better than the nebulized canola oil and distilled water in Chapter 5. Lignin seems to be a pretty prospective additive in cutting fluids. However, one thing that should be noticed is that too little or too much amount of lignin has no improvement or even negative influences to the cutting processes. In addition, in synthesis of the lignin containing 5% TRIM solution, atomization method through a collison nebulizer is a better way than injection method.

The basic research objectives referred in Chapter 1 are accomplished as expected. Two ways – eliminating surfactants and replacement of conventional additives with lignin in cutting fluids in micro-milling are finally fulfilled. Here, the obtained emulsion as cutting fluid, lignin as additive, and the mixed jet of independently atomized water and oil sprays are also prospective in conventional machining operations in macro scales.
7.2 Future Work

There is a lot of work that should be further conducted relating to the research in this thesis. They are listed below:

- As introduced in Chapter 5, the ratio of oil and water droplets in the mixture achieved through the mixed jet system is arbitrary. So in the future work, by controlling the velocities of low gas pressure from the ultrasonic atomizer and the nebulizer, different ratios of water and oil mixture can be obtained and subsequently be applied in micro-milling to compare their performances.

- In this thesis, two kinds of water and oil based green cutting fluids are introduced: mixture of independently atomized water and oil droplets and oil-in-water emulsion. It will be interesting if comparing their performances in micro-milling. The results will indicate which method is even more effective.

- Lignin as additive in cutting fluid is an audacious idea but the reality of it is not so mature recently. In this thesis, even though lignin has already been tried to be dissolved in 5% TRIM, there are still several defects. Since TRIM is not environmental friendly, the attendance of lignin in it yet cannot be treated as a completely “green” method. But the reason to mix lignin inside is that lignin is unable to dissolve in water and TRIM droplets may stick the lignin particles in the liquids. According to this, the components except for lignin in cutting fluids should be reconsidered. In the future work, vegetable oil may replace TRIM as the assisting oil for lignin in aqueous solution. Then the whole solution is pure and clean. Besides, the most difficult thing is how to mix lignin powder into aqueous solution, in this thesis, alcohol is taken advantage of as the first solvent and two methods, injection and atomization, are used to synthetize lignin-alcohol solution.
and 5% TRIM. During the synthetizing process, the volatility of alcohol is an advantage since alcohol itself can be removed from the final solution successfully. In the future research, many more interesting ways can be discovered to mix lignin into aqueous solutions. Eventually, the potential of lignin as additive in cutting fluids needs more tests. More different concentrations of lignin from those in Chapter 6 should be obtained to verify if 0.015% is indeed the best one. And different materials besides steel and aluminum can be examined.
Bibliography


