ANALYSIS OF DROPLET BEHAVIOR ON A ROTATING SURFACE IN
ATOMIZATION-BASED CUTTING FLUID SYSTEMS FOR MICRO-MACHINING

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THESIS
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Abstract

Atomization-based cutting fluid (ACF) systems have been recently found to be effective in providing both cooling and lubrication for micro-scale machining operations. The ACF systems are preferable over the conventional flood cooling methods as they effectively reduce the temperature at the workpiece-tool interface through evaporative cooling and provide superior lubrication to the cutting zone. While such ACF systems appear to be beneficial, there is a lack of a physics-based understanding of the phenomena underlying cooling and lubrication performance of ACF systems in micro-machining processes.

The research presented in this thesis investigates the effect of ACF system parameters and machining conditions on the cooling and lubrication performance in micro-machining processes in order to enable the design of efficient ACF systems. To accomplish this, experiments are first conducted to understand the cooling and lubrication mechanism of ACF systems. The knowledge gained from the experiments is then used to develop a model-based approach to the design of ACF systems for high cooling and lubrication performance in micro-machining.

On the experimental front, micro-turning experiments are carried out and the cutting performance evaluated for varying cutting fluids and at different droplet speeds. Micro-turning experiments indicate that a cutting fluid with low surface tension and low viscosity generates lower cutting temperatures whereas a fluid with low surface tension and high viscosity generates lower cutting forces. Since in most machining processes, either the workpiece or the tool is rotating, single droplet impingement experiments are
also conducted on a rotating surface using fluids with different surface tension and viscosity values. Upon impact the droplet shape is observed to be a function of both the droplet speed and the surface speed. The spreading increases with increased surface speed owing to the tangential momentum added by the rotating surface. Spreading is observed to also increase with a decrease in fluid surface tension and does not change with the fluid viscosity. It is concluded that a fluid with low surface tension and low viscosity is an effective coolant of the cutting zone, whereas, a fluid with low surface tension and high viscosity is effective for lubrication. Another set of single droplet impingement experiments are conducted on a rotating surface to capture the 3D shape of a droplet upon impingement to aid the model development.

On the modeling front, a parameterization scheme is developed to mathematically define the 3D shape of droplet upon impingement. The shape information is used to develop an energy-based model for droplet spreading. The droplet spreading model captures the experimental results within 10% accuracy. The spreading model is then used to predict the cooling and lubrication for an ACF-based micro-turning process. The model captures the cooling and lubrication trends observed in micro-turning experiments. A parametric study is conducted to identify the significant factors affecting the performance of an ACF system. Droplet speed is found to have a dominant effect on both cooling and lubrication performance, particularly, with a low surface tension fluid for cooling and a low surface tension and high viscosity fluid for lubrication.
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Nomenclature

\( a_{1f}, b_{1f} = \) semi-axis lengths of ellipse \( E_{1F} \)
\( a_{2f}, b_{2f} = \) semi-axis lengths of ellipse \( E_{2F} \)
\( a_1, b_1, c_1 = \) semi-axes of ellipsoid \( E_1 \)
\( a_2, b_2, c_2 = \) semi-axes of ellipsoid \( E_2 \)
\( A_1 = \) surface area of ellipsoidal cap APBQA
\( A_2 = \) surface area of ellipsoidal cap CPBQC
\( A_3 = \) surface area of ellipsoidal base APCQA
\( A = \) droplet contact area at the condition of maximum spread
\( c = \) penetration coefficient
\( d_o = \) droplet diameter
\( d_1 = \) length of major-axis of droplet in top-view
\( d_2 = \) length of minor-axis of droplet in top-view
\( E_v = \) energy lost to viscous dissipation
\( f = \) lubrication force generated by one droplet
\( F = \) total lubrication force generated by the droplets
\( l_o = \) distance of nozzle from the cutting zone
\( l_1 = \) contact length AD
\( l_2 = \) contact length DC
\( h = \) droplet height
\( KE_1 = \) droplet kinetic energy before impact
\( k_s = \text{thermal conductivity of the surface} \)

\( k_f = \text{thermal conductivity of the cutting fluid} \)

\( M = \text{volume flow rate of the atomizer} \)

\( n = \text{number of droplets reaching the cutting zone per second measured at mist velocity} \)

\( N = \text{number of droplets reaching into the cutting zone per second} \)

\( N_o = \text{flow rate of atomizer in droplets per second} \)

\( \text{Oh} = \text{Ohnesorge number} \)

\( q = \text{heat transferred from the surface to one droplet} \)

\( Q = \text{total heat transferred from the cutting zone to the cutting fluid} \)

\( r = \text{nozzle radius} \)

\( R = \text{radius of curvature of the droplet upon impact} \)

\( SE_1 = \text{droplet surface energy before impact} \)

\( SE_2 = \text{droplet surface energy after impact} \)

\( T_o = \text{ambient air temperature} \)

\( t_s = \text{time taken by the droplet to spread to its maximum} \)

\( u_o = \text{droplet speed} \)

\( u_s = \text{surface speed} \)

\( V_{11} = \text{volume of ellipsoidal cap APBQA} \)

\( V_{22} = \text{volume of ellipsoidal cap CPBQC} \)

\( V_1 = \text{droplet volume before impact} \)

\( V_2 = \text{droplet volume after impact} \)

\( v_x = \text{fluid velocity in x-direction} \)
\( \nu_z \) = fluid velocity in z-direction
\( \nu_m \) = mist velocity
We = Weber number

Greek Symbols

\( \alpha \) = angle at which flow emerges from the nozzle
\( \beta_1, \beta_2, \beta_3, \beta_4 \) = least square fit coefficients
\( \lambda \) = proportionality constant
\( \mu \) = fluid viscosity
\( \theta_1 \) = advancing contact angle
\( \theta_2 \) = receding contact angle
\( \theta_c \) = equilibrium contact angle
\( \theta_0 \) = equivalent contact angle
\( \rho \) = fluid density
\( \sigma_{lv} \) = surface tension between fluid and air
\( \sigma_{sl} \) = surface tension between fluid and solid
\( \sigma_{sv} \) = surface tension between solid and air
\( \psi \) = viscous dissipation function
Chapter 1

Introduction

1.1 Background and Motivation

Micro-machining, in particular, micro-milling, micro-drilling, and micro-turning, provides both a viable and potentially preferable process to satisfy the requirements for production of components with manufactured features in the range of a few to a few hundred microns with high relative accuracies for a wide range of engineering materials. However, the limitations of micro-tooling technologies (large edge radii and poor geometry control) and the resulting ploughing mechanism and minimum chip thickness effect [1] lead to increased levels of tool wear and tool failure. For improving the cutting performance in such micro-scale machining operations, atomization-based cutting fluid (ACF) systems have been found to be preferable over the conventional flood cooling methods as they effectively reduce the temperature at the workpiece-tool interface through evaporative cooling and provide superior lubrication to the cutting zone [2]. While such ACF systems appear to be beneficial, there is a lack of a physics-based understanding of the phenomena underlying cooling and lubrication performance of ACF systems in micro-machining processes.

For micro-machining processes, ACF systems have been found to be attractive wherein the micro-sized atomized droplets access the cutting zone, provide effective
lubrication at the tool-chip interface, and remove heat from the cutting zone through evaporative cooling. Jun et al. [2] used an ACF system for micro-milling process with droplets of diameter 6-10 µm impinging upon the cutting zone wherein the tool rotational speed was of the order of 2m/s. They found that atomization-based cutting fluid application is more effective than the conventional flood coolant application. The experimental results showed that the cutting forces are lower and tool life is significantly improved with the atomized cutting fluids when compared to dry and flood cooling methods. Also, application of atomized cutting fluid was found to result in good chip evacuation and lower cutting temperatures. The study suggested that the droplet impingement dynamics on a rotating surface are an important factor in determining the cooling and lubrication performance of an ACF system. However, their study did not investigate the relationship between droplet dynamics and the observed cutting performance. Furthermore, their study did not consider the effect of fluid properties, viz., surface tension and viscosity, on the efficiency of lubrication and cooling when the cutting fluid is applied in atomized form.

Atomized droplets have been used in the form of sprays for a wide range of cooling applications wherein the surface to be cooled is usually held stationary. Thus, over the years, a large knowledge base has been developed exploring the fundamental basis of the cooling observed in spray applications for cases where the target surface is stationary [3-5]. These studies have revealed that the cooling capacity of a spray is influenced by the droplet characteristics (droplet size and size distribution, droplet speed), which are also affected by the atomization method (e.g., pressure nozzle, ultrasonic vibration), atomization parameters (nozzle size, vibration frequency), and the
fluid properties (surface tension and viscosity) [6-7]. Knowledge of droplet impingement dynamics and the ensuing spreading and evaporative behavior forms the fundamental basis of understanding of the physics underlying spray cooling applications.

In general, droplet impingement upon a surface is classified into four distinct regimes: stick, rebound, spread and splash. The observed regime is dependent upon the droplet characteristics, fluid properties and surface characteristics [8-9]. The first regime, i.e., the stick regime occurs when an impinging droplet adheres to the wall or film surface in nearly a spherical form. This often happens when the impact energy is extremely low, and the surface temperature is below the pure adhesion temperature [8]. The rebounding regime occurs when the impinging droplet bounces off the wall or film. The air layer trapped between the droplet and the surface causes low energy loss resulting in bouncing. The third regime, spreading, is similar to the sticking regime but occurs when the impact energy is large. Finally, the fourth regime is where splashing or further atomization occurs and droplets break into many secondary droplets.

For the purpose of atomized cutting fluid application, the objective is to wet the cutting zone effectively through spreading. Thus, the droplet characteristics and fluid properties should be such that the droplet undergoes spreading when it impinges upon the rotating surface. It has been shown in [8] that to ensure spreading a set of conditions must be met. These conditions have been defined in fluid dynamic terms using dimensionless groups such as Weber number and Ohnesorge number [8] that include droplet characteristics and fluid properties.

A limited number of studies have been conducted for investigating droplet impingement dynamics on rotating surfaces. Povarov et al. [10] studied the impingement
regimes of droplets of diameter 0.3-4.0 mm with the boundary layer on a rotating surface. They found the droplets to be either partially reflected or deposited onto the surface based on the relative magnitudes of droplet speed and surface speed. Mundo et al. [11] investigated the deposition-splash boundary for droplet impinging upon rotating surfaces. Their tests were conducted with droplets in the diameter range 60-150 µm and for a wide range of fluid properties with surface tension in the range 22-72 mN/m and viscosity in the range 1-2.9 cP. An empirical expression for the deposition-splash boundary was proposed based on the experimental observations. The result from their study helps in predicting whether a droplet will deposit on a rotating surface or will splash to form smaller satellite droplets. Since their objective was simply to avoid droplet splashing for better surface finish in spray coating/painting applications, no investigation of the droplet spreading behavior was carried out.

In order to understand the effect of surface speed on the impingement behavior of droplets for spray coating and spray cooling applications, Chen and Wang [12] studied the impact of water droplets with sizes 500-900 µm upon a rotating Teflon surface. For such water droplets, at surface speeds above 4 m/s, necking and subsequent splitting of droplets was observed. Based on the experimental data collected, the transition boundaries for partial-rebound to deposition and deposition to split-deposition were proposed. Although they showed that the contact area for the droplets is dependent on the surface speed, their experiments were limited only to the study of water droplets. The droplet diameters used in this study were also significantly larger to those encountered in the atomized cutting fluid application. Furthermore, the studies of both Mundo et al. [11] and Chen and Wang [12] did not investigate the spreading and evaporation behavior of a
droplet impinging on a rotating surface as a function of specific fluid properties, viz., surface tension and viscosity.

There has been extensive research done to model the spreading behavior of a droplet impinging upon a stationary surface [13-15]. The droplet diameters in these studies ranged between 20 µm and 4 mm and droplet impact velocities were between 0.5-6 m/s. These studies reveal that the droplet spreading upon impact can be classified into two distinct phases, viz., the initial spreading phase that results in a maximum spread diameter followed by a recoil phase during which the droplet undergoes oscillations that change the droplet contact area and height with time [14-15]. Given the symmetry of the droplet shape upon impact, the spreading dynamics is modeled as a 2D problem. In all these studies, the droplet is modeled to spread out in the shape of either a thin cylindrical disk or a spherical cap. This shape information is then used to determine the energy of the droplet after impact and is critical in accurately modeling the spreading behavior of droplet upon impact. Attané et al. [13] showed that the accuracy of the spreading model is dependent upon the assumed shape of the spreading droplet. The experiments of Povarov et al. [10] and Chen and Wang [12] show the presence of a rotating surface changes the dynamics of the spreading process imposing a need to develop a 3D spreading model to capture the asymmetric geometry of the droplet upon impact.

While the initial studies have been successful in establishing the effectiveness of ACF systems in micro-machining processes and in investigating the impingement dynamics of droplets upon a rotating surface, several gaps in knowledge still exist. First, there is a lack of micro-machining studies that identify the combined effects of droplet characteristics and cutting fluid properties on the cooling and lubrication performance of
ACF systems. Second, there is a lack of understanding of droplet spreading behavior on a rotating surface, in particular, as a function of droplet characteristics, fluid properties and surface speed. Third, modeling work on droplet spreading on a rotating surface has not been undertaken. A spreading model that predicts droplet geometry resulting from spreading on a rotating surface will be important to predict the cooling achieved by a droplet in the cutting zone and the lubrication force generated at the tool-chip interface. Last, no study has been done to understand the relationship between droplet spreading behavior on a rotating surface and the cooling and lubrication performance of an ACF system in micro-machining processes.

1.2 Research Objectives, Scope, and Tasks

1.2.1 Research Objectives and Goals

This research investigates the effect of ACF system parameters and machining conditions on the cooling and lubrication performance in micro-machining processes in order to enable the design of efficient ACF systems. To accomplish this, the specific objectives are:

1. To gain knowledge of effect of droplet characteristics, cutting fluid properties, and surface speed on the droplet spreading behavior on a rotating surface.

2. To link the knowledge gained on the droplet spreading behavior with the cooling and lubrication performance of ACF systems in micro-machining processes.
The overarching goal of the research is to use the above knowledge to develop a model-based approach to the design of ACF systems for high cooling and lubrication performance in micro-machining.

1.2.2 Scope of Research

This research focuses on investigating and modeling the droplet spreading on a rotating surface with an aim to enable design of better ACF systems. Since ACF systems involve droplet diameters in the range of 6-20 µm, this work will consider only droplet diameters less than 50 µm. Given the high temperatures encountered during machining, it is expected that the initial dynamics prior to the maximum spreading is not critical, rather the contact geometry that the droplet achieves at the maximum spread condition. The droplet spreading model on a rotating surface, therefore, focuses on predicting the droplet spreading at the condition of maximum spread. The surface roughness values encountered in micro-machining are in the range of tens to hundreds nanometers [16] whereas, the initial diameter of the atomized droplet is between 6-20 µm. Since the droplet has 20 times larger diameter than the ridges on the machined surface, for modeling purposes it is assumed that surface is perfectly smooth. The surface speeds considered in this study will be within the range of speeds typically used in the micro-machining of metal, i.e., a few meters/second.

1.2.3 Research Tasks

The objectives of this research will be achieved in the two phases that are described in detail below.
Phase I. Focus will be on the experimental investigation of the droplet behavior on a rotating surface to better understand the physics underlying the cooling and lubrication performance of ACF systems. This will be achieved in the following sequence of tasks:

1. Conduct micro-turning experiments and evaluate the cutting performance for cutting fluids with varying physical properties and at different droplet speeds.
2. Conduct single droplet impingement experiments on a rotating surface for fluids with different surface tension and viscosity values and study the spreading and evaporation behavior.
3. Interpret the machining results in light of results from single droplet experiments to identify the factors affecting the performance of an ACF system.

Phase II. Model development will be undertaken to predict the cooling and lubrication performance of ACF systems. The specific tasks to be completed are:

1. Conduct single droplet impingement experiments to capture the 3D shape of droplet upon impact on a rotating surface.
2. Develop a parameterization scheme to define the 3D shape of a droplet and use it to model droplet spreading on a rotating surface.
3. Use the output of spreading model to predict the heat transferred from the cutting zone to the droplets and the lubrication force generated by the droplets at the tool-chip interface.
4. Accomplish model validation by using the spreading model to predict the cooling and lubrication performance of an ACF-based micro-turning application.
5. Use the validated spreading model to conduct a parametric study in an effort to develop guidelines for the design of effective ACF systems.
1.3 Overview of Thesis

Chapter 2 provides an overview of the available literature on droplet dynamics and performance of ACF systems. First, previous work on use of ACF systems in micro-machining processes will be discussed. Next, droplet dynamics on stationary and rotating surfaces will be discussed. Then, droplet spreading models for stationary surfaces will be introduced. Last, the usage of spray-based systems for cooling will be discussed.

In chapter 3, micro-turning experiments are conducted to understand the effect of droplet speed and cutting fluid properties on cutting forces and cutting temperatures. The cutting performance is evaluated for varying droplet speeds and fluid surface tension and viscosity values.

In chapter 4, droplet behavior on a rotating surface is studied to better understand the physics underlying atomized cutting fluid application. First, single droplet impingement experiments are conducted on a rotating surface using fluids of different surface tension and viscosity values to understand the spreading and ensuing evaporative behavior of a droplet from a rotating surface. The micro-turning results presented in chapter 3 are then interpreted with the help of the results from the single-droplet experiments to shed light on the underlying physics of cooling and lubrication in ACF systems.

Chapter 5 presents droplet spreading model developed with an aim to predict droplet spreading behavior on a rotating surface. First, single droplet impingement experiments are conducted on a rotating surface to capture the 3D shape of a droplet upon impingement. A parameterization scheme is then developed to mathematically define the
3D shape of droplet upon impingement. The shape information is used to develop an energy-based model for droplet spreading.

In chapter 6 model validation is accomplished using the spreading model to predict the cooling and lubrication performance of an ACF based micro-turning application. Next, a parametric study is conducted to identify the significant factors affecting the performance of an ACF system.

Chapter 7 provides the conclusions reached through the research and gives suggestions for the direction of continued work in this area.
Chapter 2

Literature Review

The following chapter provides an overview of the available literature concerning the performance of atomization-based cutting fluid (ACF) systems and associated droplet dynamics. The review is divided into five subsections. Section 2.1 discusses the use of ACF systems and their performance in machining processes. Section 2.2 introduces the basics of atomization and droplet impingement dynamics. Section 2.3 reviews previous experimental research on droplet spreading dynamics and modeling work done on droplet spreading. Section 2.4 examines the cooling and lubrication models to predict performance in a machining process. The last section summarizes the previous research to date and lists the areas where further research is needed.

2.1 Mist-based Cutting Fluid Systems

2.1.1 Minimum Quantity Lubrication

Generally speaking, application of cutting fluid in a machining process acts as a cooling and lubricating agent, hence the cutting temperature and cutting force is reduced and the tool life and machined surface finish is improved. However, the conventional flood coolant application consumes large amounts of fluid posing cost issues [17-18] and also has serious environmental pollution and health issues owing to mist generated during cutting operations [17-18]. The used cutting fluids further pose waste disposal problems
due to their hazardous nature [17-18]. In order to mitigate such effects, minimum quantity lubrication (MQL) approach has been introduced and developed wherein the cutting fluid is applied in form of a directed mist [17-18].

In MQL approach, the cutting fluid is fed to the tool and/or machining point in tiny quantities. This is done with or without the assistance of a transport medium, e.g., air. In the case of the former, the so-called airless systems, a pump supplies the tool with the medium, usually oil, in the form of a rapid succession of precision-metered droplets. In the case of the latter, the medium is atomized in a nozzle to form extremely fine droplets, which are then fed to the machining point in form of an aerosol spray.

Lacalle et al [19] assessed the efficiency of MQL in high-speed milling of wrought aluminum alloys wherein it is usual to observe the presence and growth of a build up edge. The study of flank wear evolution showed that the wear with MQL is always smaller than wear with conventional cutting fluid application. A computational fluid dynamics (CFD) simulation was done to study the lubricant flow on the rotating tool for the two cases to better understand the mechanism underlying each application. The velocity field for both the application methods is shown in Fig. 2.1. For flood coolant application (Fig. 2.1a), a wall is generated in the tool vicinity that obstructs the way of the cutting fluid towards the tool center. Therefore, the application is inefficient because it does accomplish neither the cooling function by convection, nor the lubrication function. It only acts taking out chips from the cutting zone. A similar study for MQL (Fig. 2.1b) shows that the MQL jet adequately penetrates in the inner zones of the tool edges. Therefore, the three actions expected from the fluid (cooling, lubrication and chip evacuation) are successfully performed. It was further observed that MQL application
reduced the quantity of cutting fluid used by 95% in comparison to the flood coolant application leading to considerably lower overall machining costs.

Figure 2.1 The velocity field with (a) flood coolant application (b) MQL [19]

Ueda et al [20] investigated the use of oil mist in turning of carbon steel and observed effective reduction in cutting temperatures when compared to dry cutting. As shown in Fig. 2.2, the tool temperature is about 60°C lower in MQL compared to dry turning. It was hypothesized that the deposition of cutting fluid on the tool face decreases the friction between the tool face and the chips, and this action suppresses the temperature rise during the cutting operation in MQL application. Liao et al. [21] used MQL in high-speed machining of hardened steel to investigate the performance mechanism underlying MQL application. It was found that MQL provides extra oxygen to promote the formation of a protective oxide layer in the chip–tool interface that promotes the reduction of friction (Fig. 2.3).
Figure 2.2 Effect of cutting fluid applied as mist on tool temperature in turning [20]

![Graph showing the effect of cutting fluid on tool temperature](image)

Dhar et al. [22] compared the performance of MQL to dry turning of AISI-1040 steel based on experimental measurement of cutting temperature, chip reduction coefficient, cutting forces, tool wears, surface finish, and dimensional accuracy. Results indicated that the use of near dry lubrication leads to lower cutting temperature and cutting force, favorable chip–tool interaction, reduced tool wear, improved surface
roughness, and improved dimensional accuracy. MQL reduces the cutting temperatures leading to improved chip-tool interaction. Further, cutting forces were also observed to reduce by about 5-15% attributed to retention of cutting edge sharpness due to reduction of cutting temperatures. MQL resulted in reduced flank wear and hence is expected to improve tool life. Surface finish and dimensional accuracy improved mainly due to reduction of wear and damage at the tool tip by the application of MQL.

While the above studies show that use of MQL is advantageous in terms of cutting performance and economic viability, they were conducted for macro-scale machining operations. Recent advances in medical, aerospace, electronics, and communication industries require manufactured features in the range of a few to a few hundred microns with high relative accuracies. However, the limitations of micro-tooling technologies (large edge radii and poor geometry control) and the resulting ploughing mechanism and minimum chip thickness effect \([1]\) lead to increased levels of tool wear and tool failure. For such micromachining processes the conventional cutting fluid applications are not viable approaches for two prime reasons: (1) the impact force of the cutting fluids may be greater than the cutting forces since micromachining forces are only in the order of a few Newtons \([23-24]\), and (2) the cutting zone is very small (chip loads are only a few microns or less) so fluid penetration is an important issue. The use of atomization-based cutting fluid application to circumvent such issues resulting in improved cutting performance in micromachining processes is discussed in the next section.
2.1.2 Atomization-based Cutting Fluid Systems in Micromachining

Jun et al [2] used an atomization-based cutting fluid (ACF) system for micro-end milling of aluminum. They found that for micro-machining processes, it is desirable that the ACF system produce a spray with droplet sizes in the range of 5-15 µm for effective penetration into the small cutting zone and the droplet velocity is high (several m/s) so that the chips are evacuated effectively. A schematic of the ACF system used by Jun et al. [2] is shown in Fig. 2.4. The system includes an ultrasonic vibration-based atomizer, cutting fluid reservoir tank, air supplies, and vacuum-based exhaust system to draw excessive cutting fluid in the form of mist from the air. Ultrasonic vibration was chosen as the atomization method since it allows easy control of droplet size with narrow size distribution. The atomized droplets were carried through a pipe using a low velocity air supply. In the center of the pipe lies a small tube that carried air moving at high velocity. As soon as the droplets exit the pipe, they meet with this high velocity air jet that carried the droplets to the cutting zone at a velocity equal to the air jet velocity. The speed of the air jet was controlled externally by a pressure valve. For effective application of the cutting fluid, the air speed in the pipe was at values such that the droplets did not stick to the pipe walls and travelled all the way to the pipe exit. Further, as the droplets impinged upon the cutting zone, the droplet speed was maintained at values that caused droplets to spread upon the surface and the effectively wet the cutting zone through spreading. Since another purpose of the cutting fluid was to carry away the chips from the cutting zone, the air jet velocity that carried the droplets was kept high enough to carry away the chips.
from the cutting zone. To ensure that maximum number of droplets will impinge upon the cutting zone and thereafter spread on the surface the authors used the impingement criteria developed for droplet impact upon stationary surfaces [2].

Figure 2.4 Schematic of preliminary ACF system [2]

Jun et al. [2] used the above described ACF system to examine its viability and performance in micromachining processes. Micromilling experiments were done under dry conditions, conventional flood coolant application and atomization-based cutting fluid application. The experiments showed that lower cutting forces are generated with atomization-based cutting fluid application (Fig. 2.5). At a feed rate of 0.33 μm/flute, where ploughing dominates the cutting process, the milling cutter failed after cutting eight slots in one case and five slots in the other when cutting dry. On the other hand, the cutter was able to machine more than 50 slots when cutting fluid was applied in atomized form. Significantly better tool life was also achieved when the atomized cutting fluid was
used as opposed to dry cutting. Burrs formed during dry cutting were significantly larger than during cutting with the atomized cutting fluid (Fig. 2.6).

![Figure 2.5 Peak-to-valley cutting forces [2]](image)

**Figure 2.5 Peak-to-valley cutting forces [2]**

![Figure 2.6 Photographs of burrs [2]](image)

**Figure 2.6 Photographs of burrs [2]**

Jun et al. [2] observed that when conventional flood cooling method is used, the small size chips cluster around the cutting zone, resulting increased welding of the chips to the surface and increased tool wear or chipping whereas the atomization-based cutting fluid application system provides good chip evacuation and longer tool life. Figure 2.7 shows the cutting edge wear after cutting (a) 30 slots with the flood coolant method and (b) 45 slots with the atomization-based cutting fluid application system. One of the
cutting edges was found to be chipped when cutting with the flood coolant method (Fig. 2.7a). However, with the atomized cutting fluid application, the tool wear is uniform without any chipping (Fig. 2.7b). These results seem to suggest that the atomization-based cutting fluid delivery system leads to: (1) superior tool wear performance and (2) superior chip evacuation owing to the spray velocity and less part surface damage.

![Chipped edge](image)

![Figure 2.7](image)

**Figure 2.7 Photographs of tool wear after cutting (a) 30 slots with flood cooling and (b) 45 slots with atomized fluid [2]**

Temperature measurements in [2] during cutting 1018 steel with dry, flood cooling, and atomization-based cooling conditions showed that the atomization-based method is the most effective in cooling the cutting zone. Figure 2.8 shows that the maximum temperature measured during dry cutting is more than the maximum temperature measured when the atomization-based cutting fluid is used. Also, when the atomization-based cutting fluid application system is used, it is seen that the measured
temperatures are for the most part below the room temperature 20°C. Since the size of the droplets is very small and they evaporate easily upon contact with the surface, the contact surfaces are cooled below the room temperature through evaporative cooling. Figure 2.9 shows the SEM photographs of the chips generated for the conditions of (a) dry, (b) flood cooling, and (c) atomization-based cooling. The chips generated during flood cooling do not have uniform sizes and seem to have been broken into little pieces. This may have been caused by clustering of the chips near the cutting zone and continuously colliding with the cutting tool. When the atomization-based cooling method is applied, the chips are more serrated and segmented/discontinuous owing to more effective cooling of the cutting zone.

![Figure 2.8 Results of temperature measurements](image)

Figure 2.8 Results of temperature measurements [2]
Figure 2.9 Photographs of generated chips for the conditions of (a) dry, (b) flood cooling, and (c) atomization-based cooling [2]

The experimental results in [2] for the effect droplet velocity are shown in Fig. 2.10 in terms of (a) peak-to-valley resultant forces and (b) surface roughness. It shows that the droplet impingement velocity does not appreciably affect the cutting
performance. At low feed rates, high velocity slightly improves the cutting performance, whereas low velocity is slightly preferable at high feed rates. However, the difference is quite small. This may be because the droplets spread on the contacting surface for all three velocities based on the impingement criteria described in Jun et al. [2].

Figure 2.10 Experimental results at different droplet impingement velocities [2]

Rukosuyev et al. [25] suggested the use of an ACF system equipped with a nozzle to produce more focused flow in the cutting zone. Owing to the small size of the cutting zone in micromachining operations, it is desired to have a narrow and focused spray for effective penetration into the cutting zone. If the spray is much wider than the cutting zone, only a fraction of the spray will be penetrated into the cutting zone. For an ACF system described by Jun et al. [2] the resulting spray is expected to focus at a certain point and then diverge due to entrainment of the surrounding air. Thus, it is important to determine the location of the focused point and place the nozzle at a distance from the
cutting zone at the location such that maximum number of droplets are in the vicinity of the cutting zone.

In the study of Rukosuyev et al. [25] two performance measures were defined for sprays obtained using the ACF system: focus height and length (Fig. 2.11). Focus height of the spray is the spray diameter at the focal point and focus length is the distance from the nozzle end to the focal point. Experiments were conducted to examine the focus height and focus length for varying velocities of air in the tube and the pipe (in a configuration similar to Fig. 2.4). Photographs of the spray generated for the system described by Rukosuyev et al. [25] is shown in Fig. 2.12. The velocity of air in the pipe is referred to as mist velocity ($V_m$) and the velocity of air in the tube is referred to as spray velocity ($V_s$). It was observed that an increase in the mist velocity leads to an increase in the focus length and height and increase in the spray velocity leads to a decrease in the focus length and height. Based on photographic evidence, it was shown that the number of atomized droplets in the cutting zone is a function of the angle of the nozzle used and its distance from the cutting zone. Thus, the positioning of the ACF system with respect to the cutting zone is expected to be a critical component of the observed machining performance. Although no machining experiments were conducted, their study suggested that the design of the ACF system is important for effective cooling and lubrication performance.
2.1.3 Effect of Surface Tension and Viscosity on Cutting Fluid Functionality

Bittorf et al. [26] examined the link between fluid properties (viz., surface tension and viscosity) and the functionality of the cutting fluid in a machining operation. Testing was carried out on an instrumented drilling test-bed to evaluate the effect of the properties on cutting temperatures and forces. The findings suggested that surface tension and viscosity in a cutting fluid play important roles in cooling and lubrication of the
drilling process. From the experiments conducted it was concluded that a lower surface tension will reduce temperatures during machining. Consequently, it was also established that a lower surface tension, independent of the type of chemical used to lower it, provided better cooling. It was hypothesized here that as the surface tension of the fluid is decreased, the wettability of the fluid is increased. As the wettability is increased the fluid coats the tool and workpiece more completely. The fluid is then able to transfer heat away from the area of the tool and workpiece that it is in contact with. Separate experiments with varying viscosities showed that as the viscosity of a solution increased the machining forces decreased. As the viscosity of a solution increases the layer of hydrodynamic lubrication increases and a larger gap is created between the chip and the face of the drill. The larger gap creates less rubbing, or friction, between the chip and tool. The reduction in friction leads to a reduction in frictional heat generated.

While the studies presented in Section 2.1 show that ACF systems effectively reduce the temperature at the workpiece-tool interface and provide superior lubrication to the cutting zone, there is a lack of a physics-based understanding of the phenomena underlying cooling and lubrication performance of ACF systems in micro-machining processes. In order to understand the mechanism underlying atomized cutting fluid application, a study of droplet impingement dynamics and its effect on observed cooling and lubrication is required. A review of fundamentals of droplet dynamics and spreading behavior is presented in sections 2.2 and 2.3, respectively.
2.2 Fundamentals of Droplet Dynamics

2.2.1 Atomization Basics

Atomization refers to the process of breaking up bulk liquids into droplets. Once the liquid is atomized, the droplets are moved in a controlled manner resulting in a spray. The resulting spray is characterized by the droplet size and size distribution, and the flow rate which are determined by the type of atomization method, the atomization parameters and the liquid properties [27].

The common atomizing systems produce sprays by either shearing or by external excitation [27]. In the first group are systems based on the shearing properties of co-flowing jets. A large velocity difference between the liquid jet and the surrounding medium (usually air) induces liquid surface instabilities and droplet peeling from the jet surface. The jet is rapidly broken into lumps, filaments and droplets. This process takes place when a high-speed liquid jet is injected into a quiescent or turbulent atmosphere, as is the case, for instance, in diesel engines. Such systems may handle high liquid flow rates (greater than 100 ml/min), but create widely dispersed sprays (in terms of droplet sizes) and produce high-velocity droplets (greater than 10 m/s). The resulting droplet size is a function of the jet velocity and the liquid properties [27]. A second group of spray generators uses external excitation means. The instabilities of a free surface lead to the breakup of the liquid, creating droplets. These instabilities are commonly created by superimposed oscillations at ultrasonic frequencies. A mono-disperse spray is produced in this way, but the liquid flow rate is small (below 100 ml/min). The droplet size is nearly constant and is related to the oscillation frequency. By varying the oscillation
frequency one may obtain different droplets sizes. The particle size distribution is narrow and the mean droplet diameter is well predicted by analytical expressions [27]. These two atomization methods are shown in Fig. 2.13.

\[ \text{Figure 2.13 Operating principle of the different types of atomizers: (a) shearing-type (b) ultrasonic [27]} \]

Once the fluid is atomized, it is often focused using a spray nozzle to produce a desired spray pattern. The droplet density, i.e., the spatial distribution of the atomized droplets is a direct function of the spray pattern produced. The most common types of spray nozzles used are full cone, hollow cone, and flat stream (Fig. 2.14). A full cone nozzle produces a spray pattern with the droplets distributed uniformly around a point [28]. Such nozzles are used for applications wherein uniform, overall coverage across the impact area is desired. A hollow cone produces a spray pattern with droplets distributed only along a circular rim. These are typically used for cleaning purposes and application of insecticides. A flat stream nozzle results in droplets distributed along a rectangular array and is ideally used wherever a very high spray impact is required. Nozzle selection typically depends on the type of spray pattern required for an operation, viz., cooling, cleaning, coating, lubricating, drying, or others. For machining applications wherein a uniform, round and full spray pattern is desired typically full cone nozzles are used [28].
2.2.2 Droplet Impingement Dynamics

Droplet impact on solid and liquid surfaces is a key element of a wide variety of phenomena encountered in technical applications, such as ink-jet printing, rapid spray cooling of hot surfaces (turbine blades, rolls in rolling mills for steel production, lasers, semiconductor chips, and electronic devices), fire suppression by sprinklers, internal combustion engines (intake ducts of gasoline engines or piston bowls in direct-injection diesel engines), spray painting and coating, and crop spraying [29]. Consequently, a large base of literature has been developed over the years capturing the phenomena accompanying droplet impact on solid and liquid surfaces under varying physical conditions.

The early investigations of Wachters and Westerling [30], Levin and Hobbs [31], and Stow and Hadfield [9] identified the parameters that influence the droplet impingement dynamics are the diameter \( d_0 \) and velocity \( u_0 \) of the incident droplet, the
liquid viscosity (\( \mu \)), density (\( \rho \)), and surface tension (\( \sigma \)). The conditions of the receiving surface such as the film thickness (\( h_f \)) for wet surfaces also play a major role in controlling the outcome of a droplet-surface collision. The following non-dimensional numbers based on the normal component of droplet velocity \( u_0 \) have been identified as the most relevant in determining the outcome of droplet impact:

\[
\text{We} = \frac{\mu u_0^2 d_0}{\sigma}, \quad \text{Re} = \frac{\rho u_0 d_0}{\mu}, \quad \text{Oh} = \frac{\mu}{\sqrt{d_0 \sigma \rho}}, \quad h_{nd} = \frac{h_f}{d_0}
\]

(2.1)

where, We is the Weber number, Re is the Reynolds number, Oh is the Ohnesorge number, and \( h_{nd} \) is the non-dimensional film thickness number [32]. Weber number is the ratio of the droplet kinetic energy to the droplet surface energy, Reynolds number is the measure of the ratio of droplet kinetic energy to the viscous dissipation upon impact, and Ohnesorge number relates the viscous dissipation to kinetic and surface tension energy.

Based on the experimental observations, four impingement regimes have been identified for droplet-wall or droplet-film interaction phenomenon: sticking, rebounding, spreading, and splashing as presented pictorially in Fig. 2.15.

![Figure 2.15 Various impingement regimes identified for droplet impact [8]](image-url)
The stick regime occurs when an impinging droplet adheres to the wall or film surface in a nearly spherical form. This often happens when the impact energy of the droplet is extremely low, or the wall temperature is below the pure adhesion temperature [8]. Jayaratne and Mason [33] studied the sticking of water droplets of radius 60-200 µm at a clean air/water interface. The variable parameters in the system were the droplet diameter, droplet velocity, and the angle of impact. Based on their experiments the transition criteria for the stick regime was proposed as \( \text{We} < 5 \) [8]. The rebounding regime is characterized by an impinging droplet bouncing off the wall or the film. Rebounding occurs when the air layer trapped between the drop and the surface causes low energy loss resulting in bouncing [8]. It is also facilitated by elevated surface temperatures, especially when the Leidenfrost effect sets in and the drop is propelled upward by vapor at its base [4]. Based on the experimental work of Rodriguez and Meslor [34] and Stow and Hadfield [9] the transition criteria for the rebounding regime has been found to be \( 5 \leq \text{We} < 10 \). The third regime, spreading, is similar to the sticking regime wherein the droplet deposits and spreads on the receiving surface. For spreading a high initial impact energy is required. The experiments of Stanton and Rutland [8] show that droplet spreading typically occurs when \( \text{We} \geq 10 \). The final splashing regime occurs when impact energy is such that the impact results in breaking of the impinging droplet into multiple secondary droplets. The experimental work of Yarin and Weiss [35] showed that the transition criteria for splashing is given by \( \text{We} \geq 32\pi d_0 \left( \frac{\rho}{\sigma} \right)^{3/2} u_0^{1/4} f^{3/4} \), where \( f \) is the frequency of the impinging droplets.
The above transition criteria help in identifying the outcome of a droplet-surface collision. Based on the application, impact parameters are controlled such that desired results are obtained. The study of Jun et al. [2] showed that for atomized cutting fluid application, it is desired that the droplets spread as they impinge upon the cutting zone and effectively wet the cutting zone through spreading. Thus, the droplet characteristics and cutting fluid properties were kept at values that ensured that droplets undergo spreading as they impinge upon the cutting zone. Although Jun et al. [2] applied the above transition criteria to predict the outcome of droplet impact in the cutting zone, the rotation of workpiece and/or tool is expected to change the droplet impact phenomena indicating that above transition criteria should be applied to machining applications with caution.

2.3 Droplet Spreading Behavior on a Stationary Surface

2.3.1 Experimental Study

The phenomena accompanying droplet spreading on a stationary surface has been the subject of many investigations. The droplet contact area and height upon impact and its variation over time are required, especially in cases wherein heat transfer predictions are made. Predictions for spray cooling, spray coating and ink-jet printing rely heavily on the input provided by droplet spreading data available in the literature.
Rioboo et al. [36] studied the time evolution of droplets of initial diameter 1.2-4.9 mm, velocity 0.78-4.1 m/s, viscosity 0.3-934 cP, and surface tension 21-73 mN/m spreading on solid, dry surfaces. The experiments showed that the time evolution of a droplet spreading can be divided into four distinct phases: kinetic, spreading, relaxation and equilibrium. The first stage represents the kinetic phase, when the contact diameter increases with approximately square root of time following impact, followed by the spreading phase where surface and viscous forces begin to play a role in the impact evolution. The spreading phase is followed by a relaxation phase, which may have different outcomes, depending mainly on the magnitude of the contact angle between the surface and the liquid. In the final phase, the spreading droplet attains some constant diameter (equilibrium phase). These stages are shown in Fig. 2.16. The boundaries of these four distinct phases along with the spread factor (= diameter of the spreading droplet / initial spherical droplet diameter) is shown in Fig. 2.16. The diverging lines in Fig. 2.16 show the different possible outcomes, depending on the specific parameters of the impact process.
Figure 2.16 Schematic representation of the spread factor with time [36]

Rioboo et al. [36] showed that in the kinetic phase the droplet is in the early stage of impact and the droplet spreads under the influence of inertial forces alone with the shape resembling a truncated sphere. During this phase no spreading lamella is yet visible (Frame 1 in Fig. 2.17). The diameter grows according to a power law in time, with an exponent lying between 0.45 and 0.57. The experiments done with varying parameters showed that this phase of the impact process can be completely described by the impact velocity and initial diameter. With increasing time, a lamella is ejected from the base of the drop and forms a thin film bounded by a rim leading to an increase in the contact diameter (frames 2-3 in Fig. 2.17). As the droplet spreads on the surface, the initial kinetic energy of the pre-impact droplet is in-part irreversibly dissipated by the action of viscosity and in-part converted to surface energy. The spreading phase has been observed to be influenced by many factors: increasing the impact velocity or droplet diameter leads to faster spreading, and increasing the surface tension or viscosity leads to slower
spreading. It was observed that the maximum diameter is smaller and is reached earlier when the viscosity increases. The energy dissipated during droplet spreading increases with increasing viscosity, thus the maximum spread diameter for a given impact energy decreases inversely with increased viscosity. The effect of surface tension on spreading behavior was studied by Zhang and Basaran [37]. Reduction in surface tension was observed to enhance the spreading of the droplet across the substrate.

**Figure 2.17 Droplet impact on a dry surface [36]**

The study of Rioboo et al. [36] further showed that after the spreading phase the drop may begin to recede. Frame 4 in Fig. 2.17 shows the droplet receding after reaching a maximum spread diameter. The retraction occurs when the surface tension forces are large to cause the droplet to recoil. Subsequently, the droplet undergoes oscillations on the surface the physics of which is set by the competition between kinetic, surface and viscous forces. After this phase, the equilibrium phase follows characterized by no change in the droplet shape until the droplet volume decreases due to evaporation.

Based on the study of Rioboo et al. [36], Schiaffino and Sonin [37] and Lim et al. [15] the various time scales for droplet spreading dynamics on a stationary surface are listed in Table 2.1. \( \tau_{\text{kin}} \) shows the time scale for which the kinetic phase lasts, \( \tau_{\text{osc}} \) is the time period of interfacial oscillations, \( \tau_{\text{vis}} \) represents the time scale of the interfacial oscillations. As shown in Table 2.1, \( \text{Oh} \) represents the ratio of the time scale of the interfacial oscillation period to the viscous damping time. Similarly, the Weber number
can be considered as the square of the ratio of the kinematic spreading time scale and the time scale of surface tension driven wetting resisted by inertia.

### Table 2.1 Time scales and dimensionless numbers related to droplet spreading [15]

<table>
<thead>
<tr>
<th>Kinetic</th>
<th>( \tau_{\text{kin}} \approx \frac{d_0}{u_0} )</th>
<th>( \text{Oh} = \frac{\tau_{\text{osc}}}{\tau_{\text{vis}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillation</td>
<td>( \tau_{\text{osc}} \approx \sqrt{\frac{\rho d_0^3}{\sigma}} )</td>
<td>( \text{We} = \left( \frac{\tau_{\text{osc}}}{\tau_{\text{kin}}} \right)^2 )</td>
</tr>
<tr>
<td>Viscous Damping</td>
<td>( \tau_{\text{vis}} \approx \frac{\rho d_0^2}{\mu} )</td>
<td>( \text{Re} = \frac{\tau_{\text{vis}}}{\tau_{\text{kin}}} )</td>
</tr>
</tbody>
</table>

#### 2.3.2 Modeling Spreading Behavior

**Predicting Maximum Spread Diameter**

For droplets spreading on a dry surface, the maximum spread diameter can be accurately predicted using semi-empirical analytical models based on energy balance [4-5]. The initial kinetic and surface energy partly dissipates due to viscous effects, the remainder comprising the surface energy of the final droplet assumed to be at complete rest. The droplet shape is either assumed to be a cylindrical disk or a spherical cap, and the kinetic energy and surface energy expressions are calculated directly from initial and final droplet geometries. However, the estimation of energy dissipated through viscous forces varies from one study to other. The viscous dissipation is usually estimated with certain simplifying assumptions and on the basis of available empirical information.

Chandra et al. [4] estimated viscous dissipation over the spreading process as
\[ E_v = \int_0^T \psi dV dt \approx \psi V t_s \]  \hspace{1cm} (2.2)

where, \( \psi \) is the viscous dissipation function, \( V \) is the droplet volume and \( t_s \) is the time taken by the droplet to spread to its maximum spread state. The viscous dissipation function is given by fluid mechanics principles as

\[ \psi = 2 \mu \left[ \left( \frac{\partial v_x}{\partial x} \right)^2 + \left( \frac{\partial v_x}{\partial y} \right)^2 + \left( \frac{\partial v_x}{\partial z} \right)^2 \right] + \mu \left[ \left( \frac{\partial v_y}{\partial x} \right)^2 + \left( \frac{\partial v_y}{\partial y} \right)^2 \right] + \mu \left[ \left( \frac{\partial v_z}{\partial x} \right)^2 + \left( \frac{\partial v_z}{\partial y} \right)^2 \right] + \mu \left[ \left( \frac{\partial v_z}{\partial x} \right)^2 + \left( \frac{\partial v_z}{\partial z} \right)^2 \right] \]

\[ + \mu \left[ \left( \frac{\partial v_z}{\partial y} \right)^2 + \left( \frac{\partial v_z}{\partial z} \right)^2 \right]. \]  \hspace{1cm} (2.3)

Chandra et al. [4] assumed a significant velocity gradient to exist only normal to the spreading direction and approximated the viscous dissipation function as

\[ \psi \approx 2 \mu \left( \frac{u_0}{h} \right)^2 \]  \hspace{1cm} (2.4)

indicating that significant viscous dissipation is assumed to occur over the entire thickness of the spread droplet. The spreading time is estimated by assuming it to be the time taken for the droplet height \( h \) to go from its maximum value \( d_0 \) to 0 at velocity \( u_0 \),

\[ t_s \approx \frac{d_0}{u_0}. \]  \hspace{1cm} (2.5)

Using Eqs. 2.2-2.4 the total energy dissipated through viscous forces was estimated. The spreading model of Chandra et al. [4] over-predicted the spread diameter by about 40%.

Pasandideh Fard et al. [39] improved the model of Chandra et al. [4] by assuming significant dissipation to occur only within the boundary layer of the spreading droplet. The dissipation function was thus given by

\[ \psi \approx \mu \left( \frac{u_0}{\delta} \right)^2 \]  \hspace{1cm} (2.6)
where, $\delta$ is the boundary layer thickness at the solid-liquid interface calculated by assuming a stagnation-point flow once the droplet impinges upon the surface. They also estimated the spreading time $t_s$ by assuming that the droplet spreads into a cylindrical disk. Their calculations resulted in the spreading time as

$$t_s \approx \frac{8 \, d_o}{3 \, u_o}.$$  

(2.7)

The model of Pasandideh Fard et al. [39] predicted the experimental results within 15% accuracy, a significant improvement over the model of Chandra et al. [4]. Mao et al. [5] also developed a similar spreading model with the viscous dissipation term estimated empirically using their experimental results. Their model predicted the experimental results in the literature within 10% accuracy. However, since the model is empirical, its validity is limited to the experimental conditions used by Mao et al. [5].

**Predicting Droplet Recoil**

In cases where drop spreading is followed by the receding stage, the analytical approach is still possible but calls for a more elaborate dynamic model incorporating the time variation of the flow field within the spreading droplet. Bechtel et al. [14] used Lagrangian methods with stagnation point flow field and a spherical cap model to analyze the droplet recoil on a flat, rigid surface. The analysis results in a differential equation for droplet height as a function of time that can be solved numerically for three independent parameters: Weber number of the incoming drop, ratio of the surface tension in air to that at the contact surface, and a viscosity parameter. The viscosity parameter represents the damping of the droplet oscillations following recoil and was estimated...
analytically by considering frictional stresses at an oscillating fluid boundary. Bechtel et al. [14] used the results of Wachters and Westerling [30] to test the accuracy of the model. Although their model did not predict the exact variation of droplet diameter with time, they were able to capture the trend in the time evolution of droplet diameter.

Kim and Chun [40] extended the model of Bechtel et al. [14] by including the case wherein the droplet spreads in form of a cylindrical disk (Fig. 2.18). They experimentally studied the recoiling of droplet of different liquids on varying solid surfaces. The viscous parameter of Bechtel et al. [14] was modified by including an empirically determined dissipation factor. It was shown that the model closely predicts the experimental results obtained for the varying dynamic impact conditions and surface conditions. Based on their results, it was found that the spherical cap model and the cylindrical disk model are valid for varying impact conditions. The spherical cap model was observed to be appropriate for cases where the recoiling is resisted by viscosity and the cylindrical disk model for cases where recoiling is resisted by inertia. The Ohnesorge number was determined to be the parameter that governs the recoiling dynamics, with high Oh number (>0.006) indicating recoil resisted by viscosity and low Oh number (<0.006) indicating recoil resisted by inertia.

![Diagram](image)

**Figure 2.18 Geometry of the (a) spherical cap model (b) cylindrical disk model [40]**
2.4 Droplet Behavior on a Rotating Surface

2.4.1 Droplet Impingement Dynamics

While the above modeling studies provide valuable insight into the droplet dynamics upon impingement, these studies were limited only to stationary surfaces. The presence of a rotating surface in a machining process is expected to change the dynamics of the spreading process imposing a need to study droplet impingement on rotating surfaces. A limited number of studies have been conducted for investigating the transition criteria for droplets impinging upon a rotating surface. Povarov et al. [10] studied the regimes of interaction of normal impact of droplets of diameter 0.3-4.0 mm and velocity 0.1-10 m/s with the boundary layer on a surface rotating at high speed of 10-120 m/s. In their experiments, three types of interaction of the droplet with the rotating surface were distinguished: 1) the droplet is captured by the surface on contact and spreads out over its surface; 2) the droplet enters the boundary layer on the surface, is slightly deformed, and is partially spread out over the surface and partially reflected from it; 3) the droplet is strongly deformed in the boundary layer and, without touching the surface, is reflected away from it. The solution of Navier-Stokes equation for boundary layer on an infinitely large disk showed that the behavior of a droplet in the boundary layer is determined mainly by the gradient of the normal velocity component of the impinging droplet.

The study of Povarov et al. [10] showed that the first form of interaction between droplet and a rotating surface (no reflection from the surface) corresponds to a low droplet velocity $u_0$. The droplet passes through the boundary layer and, still undeformed,
enters into contact with the surface, gradually spreading out in the direction of rotation of the surface. At higher values of surface speed \((u_s)\) but for the same droplet velocity, the second type of interaction is observed (Fig. 2.19a). As shown in Fig. 2.19a, for this case a part of the droplet is reflected from the surface. As it approaches the surface, the droplet is slightly deformed; the lower part of the drop contacts the disk surface and is carried along with it, but the upper part is hardly displaced in the direction of rotation (frames 1-3). Similar to the case of collision with a fixed surface, the bottom part of the droplet is spread out in the region of contact. The motion of the surface promotes the spreading of the contacting part of the drop. As a result of the velocity gradient in the boundary layer, a wedge of air forms under the drop, which begins to rise (frames 4-8). Further increase in surface speed leads to total reflection of the droplet on interaction with the boundary layer of the rotating surface (Fig. 2.19b). In this case the droplet is significantly deformed as it enters the boundary layer (frames 2 and 3), as a result both of the dynamic pressure difference exerted on the droplet by the flow gradient and also of the reduction in static pressure close to the surface of the rotating disk. The lower part of the droplet is displaced in the direction of rotation of the surface, and under the action of the increasing lift force begins to rise above the surface.
In the study of Povarov et al. [10] it was further shown that the droplet-surface interaction conformed to a similar pattern for the entire droplet diameters investigated: $0.5 < d_0 < 4.0$ mm. The boundaries between the observed types of collision for droplets of various diameters are shown in Fig. 2.20. The boundary between interactions of types I (complete "adherence") and II (partial reflection) was found to be practically independent of the droplet diameter. In the experiments, type-I collisions were observed over the whole range of droplet diameters tested when $u_0/u_s < 0.15$. The position of the boundary between types II and III (complete reflection) is determined by the droplet diameter. Figure 2.20 shows that for surface speeds under 10 m/s and droplet speeds over 1 m/s, the
droplet collision lies in region I irrespective of the droplet diameter showing that the droplet undergoes complete adherence upon impact.

Figure 2.20 Effect of velocity ratio on reflection of droplet from a rotating surface: 1) droplet diameter $d_0 = 0.3$ mm; 2) 0.8 mm; 3) 4 mm. I) region of complete adherence; II) partial reflection; III) total reflection [10]

Mundo et al. [11] investigated the transition from deposition to splashing for droplets impinging upon a rotating surface. The experiments were conducted for varying initial droplet diameters ($60 < d_0 < 150$ µm), velocities ($12 < u_0 < 18$ m/s), fluid viscosities ($1.0 < \mu < 2.9$ cP) and surface tensions ($22 < \sigma < 72$ mN/m). The liquids used to establish the different viscosities and surface tensions were ethanol, water and a mixture of water-sucrose-ethanol. The experiments showed that for droplet impact at high Reynolds numbers ($Re > 500$) splashing is observed whereas for low Reynolds number
deposition is observed as shown in Fig. 2.21. A schematic view of the splashing and deposition process is shown in Fig. 2.22.

Figure 2.21(a) Splashing of a liquid droplet with $Re = 598.8$, $Oh = 0.0518$ on a smooth surface, (b) Deposition of a liquid droplet with $Re = 251.4$, $Oh = 0.0492$ on a smooth surface [11]

Figure 2.22 Schematic of the (a) splashing process, (b) deposition process [11]

Mundo et al. [11] showed that at high Re numbers, as the droplet touches the surface, a liquid film spreads outwards. A corona around the deforming droplet is formed and grows in time as the droplet fluid continues to feed the film. Once the lower half of the droplet has undergone deformation, the total volume flow rate into the wall film
begins to decrease. Thus the corona, having been stretched in its radial expansion, also now has less fluid feeding the film and hence becomes thinner. An instability develops leading to a circumferential wreath which propagates upward in the corona and finally results in a disintegration into secondary droplets. At low Re numbers, the liquid film spreads around the point of impingement, but there is not enough momentum normal to the wall to form a corona. Rather, the kinetic energy necessary to overcome surface tension and gravity to form a corona is dissipated during the deformation process. The deposition of a droplet on a rough surface at low Reynolds number was found to be similar to the deposition process for the technically smooth surface. It was concluded that an increase in the surface roughness suppresses the splashing of the impinging droplet.

The observed limits of deposition and splashing in Mundo et al. [11] were correlated in terms of the Re and Oh numbers. A remarkably strong correlation was observed given by the relation $K = OhRe^{1.25}$. A value of $K$ exceeding 57.7 leads to incipient splashing, whereas $K$ less than 57.7 leads to complete deposition of the liquid, as illustrated in Fig. 2.23. The strong correlation shown in Figure 2.23 indicates that in the case of splashing, the influencing factor is the momentum of the primary droplets in the direction normal to the surface and not the total momentum vector.
2.4.2 Droplet Spreading Behavior

In order to understand the effect of surface speed on the impingement behavior of droplets for spray coating and spray cooling applications, Chen and Wang [12] studied the impact of water droplets with sizes 500-900 μm upon a rotating Teflon surface. Figure 2.24 shows the coordinate system used to study the droplet impact. If the impact angle relative to the rotating surface is \( \theta \) then in frame of reference of the surface the normal and tangential droplet speeds are given, respectively, by

\[
\begin{align*}
    u_n &= u_0 \sin \theta, \text{ and } u_t = \omega R - u_0 \cos \theta \\
\end{align*}
\]  

(2.8)

where \( R \) is radius of the workpiece, \( \omega \) is rotational speed of the workpiece. The velocity expressions in Eqn. 2.8 are used to define modified Weber numbers given by

\[
We_n = \left( \frac{\rho d_0}{\sigma} \right) w_0^2 \sin^2 \theta
\]  

(2.9)
\[ We_t = \left( \frac{\rho d_0}{\sigma} \right) (\omega R - w_0 \cos \theta)^2 \]  

(2.10)

where, \( We_n \) is the normal Weber number, \( We_t \) is the tangential Weber number. The normal Weber number represents the ratio of the normal-direction collisional energy to the surface energy of the drop before impact and the tangential Weber number represents the ratio of the tangential-direction collisional energy to the surface energy of the drop before impact. Based on the relative values of \( We_n \) and \( We_t \) three impingement regimes, viz., partial rebound, deposition, and split deposition were observed. The photographic representation of these three regimes is shown in Fig. 2.25. Figure 2.26 shows the observed impact patterns are plotted as a function of \( We_n \) and \( We_t \).

Figure 2.24 Variables and coordinates system [12]
Figure 2.25 Impact regimes for varying values of $We_n$ and $We_t$ numbers [12]

Partial rebound ($We_n=30, \ We_t=0$)

Deposition ($We_n=30, \ We_t=60$)

Split deposition ($We_n=30, \ We_t=110$)

Figure 2.26 Impact regimes (a) Partial rebound (b) Deposition (c) Split deposition [12]
As shown in Fig. 2.26, partial rebound results from close-to-normal impacts with medium to high Weber numbers. The droplet hits the surface and spreads radially into a rather axi-symmetric disk. The retraction of the disk generates an upward internal flow, which stretches the end of the liquid rod into one drop jumping off the surface; while leaving a portion of the liquid on the surface, as shown in Fig. 2.25a. Deposition refers to an impact in which the drop simply spreads and retracts into one drop sticking to the surface (see Fig. 2.25b). Deposition happens in low-energy impacts or impacts with a medium tangential Weber number. Split deposition denotes an impact which results in the drop being split into two droplets, as shown in Fig. 2.25c. This type of impact happens at a high tangential Weber number; the high tangential speed stretches the drop into an elliptical disk, if the elongation is sufficient, the retraction of the disk would generate a necking in the middle to produce two droplets. In Fig. 2.26 the broken lines show the transition between the three regimes. For small \( We_t \), if \( We_n < 10 \), all impacts resulted in deposition. For \( We_n > 10 \), as \( We_t \) was increased, the minimal \( We_n \) required for the onset of rebound was seen to increase almost linearly. In other words, it is more difficult for a drop to rebound from a moving surface, as the surface speed goes up. As to the split deposition regime, for \( We_n < 40 \), the \( We_t \) required to split the drop remained about the same (i.e. \( We_t \approx 100 \)). Then for \( We_n > 40 \), the \( We_t \) required for split deposition rapidly increased, again almost linearly.

In order to find the relationship between droplet elongation and \( We_t \), Chen and Wang [12] defined dimensionless excess spread area as

\[
X_A = \frac{bd_m - d^2_m}{d^3_0}
\]  

(2.11)
where, $b$ is the droplet contact length at the condition of maximum spread and $d_m$ is droplet contact length on a stationary surface calculated for same impact conditions. Figure 2.27 shows the dimensionless excess spread area plotted against tangential Weber number for varying values of normal Weber number ($23 < We_n < 81$) in the range. An almost linear relationship exists between $X_A$ and $We_t$ showing that higher $We_t$ induces more dimensionless excess spread area. This implies that for higher $We_t$ or higher droplet velocity, the droplet spreads more on a rotating surface in comparison to a stationary surface.

While the above studies give insight into the regime in which droplet impact will lie once it hits a rotating surface, no investigation was made to study the droplet spreading behavior on the rotating surface. The experiments of Chen and Wang [12] showed that the contact area of droplet spreading upon a rotating surface is different from the droplet impinging under the same conditions upon a stationary surface. However, no relationship between the spread area and droplet characteristics and fluid properties was derived. Further droplet study needs to be conducted to understand the effect of droplet characteristics, cutting fluid properties, and surface speed on the droplet spreading behavior on a rotating surface so as to elucidate the physics underlying cooling and lubrication performance of ACF systems in micromachining.
Figure 2.27 Dimensionless excess spread area versus \( W_{et} \) [12]

2.5 Performance Evaluation of an ACF System in Micromachining Processes

In order to predict the cooling and lubrication performance of ACF systems in micromachining processes, droplet cooling and lubrication models need to be applied to the machining system. Sections 2.5.1-2.5.2 reviews the models developed in the literature.

2.5.1 Evaporative Cooling Models

The study of Jun et al. [2] showed that the cooling effect of atomized droplets is attributed to evaporation of the impinging droplets. Study of heat transfer from a solid surface to droplets has been the subject of many experimental and analytical
investigations [41-42]. The analytical models capturing the heat transferred from surface to droplet require droplet contact area, height and contact angles along with other physical inputs. Based on the boundary condition at the solid-liquid interface (constant heat flux or constant temperature) different mathematical formulations are available. For ACF systems, heat is continuously being lost from the cutting zone resulting in a drop in the temperature, indicating that constant temperature boundary condition cannot be applied rather constant heat flux is more appropriate.

di Marzo et al. [41] developed a semi-analytical model for heat transfer from a solid surface to a droplet for constant and uniform heat flux at the solid-liquid boundary and found it to accurately capture the transient surface temperature distribution. They further commented that for multi-droplet systems, the temperature distribution can be predicted by super-position of the transient surface thermal behavior due to a single evaporating droplet. The temperature at a point situated at distance \( r \) from the center of the droplet base was given by

\[
T_0 - T_s = \frac{h_i \rho V}{\pi R \tau k} \int_0^\infty J_0(\Gamma r) J_1(\Gamma R) \text{erf} \left( \frac{\Gamma \sqrt{\alpha \tau}}{R} \right) \frac{d\Gamma}{\Gamma}
\] (2.12)

where, \( h_i \) is the latent heat of vaporization of the droplet, \( V \) is the droplet volume, \( R \) is radius of droplet base, \( k \) is the thermal conductivity of the solid surface, \( \alpha \) is the thermal diffusivity of the solid surface, \( \tau \) is the total time taken for droplet to evaporate, \( J_0 \) and \( J_1 \) are the Bessel functions and \( \text{erf} \) is the error function. A drawback of the above model is that it requires the evaporation time of the droplet to be estimated experimentally. Therefore, the applicability of the above model is limited.
Sadhal and Plesset [42] derived an approximate solution for overall heat flow from a solid surface to a droplet by solving the steady heat-conduction equation. The geometry consisted of a spherical segment droplet on a semi-infinite solid. In obtaining the solution it was assumed that heat is transported to or from the solid only through the droplet and that there is perfect thermal contact at the solid-liquid interface. The model of Sadhal and Plesset [42] yield simple mathematical expression for predicting the heat flow to the droplet thereby being an attractive model that can be used for estimating cooling in micromachining processes. The heat transferred from the surface to one droplet is given by

\[ q = \frac{kT_0 A^0 A}{h} \]  

(2.13)

where, \( k \) is the thermal conductivity of the surface, \( T_0 \) is the ambient air temperature, \( A \) is the contact area at the droplet base. \( A^0 \) is the integral given by

\[ A^0 = 2 \int_0^\infty \frac{\left( k_f / k_s \right) \text{sech}^2 \pi \Gamma}{\left[ \tanh \pi \Gamma \tanh \theta_0 \Gamma + \left( k_f / k_s \right) \right]} d\Gamma \]  

(2.14)

where, \( k_f \) is the thermal conductivity of the cutting fluid, and \( \theta_0 \) is the contact angle at the solid-liquid interface.

The above studies show that the cooling effect generated by atomized droplets is captured mathematically using evaporative cooling models. The model of Sadhal and Plesset [42] can be applied directly to predict the heat transferred from a solid surface to the droplet.
2.5.2 Lubrication Models

Limited experimental studies have been done to investigate the lubrication mechanism when cutting fluid is applied in form of mist in machining processes. Liu et al. [43] studied the effect of water vapor as a lubricant in machining and explained the friction mechanism by assuming vapor access into the cutting zone through capillary action. Their study showed that water vapor possesses better lubricating capacity because of its excellent penetration performance and formation of low shear strength lubrication layer. Machado and Wallbank [44] based on their experimental evidence for conditions at the tool-chip interface argued that that penetration through capillary action is not likely. It was suggested that a more probable mechanism appears to be formation of barrier layers at the tool-chip interface resulting in reduced contact at the interface leading to reduction in cutting forces.

Lubrication between two surfaces can be achieved by using a thin viscous film to prevent solid to solid contact. The film must generate extremely large pressure differences between the solids so that the friction generated due to contact is reduced. Langlois [45] assumed a couette flow between two plates sliding over each other with liquid in between and derived the expression for lubrication force generated by the liquid (Fig. 2.28).
Using the formulation of Langlois [45], the lift force generated per width by the fluid film is given by

\[
f = \frac{6\mu l^2 U}{(h_1 - h_2)^2} \left[ \ln \left( \frac{h_1}{h_2} \right) - 2 \left( \frac{h_1 - h_2}{h_1 + h_2} \right) \right].
\]

(2.15)

where, \( h_1, h_2, l \) are shown in Fig. 2.28, and \( U \) is the velocity of the sliding surface.

Yang and Shivpuri [46] conducted experiments for lubricant deposited on a surface in form of a droplet and commented that the lubrication achieved is a function of both droplet geometry achieved on the surface and the fluid properties. However, no expression for lubrication force achieved by the deposited droplets was calculated. Hiratsuka et al. [47] experimentally investigated the load carrying capacity generated by water droplets placed between hydrophilic surfaces. An increase in the droplet volume was observed to diminish the load carrying capacity of the droplet (Fig. 2.29). The low value of the friction coefficient generated by the water droplets was explained by the losses of energy for the adhesion hysteresis of water on the hydrophobic surface.
The above studies show that atomized droplets are capable of providing effective lubrication between two solid surfaces. Though no specific models have been developed that can be directly applied to predict lubrication achieved by a droplet, the lubrication model of Langlois [45] appears to be capable of capturing the lubrication effect generated by the droplet.

Figure 2.29 Load-carrying capacity $R$ of the volume of water droplets $V$ placed between the hydrophobic surfaces [47]

2.6 Gaps in Knowledge

Atomization-based cutting fluid (ACF) systems have been found to be preferable over the conventional flood cooling methods for improving the cutting performance in micromachining operations as they effectively reduce the temperature at the workpiece-tool interface through evaporative cooling and provide superior lubrication to the cutting zone. While such ACF systems appear to be beneficial, there is a lack of a physics-based understanding of the phenomena underlying cooling and lubrication performance of ACF systems in micro-machining processes.
First, there is a lack of micro-machining studies that identify the combined effects of droplet characteristics and cutting fluid properties on the cooling and lubrication performance of ACF systems. Though the study of Jun et al. [2] established that the droplet characteristics and cutting fluid properties effect the performance of ACF systems, no investigation of their specific effect on the observed cutting performance was made.

Second, there is a lack of understanding of droplet spreading behavior on a rotating surface, in particular, as a function of droplet characteristics, fluid properties and surface speed. A limited number of studies have been done to investigate the droplet impingement dynamics on rotating surfaces. Although the experimental work of Chen and Wang [12] showed that the contact area for the droplets is dependent on the surface speed, they did not investigate the spreading behavior as a function of specific fluid properties, viz., surface tension and viscosity. Further, the droplet diameters used in this study were also significantly larger (about 10 times) to those encountered in the atomized cutting fluid application.

Third, modeling work on droplet spreading on a rotating surface has not been undertaken. A spreading model that predicts droplet geometry resulting from spreading on a rotating surface will be important to predict the cooling achieved by a droplet in the cutting zone and the lubrication force generated at the tool-chip interface. A large number of analytical and numerical models have been developed for droplet impact on stationary surfaces so as to enable design of better spray processes. Although these studies give valuable insight into the methodology adopted for modeling droplet spreading behavior, a
spreading model which takes into account the speed of the rotating surface needs to be developed.

Lastly, no study has been done to understand the relationship between droplet spreading behavior on a rotating surface and the cooling and lubrication performance of an ACF system in micro-machining processes. The mist-based cutting fluid applications presented in the literature have mostly been experimental with little emphasis on investigating the relationship between the system parameters and machining conditions on the observed cooling and lubrication performance.

The limitations of the experimental work on the physics of droplet spreading on a rotating surface and its relation to cooling and lubrication of ACF systems provide the motivation for the research presented in the next four chapters. The first limitation is addressed by conducting micro-turning experiments to understand the effect of droplet speed and cutting fluid properties on cutting forces and cutting temperatures. Droplet impingement experiments are then conducted on a rotating surface using fluids of different surface tension and viscosity to address the second limitation. Next, a droplet spreading model is developed to predict droplet spreading behavior on a rotating surface. The last limitation is addressed by validating a micromachining model using the spreading model to predict the cooling and lubrication performance of an ACF based micro-turning application and conducting a parametric study to identify the significant factors affecting the performance of an ACF system.
Chapter 3

Micro-turning experiments

Atomization-based cutting fluid (ACF) system was used by Jun et al. [2] in micro-milling operation, with promising performance shown as compared to dry and flood coolant applications. However, no investigation of effect of droplet characteristics and cutting fluid properties on cutting performance was done. In this chapter, an ACF system is used for micro-turning experiments to understand the effect of droplet speed and cutting fluid properties on cutting forces and cutting temperatures. The chapter is divided into three subsections. Section 3.1 presents the experimental setup and design, followed by section 3.2 wherein experimental results are presented and discussed. The chapter summary is presented in Section 3.3.

3.1 Experimental Setup and Design

3.1.1 Test-bed Design

A schematic of the ACF system employed for micro-turning operation is shown in Fig. 3.1. This set-up is similar to that used in the study by Jun et al. [2]. The ACF system consists of an ultrasonic vibration-based atomizer, a cutting fluid reservoir, and a regulated air supply. The atomizer uses ultrasonic vibrations of frequency 1 kHz to atomize the cutting fluid. Once the fluid atomizes, the droplets are carried through a pipe. In the center of the pipe lies a smaller tube that carries regulated air supply. The droplets
flowing through the pipe are carried to the cutting zone by the air jet flowing through the small tube. The inner diameter of the pipe and tube is 10 mm and 4 mm, respectively. The diameter of the atomized droplets was measured using Hirox CX-10C optical microscope and was observed to lie in the range 8-15 µm. The atomization rate of the ultrasonic atomizer was measured to be about 1 ml/min. The air supply was regulated using an external pressure control valve to maintain the air jet speed in the range 0.5-10 m/s.

![Figure 3.1 Schematic of the ACF system used for micro-turning operation](image)

The ACF system shown in Fig. 3.1 is used as a separate unit on Microlution Inc.’s three-axis CNC micro-scale machine tool (mMT) developed at the Micro-Scale Machining and Machining Tool Research Laboratory at the University of Illinois at
Urbana-Champaign. The testbed is equipped with AC linear motors and an electric NSK spindle supported by air bearings. The maximum operational speed of the electric spindle is 50,000 RPM. The axis encoders have a resolution of 0.02 µm. The mMT is typically used for micro-milling and micro-drilling operations. In order to use it for a micro-tuning operation, the workpiece is mounted in the spindle and the tool mounted on the xy stage (Fig. 3.2). The system was installed in a room with ambient temperature 24±1°C and relatively humidity 60±1%. A photo of the experimental setup is shown in Fig. 3.2. The mist is directed towards the cutting zone from below.

Figure 3.2 Setup of the micro-turning ACF system
3.1.2 Cutting Force and Temperature Measurement

The machinability measures for the micro-turning experiments were the cutting force and cutting temperature. A Kistler load cell (9018 tri-axial) was used to measure the cutting force along the x, y, and z axes during the turning process at a sampling frequency of 30 kHz. The load cell was mounted behind the tool holder (Fig. 3.2). The magnitude of cutting force measured in the direction of the feed motion (z-direction) has been seen to best reflect the effect of cutting fluid penetration [48]. Therefore, the force in the feed direction is used here as a measure to evaluate the machining performance of the various cutting fluids.

An Omega SA1XL-J-SB type thermocouple (range 0-750°C) along with Analog Devices 5B47 linearized thermocouple input module was used to measure the temperatures during cutting at a sampling frequency of 800 Hz. Thermocouple with a protective steel jacket was used to avoid interference with the electric voltage signals from the machine tool. The thermocouple was calibrated using ice water and boiling water and was found to have a calibration constant of 0.8 °C/volt. The thermocouple junction was positioned 0.9 mm away from the nose of the cutting tool and thermocouple wire attached to the shank of the cutting tool using superglue (Fig. 3.3). The maximum temperature recorded during the cutting operation was used as the cutting temperature measure for the associated test. Figures 3.4 and 3.5 show the typical cutting force and cutting temperature plots for the experiments presented in this study.
Figure 3.3 Cutting tool- thermocouple assembly

Figure 3.4 Typical cutting force plot (in the direction of feed)
3.1.3 Experimental Design

Three test fluids are used here to study the effect of fluid properties on cutting performance: De-ionized (DI) Water and the semi-synthetic fluids Castrol Clearedge 6519 at 12.5% dilution and Castrol Clearedge 6519 at 25% dilution. The Castrol Clearedge 6519 at 12.5% dilution is prepared by adding 12.5 ml of Castrol Clearedge 6519 to 87.5 ml DI Water. Castrol Clearedge at 25% dilution is by adding 25 ml of Castrol Clearedge 6519 to 75 ml DI Water. The physical properties of the three cutting fluids are listed in Table 3.1. These cutting fluids were chosen to study separately the effect of surface tension and viscosity on the cooling and lubrication performance. Note that the 12.5% Castrol 6519 and 25% Castrol 6519 have the same surface tension but different viscosities, whereas, DI water and 12.5% Castrol 6519 have similar viscosity.
but varying surface tension. While a high concentration of 25% Castrol 6519 is not used in flood-coolant applications, the atomization-based cutting fluid application consumes only a very small amount of cutting fluid (about 1 ml for each turning operation reported here), which makes the use of such a high percentage of semi-synthetic fluids to be economically viable. Furthermore, as borne out by the machining results in the following section, such a high percentage of Castrol 6519 significantly reduces the cutting forces encountered in micro-scale turning.

**Table 3.1 Cutting Fluid Properties**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface Tension (mN/m)</th>
<th>Density (kg/m$^3$)</th>
<th>Viscosity (cP)</th>
<th>Thermal Conductivity (W/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI water</td>
<td>72</td>
<td>1000</td>
<td>1.01</td>
<td>0.58</td>
</tr>
<tr>
<td>12.5% Castrol 6519</td>
<td>42</td>
<td>996.25</td>
<td>1.49</td>
<td>0.52</td>
</tr>
<tr>
<td>25% Castrol 6519</td>
<td>42</td>
<td>992.5</td>
<td>2.91</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Micro-turning experiments were conducted on a 1018 steel rod of diameter 6 mm. Since the minimum chip thickness ratio ($\lambda$) for 1018 steel is 0.6 [49], in order to keep cutting in the shearing domain, turning experiments were conducted at a feed of 5 $\mu$m/rev, which corresponds to $\lambda$=1.4. A length of 1 mm was turned for each test. Tests were conducted with the three cutting fluids at different droplet speeds in the range 0-10 m/s. A total of 18 of such experiments were conducted. A test was also conducted under dry conditions. The distance between the plane where droplets exit the ACF system and the cutting zone was maintained at 20 mm for all the tests. Table 3.2 lists the experimental conditions used for the micro-turning tests.
### 3.2 Experimental Results

#### 3.2.1 Cutting Temperatures

Figure 3.6 shows the variation of cutting temperature with droplet speed for the three cutting fluids. The data for cutting temperature is also listed in Table 3.3. Note that the temperature for dry cutting is 91°C. All the fluids show significant temperature drop when compared to dry cutting operation indicating effective cooling of the cutting zone. It can be seen that 12.5% Castrol 6519 generates the lowest cutting temperatures, or cools the cutting zone the most. At the same time, 25% Castrol 6519 cools more than DI water, but less than 12.5% Castrol 6519.

The trend in the cutting temperatures suggests an interaction effect between the fluid surface tension and viscosity. At low values of viscosity (DI Water, 12.5% Castrol 6519), lower surface tension (12.5% Castrol 6519) generates lower cutting temperatures. However, as the viscosity of the cutting fluid increases from 1.49 cP (12.5% Castrol 6519) to 2.91 cP (25% Castrol 6519), it appears to offset the advantage offered by the
lower surface tension in reducing the cutting temperatures. For all the fluids, the cutting temperature decreases steadily as droplet speed increases to 6 m/s, and then remains more or less constant.

![Figure 3.6 Cutting temperature versus droplet speed](image)

**Table 3.3 Cutting temperature data**

<table>
<thead>
<tr>
<th>Droplet Speed (m/s)</th>
<th>Dry cutting</th>
<th>DI Water</th>
<th>12.5% Castrol 6519</th>
<th>25% Castrol 6519</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>86</td>
<td>70</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>54</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>79</td>
<td>55</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>71</td>
<td>55</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>78</td>
<td>50</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>46</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

91°C

The above results show that 12.5% Castrol 6519 (surface tension of 42mN/m and viscosity of 1.49cP) results in the highest drop in cutting temperatures when compared to DI Water (surface tension of 72mN/m and viscosity of 1.01cP) and 25% Castrol 6519.
(surface tension of 42mN/m and viscosity of 2.91cP). The study of Jun et al. [2] showed that the cooling in atomized cutting fluid application is attributed to evaporative cooling. The study of diMarzo et al. [41] showed that a faster evaporating droplet implies increased heat transfer from the solid surface to the droplet. Thus, lowest cutting temperatures are expected to be generated by the fluid that evaporates at the highest rate. Based on the trends in cutting temperatures it is expected that droplets of 12.5% Castrol 6519 evaporate fastest and the droplets of DI Water evaporate at the slowest rate. The study of Chandra et al. [49] showed that for fluids with varying surface tension, highest evaporation rate is observed for droplets of fluids with lowest surface tension. Low surface tension leads to more spreading generating droplets with larger spread area on the surface and smaller thickness leading to faster transfer of heat from the surface and a higher evaporation rate. Thus, it is expected that the droplets of 12.5% Castrol 6519 spread the most whereas the droplets of DI Water spread the least on the rotating surface.

The machining experiments reveal that the cutting temperatures reduce with an increase in the droplet speed to about 6 m/s after which little change in temperature is seen. Therefore, for the case in point it is likely that the evaporation rate increases with increase in the droplet speed to about 6 m/s and remains more or less constant for droplet speeds beyond 6 m/s. Based on the study of Mao et al. [5], an increase in droplet speed leads to increased spreading on the surface. The evaporation rate, therefore, increases as the speed of the impinging droplet increase. Further research is required to understand the more and less constant cutting temperatures observed beyond the droplet speeds of 6 m/s.
3.2.2 Cutting Forces

Figure 3.7 shows the steady-state cutting force (measured in the direction of feed) recorded at varying droplet speeds for the three cutting fluids. The cutting force data is also listed in Table 3.4. The results suggest that for DI Water and 12.5% Castrol 6519 there is no significant effect of droplet speed on the cutting force. Therefore, the cutting forces for these two fluids are averaged across droplet speeds. The average cutting force with 90% statistical confidence intervals was found to be 1.367 ± 0.118 N for DI water and 1.255 ± 0.173 N for 12.5% Castrol 6519. The corresponding value for dry cutting conditions is 1.55 N.

![Figure 3.7 Cutting force versus droplet speed](image)
The average cutting force values indicate that there is no strong evidence of reduction in forces with the use of DI Water or 12.5% Castrol 6519. However, as the fluid viscosity increases to 2.91cP (due to increase in oil content) for 25% Castrol 6519, the cutting forces are seen to be significantly lower (almost 50%). Further, it appears that for this fluid the cutting forces are lowest for low droplet speed and while increasing as droplet speed increases are still lower than for the other two fluids. This indicates that even at high cutting speeds encountered in micro-machining, atomized cutting fluid can have effective penetration into the cutting zone and produce a lubricating effect.

As presented above, DI Water and 12.5% Castrol 6519 generate average cutting force of 1.367 N and 1.255 N, respectively and 25% Castrol 6519 generates the lowest cutting forces at all droplet speeds tested. Thus, for the fluids tested it appears that the lubricity is a stronger function of the fluid viscosity (attributed to the oil content of the cutting fluid) and a weaker function of the fluid surface tension. The study of Langlois [45] showed that lubrication achieved between two sliding surfaces is a strong function of the fluid viscosity and the area covered by the intermediate fluid film and its thickness. Effective lubrication is achieved by a fluid with high viscosity indicating effective

---

**Table 3.4 Cutting force data**

<table>
<thead>
<tr>
<th>Droplet Speed (m/s)</th>
<th>Dry cutting</th>
<th>1.55 N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DI Water</td>
<td>12.5% Castrol 6519</td>
</tr>
<tr>
<td>0.5</td>
<td>1.39</td>
<td>1.09</td>
</tr>
<tr>
<td>2</td>
<td>1.32</td>
<td>1.12</td>
</tr>
<tr>
<td>4</td>
<td>1.18</td>
<td>1.28</td>
</tr>
<tr>
<td>6</td>
<td>1.43</td>
<td>NA</td>
</tr>
<tr>
<td>8</td>
<td>1.26</td>
<td>1.15</td>
</tr>
<tr>
<td>10</td>
<td>1.44</td>
<td>1.15</td>
</tr>
</tbody>
</table>

---

69
friction reduction owing to the increased oil content. Thus, the lubrication force generated in the cutting zone is a stronger function of the fluid viscosity and has a weaker dependence on the spread area and height of the impinging droplets.

Based on above observations, it can be concluded that for atomized cutting fluid application, choice of the cutting fluid is dependent on the desired machining performance. Although, low surface tension fluid is observed to reduce the cutting temperatures, a change in viscosity owing to oil content appears to have differing effects on cutting force and on cutting temperature. For a given surface tension, the fluid with higher viscosity generates lower cutting forces but higher cutting temperatures. However, the reduction in cutting forces is much greater than the modest increase in cutting temperature.

3.3 Chapter Summary

Micro-turning experiments are conducted to examine the effect of fluid properties on cutting forces and cutting temperatures. The experiments indicate that a cutting fluid with low surface tension and low viscosity generates lower cutting temperatures. Cutting temperatures are observed to decrease steadily with an increase in the droplet speed up to 6 m/s beyond which no significant reduction in temperature is seen. A fluid with low surface tension and high viscosity is observed to generate lower cutting forces. The experimental results indicate that fluid surface tension and viscosity (owing to increased oil content) values result in a trade-off in the machining performance for the atomized cutting fluid application. A decrease in surface tension is observed to aid cooling in the
cutting zone. However, for a given surface tension value, the fluid with higher viscosity significantly reduces the cutting force but results in a modest increase in the cutting temperatures.

The micro-turning experiments reported here give valuable insight into the dependence of the cutting performance on the droplet speed and the fluid properties for atomized cutting fluid application. The experiments also give useful information about the spreading behavior underlying the observed cooling and lubrication performance. In order to better understand the physics underlying cooling and lubrication in ACF systems, spreading and evaporation behavior of droplets impinging upon a rotating surface needs to be studied. In chapter 4, single droplet impingement experiments are conducted on a rotating surface using fluids of different surface tension and viscosity values to understand the spreading and ensuing evaporative behavior of a droplet impinging upon a rotating surface.
Chapter 4

Single Droplet Impingement Experiments

The micro-turning experiments presented in Chapter 3 suggest that the cooling and lubrication performance of ACF systems is determined by the spreading behavior of the droplets impinging upon the cutting zone. To better understand the physics underlying the cooling and lubrication mechanism of ACF systems, the droplet spreading behavior on a rotating surface needs to be studied. To this end, in this chapter controlled single droplet impingement experiments are designed and conducted to understand the spreading behavior of a droplet impinging upon a rotating surface. These experiments are designed such that the droplet speed, surface speed, and fluid physical properties can be controlled independently to study their effect on the droplet spreading behavior. Such insights will make it possible to better design both the cutting fluids and the atomization process for efficient performance of ACF systems in micromachining processes. The chapter is divided into three subsections. Section 4.1 presents the experimental setup and design, followed by section 4.2 wherein experimental results are presented. Section 4.3 discusses the result of the micro-turning experiments of chapter 3 in light of the single droplet impingement experiments. The chapter summary is presented in Section 4.4.
4.1 Experimental Setup and Design

4.1.1 Test-bed Design

The experimental setup to study the single droplet behavior on rotating surfaces is shown schematically in Fig. 4.1. The experimental setup consists of a droplet-on-demand (DOD) unit comprising of a droplet dispense head (1) and a signal driver (2) (supplied by Engineering Arts, Phoenix, AZ) along with an electric motor and a spindle (3), a high-speed video camera (4) with light source (5). The DOD unit works in conjunction with a flexible waveform signal driver that generates on command either a single droplet or a stream of droplets. The signal driver feeds a non-contact glass piezo-dispenser with an orifice. An orifice of diameter 32 \( \mu \text{m} \) is used that generates droplets in the size range of 30-50 \( \mu \text{m} \) depending on the fluid type and the driver amplitude. The droplet velocities range from 2 m/s to 3 m/s depending on the amplitude of the signal produced by the driver.

The rotating workpiece is a 3 mm diameter steel rod with surface roughness (Ra) of 0.035 \( \mu \text{m} \). The rotational speed of the spindle is 1000-32,000 RPM and is used to control the speed of the rotating workpiece. A Phantom v7.0 high speed camera is used with a 20X magnification lens to capture the droplet impact. The camera is tilted at 5° with respect to the axis of the rotating cylinder so as to capture clearly the droplet interacting with the moving surface. The system was installed in a room with ambient temperature 24±1 °C and relatively humidity 60±1 %. A photo of the setup is provided in Fig. 4.2.
Figure 4.1 Schematic of the single droplet generator experimental setup

Figure 4.2 Experimental setup for single droplet impingement study

4.1.2 Experimental Design

The three fluids used in the micro-turning experiments reported in chapter 3 (viz., DI water, 12.5% and 25% Castrol 6519) were used for the single droplet impingement experiments. Apart from the three cutting fluids, three additional fluids, viz., 0.0001%
Neodol-6, 2% Pluronic L-64, and 0.01% Neodol-6 (listed in Table 4.1 with physical properties) were used to identify the effect of fluid properties on the spreading and evaporative behavior of droplets impinging on a rotating surface. The additional fluids were prepared by adding varying quantities of surfactants (percentage and chemical type listed in Table 4.1) to DI water. These additional fluids were chosen to study separately the effect of surface tension and viscosity on the droplet behavior. Note that the 12.5% Castrol 6519, 25% Castrol 6519, and 2% Pluronic L-64 have the same surface tension but different viscosities, whereas, DI water, 0.0001% Neodol-6, 2% Pluronic L-64, and 0.01% Neodol-6 have the same viscosity but varying surface tension. Single droplet impingement experiments were conducted with all the six fluids at three surface speeds of 0.8, 2.5 and 4.2 m/s. These speeds were chosen to capture the speed range encountered in micro-machining commonly.

A burst of 200 droplets at a frequency of 50 Hz was used for the videography of droplet impact at a rate of 24,000 frames-per-second with 2 µs exposure. The images were captured at a resolution of 320x240 pixels with 42 µs time difference between consecutive images. Approximately 9000 frames were captured for each experimental condition. The images from the videos were then extracted and the size measurements made using Vision Gauge Imaging & Measuring Software.
Table 4.1 Physical properties of the fluids used for single droplet experiments

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface Tension (mN/m)</th>
<th>Viscosity (cP)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI Water</td>
<td>72</td>
<td>1.01</td>
<td>1000</td>
</tr>
<tr>
<td>12.5% Castrol Clearedge 6519</td>
<td>42</td>
<td>1.49</td>
<td>996.25</td>
</tr>
<tr>
<td>25% Castrol Clearedge 6519</td>
<td>42</td>
<td>2.91</td>
<td>992.5</td>
</tr>
<tr>
<td>0.0001% Neodol-6</td>
<td>62</td>
<td>1.04</td>
<td>1000</td>
</tr>
<tr>
<td>2% Pluronic L-64</td>
<td>43</td>
<td>1.07</td>
<td>1000</td>
</tr>
<tr>
<td>0.01% Neodol-6</td>
<td>33</td>
<td>1.03</td>
<td>1000</td>
</tr>
</tbody>
</table>

4.2 Experimental Results

4.2.1 Time evolution of droplets on a rotating surface

The images captured using the setup described in section 4.1 were examined to understand the effect of surface speed and fluid properties on the droplet behavior. Based on the observation of high speed images, the nature of the droplet shape following impact is shown in Figs. 4.3 a-c, where, \( d_0 \) is the initial droplet diameter, \( d \) is the contact diameter of the droplet along the direction of the surface rotation, and \( h \) is the corresponding droplet height.

![Figure 4.3](image)

Figure 4.3 (a) Droplet before impact (b) Droplet after impact (c) Droplet in the steady state
After impact, the droplet takes the shape of an asymmetrically-deformed ellipsoidal cap as it spreads on the surface, as shown in Fig. 4.3 b. The advancing and receding contact angles are shown as $\theta_a$ and $\theta_r$. In the steady state, the droplet is observed to have the shape of a spherical cap with contact angle, $\theta_c$, as shown in Fig. 4.3 c. The ratios $d/d_0$ and $h/d_0$ are used here to study the evolution of the droplet shape with time on a rotating surface.

The temporal evolution of droplets impacting a dry, stationary surface has been characterized through four distinct phases, viz., kinetic phase, spreading phase, relaxation phase, and evaporation phase [36]. Similar phases are observed here for droplets impacting a rotating surface. The boundaries of these four distinct phases along with the ratios $d/d_0$ and $h/d_0$ for DI Water droplets impacting a surface rotating at speeds of 0.8 m/s and 2.5 m/s are shown in Figs. 4.4a-b, respectively. The time scale in Figs. 4.4a-b is logarithmic. It is observed that for a given droplet (fluid properties, droplet size, and droplet speed) and surface characteristics (material and surface roughness), the phase duration and the ratios $d/d_0$ and $h/d_0$ are a strong function of the surface speed. The initial droplet diameter in this case is 50 μm and the impact velocity is 2 m/s.
Figure 4.4 Time evolution for DI Water droplet on a surface rotating (scale bar= 20µm)
The initial *kinetic phase* is the shortest phase during which, the droplet is just in contact with the target surface and dynamics is dominated by the inertial forces. The duration of this phase depends on the initial droplet size ($d_0$) and the droplet impact speed ($u_0$). Based on the calculations of Rioboo et al. [36] this phase is estimated to last for less than $2 \mu$s for a droplet with initial diameter $50 \mu$m and impact velocity of $2$ m/s and is, therefore, not captured by the camera. Since the spreading in this phase is dictated by droplet kinetic energy alone, the droplet spreads at a rate equal to the droplet impact speed and the spreading diameter is expected to grow linearly with time [36].

Once the kinetic phase ends, the surface tension and viscous forces start playing a more dominant role and the droplet continues to spread. This phase is termed as the *spreading phase*. As seen in Figs. 4.4a-b, in the spreading phase the droplet has the shape of an asymmetrically-deformed ellipsoidal cap. This deformation is attributed to the tangential forces exerted by the rotating surface. Figs. 4.4a-b show that while a surface rotating at the speed of $0.8$ m/s elongates the droplet to $1.2$ times the initial diameter, a surface rotating at the speed of $2.5$ m/s elongates the droplet to about $1.8$ times its initial diameter.

On examining the droplet shape in Figs. 4.4a-b, it appears that the droplet geometry during spreading is dependent on the resultant ($u_r$) of the droplet speed ($u_0$) and surface speed ($u_s$) (Fig. 4.5). For a droplet impact speed of $2$ m/s and surface speed of $0.8$ m/s, $u_r = 2.15$ m/s. Thus, $u_r \approx u_0$ and the impact is close to normal resulting in an almost spherical shape in the spreading phase (Fig. 4.4a). On the other hand, for a droplet spreading on a surface moving at a speed of $2.5$ m/s, $u_r = 3.2$ m/s resulting in a deformed ellipsoidal shape.
At the end of the spreading phase, the surface forces may or may not cause the
droplet to recoil. This phase is known as the relaxation phase (Figs. 4.4a-b). In the
relaxation phase shown in Fig. 4.4a, the droplet does not recoil and no change in either
droplet diameter (d) or height (h) is observed. However, for the relaxation phase depicted
in Fig. 4.4b, the droplet is observed to recoil. There is decrease in the droplet diameter (d)
that results in a corresponding increase in the height (h) of the droplet in order to keep its
volume constant (the evaporation has not yet started). It is observed that in either case, at
the end of the relaxation phase, the droplet takes the shape of a spherical cap (Fig. 4.4a-b)
similar to that observed for droplets on a stationary surface [4-5]. However, the droplet
diameter after retraction depends on the surface speed. In Fig. 4.4a, where surface speed
is 0.8 m/s, at the end of the relaxation phase d/d_0 = 1.2 while in Fig. 4.4b where surface
speed is 2.5 m/s, d/d_0 = 1.7 at the end of the relaxation phase.

In the next phase, viz., the evaporative phase, the droplet volume begins to reduce
owing to evaporation. The evaporation phase may or may not coincide with the relaxation
phase depending on the thermodynamical fluid properties, the area occupied by the
droplet on the surface, the droplet thickness, and the surface temperature [49]. As can be
seen in Figs. 4.4a-b, in these single droplet experiments the evaporation of DI water
begins much after the droplet reaches the steady state, making the relaxation and evaporation phases distinct. However, for micro-machining applications the high temperature in the cutting zone is likely to make these phases to overlap.

Figure 4.6 depicts the temporal evolution of the 12.5% Castrol 6519 droplet on a surface rotating at the speed of 0.8 m/s. In comparison with DI Water (surface tension= 72 mN/m, viscosity= 1 cP), 12.5% Castrol 6519 has much lower surface tension (42 mN/m) but a modest increase in viscosity (1.49 cP). Unlike the behavior of DI Water seen in Fig. 4.4a, here the evaporation phase appears to begin much earlier, at ~0.1 ms rather than 10 ms. It can be seen in Fig. 4.6 that 12.5% Castrol 6519 forms thinner droplets (smaller h/d₀) with larger contact diameter (larger d/d₀). This geometry of the droplet aids the evaporation at the fluid-air interface, thereby, speeding up the onset of the evaporation phase.

![Figure 4.6 Time evolution for 12.5% Castrol 6519 droplet on a surface rotating at 0.8m/s (scale bar= 20µm)](image)

Figure 4.6 Time evolution for 12.5% Castrol 6519 droplet on a surface rotating at 0.8m/s (scale bar= 20µm)
The spreading and evaporative behavior of a droplet sheds light on the extent of lubrication and heat transfer from the rotating surface. This behavior is discussed in the following two sections.

4.2.2 Droplet Behavior in the Spreading Phase

In order to evaluate the effect of surface speed on the droplet spreading behavior, droplet contact diameter (d) is measured in the spreading phase. The dimensionless diameter (d/d₀) is compared for fluids of varying surface tension and viscosity to understand the combined effect of surface speed and fluid properties on the droplet spreading behavior. For all the data presented in this section, the contact diameter is measured ~30 µs after impact for a surface rotating at 0.8 m/s and 2.5 m/s. For a surface rotating at 4.2 m/s, the contact diameter is measured ~15 µs after the impact as the high surface speed makes the droplet go out of the field view of the camera rendering no information of the contact diameter at 30 µs.

Figures 4.7a-c shows the contact diameter of droplets of 12.5% Castrol 6519 impinging on surface of varying speed. An increase in surface speed from 0.8 m/s to 2.5 m/s increases the contact diameter from 80 µm to 102 µm. On further increasing the surface speed to 4.2 m/s, the contact diameter is observed to increase to 140 µm in just half the time. Thus, for a rotating surface the spreading behavior is a function of the surface speed.

Figures 4.8a-b show the contact diameter of droplets of DI water and 12.5% Castrol 6519 impinging on a surface rotating at 4.2 m/s. While DI water droplet spreads
to 112 µm in 12 µs, the droplet of 12.5% Castrol 6519 spreads to 145 µm in about the same time, 15 µs. Figure 4.8 shows that fluids with varying physical properties have different contact diameter even at a relatively high surface speed of 4.2 m/s.

Figure 4.7 Droplets of 12.5% Castrol 6519 spreading on a surface moving at (a) 0.8 m/s (b) 2.5 m/s (c) 4.2 m/s
Figure 4.8 (a) Droplet of DI Water spreading on a surface moving at 4.2 m/s (b) Droplet of 12.5\% Castrol 6519 spreading on a surface moving at 4.2 m/s

Figure 4.9 shows the variation of dimensionless diameter ($d/d_0$) with surface tension for fluids with viscosity $\sim$1 cP. The droplet speed is 2 m/s for all the data points presented in Fig. 4.9. In general, the dimensionless diameter decreases with an increase in surface tension, which is similar to the droplet behavior on stationary surface [37]. The dimensionless diameter is observed to have a direct dependence on the surface speed as well. Irrespective of the surface tension value, an increase in surface speed is seen to increase the dimensionless diameter, which implies more spreading on the surface.
Figure 4.9 Dimensionless diameter ($d/d_0$) versus surface tension (Fluid viscosity of 1cP)

Figure 4.10 shows the variation of dimensionless diameter ($d/d_0$) with viscosity. The fluid surface tension is kept constant at 42 mN/m and the droplet speed is 2 m/s for the data presented in Fig. 4.10. For the range of viscosities tested, which encompasses most cutting fluids, the dimensionless diameter does not seem to be a function of the fluid viscosity. Figure 4.10 again demonstrates the surface speed effect, i.e., the dimensionless diameter is observed to increase with an increase in the surface speed.
In summary, the droplet contact diameter \((d)\) decreases with increase in fluid surface tension but does not change much with a change in the viscosity. Irrespective of the fluid properties, surface speed is observed to increase the droplet contact diameter. Figures 4.9-4.10 show that a change in the surface speed from 0.8 m/s to 4.2 m/s doubles the droplet contact diameter in the direction of rotation of the surface.

### 4.2.3 Droplet Behavior in the Evaporative Phase

Since in the evaporation phase droplet is in form of a spherical cap, measurement of two geometric parameters, viz., the radius of curvature \((R)\) and the droplet height \((h)\), enables the calculation of the droplet volume \((V)\). The initial droplet volume \((V_0)\) is calculated by measuring the initial droplet diameter \((d_0)\). The droplet volume \((V)\) was
measured after each rotation of the rod and compared with the initial droplet volume \( (V_0) \) to study the change of droplet volume with time. Figure 4.11 shows the reducing droplet volume for DI water evaporating from a surface rotating at 2.5 m/s. The figure shows that over a period of 212 ms, the droplet has evaporated to one fourth its original volume. On the other hand, 12.5% Castrol 6519 was observed to evaporate to one fourth its original volume in only 45 ms, which is approximately \( \frac{1}{5^{\text{th}}} \) the time taken by DI Water. The volume calculations were performed for all the fluids listed in Table 4.1 to understand the relationship between evaporation behavior and fluid properties.

Figure 4.11 Evaporation of droplet of DI water

Figure 4.12 shows the plot of the dimensionless volume \( (V/V_0) \) versus time for a droplet of DI water, at different surface speeds. The droplet speed is 2 m/s for the data
presented in Fig. 4.12. As compared to the stationary surface, a rotating surface is observed to have a higher evaporation rate as indicated by the significant drop in the dimensionless volume. This is owing to the surface rotation, which increases the convective heat transfer at the droplet-air interface, thereby, increasing the evaporation rate. From Fig. 4.12 it is evident that for the range of surface speeds used in this study, as long as the surface is rotating, the magnitude of the surface speed within this range does not appear to have a significant effect on the evaporation rate.

![Figure 4.12 Variation of dimensionless volume with time for DI Water](image)

Figure 4.12 Variation of dimensionless volume with time for DI Water

Figure 4.13 shows the variation of the dimensionless volume ($V/V_0$) with time for DI water, 0.0001% Neodol-6, and 0.01% Neodol-6 measured at the surface speed of 2.5 m/s. Viscosity is constant at ~1 cP and droplet speed is 2 m/s for the data presented in Fig. 4.13. It can be seen that as the surface tension decreases, the rate of evaporation increases. As discussed under the analysis of the spreading phase in Section 4.2.2, a
decrease in surface tension leads to formation of droplets having larger contact diameter. This elongation of the droplets leads to an increase in evaporation rate [49].

Figure 4.14 shows the variation of the dimensionless volume with time for both 12.5% and 25% Castrol 6519 at a surface speed of 2.5 m/s. Surface tension is constant at 42 mN/m and droplet speed is kept at 2m/s for the data presented in Fig. 4.14. For these two fluids, it can be seen that as the fluid viscosity increases, evaporation rate reduces. As seen in Section 4.2.2, the contact diameter for these two fluids is equal (Fig. 4.10). However, there is a two-fold increase in the oil phase content that appears to inhibit the evaporation rate.

![Figure 4.13 Variation of dimensionless volume with time for varying surface tension (viscosity constant at 1cP)](image)
In summary, droplet evaporation is a strong function of both the fluid surface tension and viscosity. Low surface tension and low viscosity are observed to increase the evaporation rate. The surface rotation is seen to increase the evaporation rate relative to a stationary surface, owing to convective heat transfer. However, among different surface speeds studied here, not much change in evaporation rate is observed.

4.3 Discussion

The trends in the droplet behavior reported in section 4.2 are now used to explain the machining observations presented in chapter 3. A faster evaporating liquid implies increased heat transfer from the machined surface and therefore, lower temperatures in the cutting zone. The single droplet experiments reveal that a fluid with low viscosity and low surface tension has an increased evaporation rate, which is expected to result in
better cooling of the surface. This is supported by the results presented in chapter 3, where 12.5% Castrol 6519 (surface tension of 42 mN/m and viscosity of 1.49 cP) results in the highest drop in cutting temperatures when compared to DI Water (surface tension of 72 mN/m and viscosity of 1.01 cP) and 25% Castrol 6519 (surface tension of 42 mN/m and viscosity of 2.91 cP). While the single droplet experiments did not study the effect of droplet speed on evaporation, the machining experiments reveal that the cutting temperatures reduce with an increase in the droplet speed to about 6 m/s after which little change in temperature is seen. Therefore, for the case in point it is likely that the evaporation rate increases with increase in the droplet speed to about 6 m/s.

As presented in chapter 3, DI Water and 12.5% Castrol 6519 generate average cutting force of 1.367 N and 1.255 N, respectively and 25% Castrol 6519 generates the lowest cutting forces at all droplet speeds tested. In the single droplet experiments reported in section 4.2.2, DI Water droplet was observed to spread to 2.3 times its initial diameter, whereas both 12.5% and 25% Castrol 6519 droplets spread to 2.7 times the initial diameter. Although both 12.5% and 25% Castrol 6519 have same spread diameter, the viscosity of 25% Castrol is much higher. Thus, for the fluids tested it appears that the lubricity is a stronger function of the fluid viscosity (attributed to the oil content of the cutting fluid) and not strongly dependent on the spread diameter. The lubrication achieved in the cutting zone is a function of both the droplet geometry and the fluid properties [46]. Effective lubrication is achieved by a fluid with low surface tension (effective wetting) and high viscosity (effective friction reduction). Furthermore, the single droplet experiments showed that the 25% Castrol 6519 evaporates slower so this should further contribute to the lubrication effect.
Based on above observations, it can be concluded that for atomized cutting fluid application, choice of the cutting fluid is dependent on the desired machining performance. Although, low surface tension fluid is observed to reduce the cutting temperatures, a change in viscosity owing to oil content appears to have differing effects on cutting force and on cutting temperature. For a given surface tension, the fluid with higher viscosity generates lower cutting forces but higher cutting temperatures. However, the reduction in cutting forces is much greater than the modest increase in cutting temperature.

4.4 Chapter Summary

The spreading and evaporative behavior of droplets impacting a rotating surface has been investigated with an aim to better understand the lubricating and cooling effect of atomized droplets in micro-machining. The single droplet experiments show that the droplet evolution on a rotating surface occurs in four phases, viz., kinetic, spreading, relaxation and evaporation which is similar to the evolution observed in case of a stationary surface. In the spreading phase, the droplets are observed to take either the shape of a spherical cap or a deformed-ellipsoidal cap based on the resultant of the droplet impact speed and the surface velocity. The droplet spreading is observed to increase with an increase in the surface speed. It is also observed to increase with a decrease in surface tension but does not appear to change with the fluid viscosity. The evaporation rate of a droplet on a rotating surface is observed to be higher than that of a droplet on a stationary surface owing to increased convective heat transfer. A fluid with
low surface tension and low viscosity is observed to have higher evaporation rate than a fluid with high surface tension and/or high viscosity. The micro-turning experiments and the single droplet experiments indicate that the cutting temperatures are a strong function of the droplet evaporation behavior. On the other hand, the cutting forces appear to be dependent on the fluid viscosity and do not exhibit strong dependence on the droplet contact diameter. The fluid surface tension and viscosity (owing to increased oil content) values appear to result in a trade-off in the machining performance for the atomized cutting fluid application. A decrease in surface tension is observed to aid cooling in the cutting zone. However, for a given surface tension value, the fluid with higher viscosity significantly reduces the cutting force but results in a modest increase in the cutting temperatures.

In the study reported here, single droplet impingement experiments are conducted on a rotating surface using fluids of different surface tension and viscosity values to understand the spreading and ensuing evaporative behavior of a droplet impinging upon a rotating surface. The above study gives useful insight into the physics underlying cooling and lubrication mechanism in ACF systems. In order to design efficient ACF systems, droplet spreading on a rotating surface needs to be modeled so that cooling and lubrication performance of an ACF system in micro-machining processes can be predicted.
Chapter 5

Modeling Droplet Spreading on a Rotating Surface

The experiments presented in Chapter 4 show that the cooling and lubrication performance of atomization-based cutting fluid (ACF) systems are dependent on the spreading behavior of the droplets impinging upon the cutting zone. Therefore it appears that the design of an efficient ACF system can benefit greatly from the development of a model for predicting spreading behavior of droplet on a rotating surface. To this end, an energy-based spreading model for droplet impinging upon a rotating surface has been developed here.

The experiments conducted in Chapter 4 show that the presence of a rotating surface changes the dynamics of the spreading process imposing a need to develop a 3D spreading model to capture the asymmetric ellipsoidal-cap geometry of the droplet upon impact. Thus, additional single droplet impingement experiments are required to capture the 3D shape of a droplet impinging upon a rotating surface that can then be used model droplet spreading on a rotating surface.

In this chapter, single droplet impingement experiments are conducted to capture the 3D shape of the droplet upon impact. A mathematical parameterization scheme is then developed to characterize the 3D shape of a droplet impinging on a rotating surface. The high-speed images from the single-droplet impingement experiments serve as a basis
to develop the mathematical equations describing this 3D shape. The mathematical parameterization is then used as an input to an energy-based droplet spreading model. The droplet spreading model uses the shape parameterization along with other parameters including, fluid properties (viz., surface tension, viscosity, density), droplet characteristics (viz., droplet diameter and droplet speed) and surface speed to calculate the droplet energy and droplet volume after impact. Energy conservation and volume conservation are then applied along with droplet shape geometry relationship to predict the droplet contact lengths and height at the condition of maximum spread.

The chapter is divided into five subsections. Section 5.1 presents the experimental set-up and design. The results of the single droplet experiments that depict the 3D shape of the droplet upon impact are presented in section 5.2. Section 5.3 describes the parameterization scheme developed to capture the 3D droplet shape. Section 5.4 presents the development of an energy-based spreading model. This section also presents the spreading model validation results using the single droplet experiments. Chapter summary is presented in section 5.5.

5.1 Experimental Setup and Design

5.1.1 Test-bed Design

The experimental setup to study the droplet behavior on a rotating surface is shown in Fig. 5.1. This set-up is similar to that used in Chapter 4. The set-up includes a droplet-on-demand (DOD) unit comprised of a droplet dispense head (1) and a signal driver (2) (supplied by Engineering Arts, Phoenix, AZ) along with an electric motor and a
spindle (3), a high-speed video camera (4) with light source (5). An orifice of 32 µm diameter was used along with the DOD unit to generate on-demand droplets.

The rotating workpiece was a 3 mm diameter steel rod with surface roughness (R_a) of 35 nm. The R_a value of this shaft is comparable to that of the machined surfaces obtained by Adair et al. [16] during micro-turning of 52100 bearing steel. A Phantom v7.0 high-speed camera was used with a 20X magnification lens to capture the droplet impact at a rate of 30,000 frames-per-second with 5 µs exposure. In order to capture the 3D shape of the droplet upon impact, two different tilt angles were used for the high-speed camera. The lens was tilted at 5^° and 75^° with respect to the axis of the cylinder in order to capture the side view and the top view of the droplet interacting with the surface, respectively (Fig. 5.1). The system was installed in a room with ambient temperature 24±1°C and relatively humidity 60±1%.

![Figure 5.1 Schematic of experimental set-up](image)
5.1.2 Experimental Design

In order to examine the effect of surface tension and viscosity independently, four fluids were specially engineered as listed in Table 5.1. Single droplet impingement experiments were conducted with all four fluids at two droplet speeds of 1.2 m/s and 2.4 m/s and at two surface speeds of 1 m/s and 2 m/s. The chosen surface speed values are typical of micro-machining of steel. A $2^4$ full factorial design of experiments was conducted. A burst of 200 droplets at a frequency of 50Hz was used for the videography of droplet impact. The images were captured at a resolution of 456x96 pixels with 34 µs time difference between consecutive images. Approximately 9000 frames were captured for each experimental condition. The images from the videos were then extracted and processed using MATLAB to measure the droplet contact lengths and characterize the droplet shape. The gray scale image captured from the camera was converted to a binary image using MATLAB to detect the droplet profile accurately. The droplet profile was scanned to capture the pixels defining the droplet boundary. The captured pixel matrix was then used to determine the mathematical equation defining the droplet profile.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface Tension (mN/m)</th>
<th>Viscosity (cP)</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI Water</td>
<td>72</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>DI Water + Sucrose</td>
<td>72</td>
<td>2.9</td>
<td>1000</td>
</tr>
<tr>
<td>10% Ethanol</td>
<td>45</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>10% Ethanol + Sucrose</td>
<td>45</td>
<td>2.9</td>
<td>1000</td>
</tr>
</tbody>
</table>

Figures 5.2a-c depict the axes convention followed for the droplet impingement study. As depicted in Fig. 5.2, the axes are fixed in the frame of reference of the droplet generator nozzle. The positive X-axis lies along the direction of rotation of the surface,
the positive Z-axis lies along the inward axis of the cylindrical rod, and the positive Y-axis lies in direction opposite to the droplet impact. The side-view of the droplet yields the shape information of the spreading droplet in the XY plane (Fig. 5.2a), whereas the top-view of the droplet yields the shape information of the spreading droplet in the XZ plane (Fig. 5.2b).

![Diagram](image)

**Figure 5.2 Axes definitions for single-droplet studies**

### 5.2 Experimental Results

The single-droplet experiments presented in Chapter 4 showed that the droplet impingement on a rotating surface is characterized by an initial spreading phase followed by a recoil phase. The study showed that for droplets with diameter of the order of 50 µm with droplet speed of the order of 2 m/s impacting a surface rotating at about 2 m/s, the
spreading phase lasts for a maximum of 50 µs after impact. Once the spreading phase ends, the recoil phase begins wherein the droplet may start to recede resulting in a decrease in the contact area. The recoil phase lasts until about 1 ms.

Figures 5.3-5.6 depict droplet geometry at the end of the spreading phase for varying experimental conditions. $\theta_1$ and $\theta_2$ denote the advancing and receding contact angles in the side-view of the droplet, respectively, and $d_1$ and $d_2$ denote the major and the minor axes of the droplet in its top-view, respectively. Figures 5.3-5.6 show that the magnitude of the advancing and receding contact angles and the length of major and minor axes affects the overall shape of the ellipsoidal-cap.

![Side view (XY plane)](image1.png) ![Top view (XZ plane)](image2.png)

(a) DI water droplet (surface tension= 72 mN/m, viscosity= 1cP, droplet speed= 1.2 m/s, surface speed= 1 m/s)

(b) Ethanol droplet (surface tension= 45 mN/m, viscosity= 1cP, droplet speed= 1.2 m/s, surface speed= 1 m/s)

Figure 5.3 Side and top view of varying surface tension droplets at the end of spreading phase for (a) test 1 and (b) test 9 in Table 5.2
Figure 5.4 Side and top view of varying viscosity droplets at the end of spreading phase for (a) test 9 and (b) test 13 in Table 5.2

Figure 5.5 Side and top view of droplets impinging upon surfaces of varying surface speed at the end of spreading phase for (a) test 13 and (b) test 14 in Table 5.2
Figures 5.3a-b show that the ethanol droplet has a higher $d_1$ than the DI water droplet under the same experimental conditions. This is attributed to the lower surface tension value of ethanol. Figures 5.4a-b that higher viscosity leads to a decrease in values of both $d_1$ and $d_2$ indicating that a more viscous droplet spreads to a smaller extent [5]. Figures 5.5a-b show that higher surface speed leads to an increase in values of both $d_1$ and $d_2$ indicating that the droplet spreads to a larger extent. The increase in surface speed is expected to increase the spreading. Figures 5.6a-b show that a droplet with higher droplet speed has a higher value of $d_1$ and $d_2$ indicating more spreading. In this case the increase in spreading is attributed to higher droplet speed [5]. The complete set of quantitative results from the single droplet experiments are presented in Table 5.2.
Table 5.2 Single droplet experiment results

<table>
<thead>
<tr>
<th>Test</th>
<th>Surface Tension (mN/m)</th>
<th>Viscosity (cP)</th>
<th>Droplet Speed (m/s)</th>
<th>Surface Speed (m/s)</th>
<th>At Maximum Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$d_1/d_0$</td>
</tr>
<tr>
<td>1</td>
<td>72</td>
<td>1</td>
<td>1.2</td>
<td>1</td>
<td>1.46</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
<td>1</td>
<td>1.2</td>
<td>2</td>
<td>1.54</td>
</tr>
<tr>
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<td>72</td>
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<td>2.4</td>
<td>1</td>
<td>1.79</td>
</tr>
<tr>
<td>4</td>
<td>72</td>
<td>1</td>
<td>2.4</td>
<td>2</td>
<td>2.00</td>
</tr>
<tr>
<td>5</td>
<td>72</td>
<td>3</td>
<td>1.2</td>
<td>1</td>
<td>1.94</td>
</tr>
<tr>
<td>6</td>
<td>72</td>
<td>3</td>
<td>1.2</td>
<td>2</td>
<td>1.72</td>
</tr>
<tr>
<td>7</td>
<td>72</td>
<td>3</td>
<td>2.4</td>
<td>1</td>
<td>1.67</td>
</tr>
<tr>
<td>8</td>
<td>72</td>
<td>3</td>
<td>2.4</td>
<td>2</td>
<td>1.70</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>1</td>
<td>1.2</td>
<td>1</td>
<td>1.96</td>
</tr>
<tr>
<td>10</td>
<td>45</td>
<td>1</td>
<td>1.2</td>
<td>2</td>
<td>2.04</td>
</tr>
<tr>
<td>11</td>
<td>45</td>
<td>1</td>
<td>2.4</td>
<td>1</td>
<td>2.28</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>1</td>
<td>2.4</td>
<td>2</td>
<td>2.37</td>
</tr>
<tr>
<td>13</td>
<td>45</td>
<td>3</td>
<td>1.2</td>
<td>1</td>
<td>2.10</td>
</tr>
<tr>
<td>14</td>
<td>45</td>
<td>3</td>
<td>1.2</td>
<td>2</td>
<td>2.00</td>
</tr>
<tr>
<td>15</td>
<td>45</td>
<td>3</td>
<td>2.4</td>
<td>1</td>
<td>2.33</td>
</tr>
<tr>
<td>16</td>
<td>45</td>
<td>3</td>
<td>2.4</td>
<td>2</td>
<td>2.08</td>
</tr>
</tbody>
</table>

5.3 Droplet Shape Parameterization

In order to model the 3D shape of the droplet, both the side-view and the top-view of the droplet need to be parameterized mathematically.

5.3.1 Side-view parameterization

Figure 5.7 shows the geometry for parameterizing the side-view of the droplet. The droplet profile ABCDA is marked in bold lines. The droplet contact length (ADC) is $l_1 + l_2$ and the droplet height (BD) is $h$. The contact angle at A is $\theta_1$ and the contact angle at C is $\theta_2$. The two constituent ellipses $E_{1F}$ and $E_{2F}$ are shown in dashed lines. The ellipses $E_{1F}$ and $E_{2F}$ share a common tangent at point B. The equation of droplet profile AB is given by ellipse $E_{1F}$ and the equation of droplet profile BC is given by ellipse $E_{2F}$. The
system origin is chosen such that \( E_{1F} \) is centered at \( O_1 (0, y_0, 0) \) and \( E_{2F} \) is centered at \( O_2 (0, 0, 0) \).

Let the semi-axis lengths of ellipses \( E_{1F} \) and \( E_{2F} \) be \((a_{1f}, b_{1f})\) and \((a_{2f}, b_{2f})\), respectively. In order to find the mathematical equation of the droplet profile ABCDA, these semi-axis lengths will be expressed in terms of the droplet shape parameters \((l_1, l_2, h, \theta_1, \theta_2)\). The ellipse \( E_{1F} \) is centered at \( O_1 (0, y_0) \) and has semi-axis lengths \( a_{1f} \) and \( b_{1f} \).

Thus the equation of the ellipse \( E_{1F} \) is given by

\[
\frac{x^2}{a_{1f}^2} + \frac{(y-y_0)^2}{b_{1f}^2} = 1. 
\]

(5.1)

The point A \((l_1, y_0+b_{1f} - h)\) lies on the ellipse \( E_{1F} \) and hence satisfies Eqn. 5.1. Substituting the coordinates of A into Eq. 5.1 yields the relation

\[
\frac{l_1^2}{a_{1f}^2} + \frac{(b_{1f} - h)^2}{b_{1f}^2} = 1.
\]

(5.2)
As the contact angle at A is $\theta_1$, the slope of tangent to ellipse $E_{1F}$ at point A is given by

$$\tan \theta_1 = \frac{l_1}{b_{1f} - h} \left( \frac{a_{1f}}{b_{1f}} \right)^2.$$ \hspace{1cm} (5.3)

Using Eqs. 5.2 and 5.3, the semi-axis lengths $a_{1f}$ and $b_{1f}$ are calculated as

$$a_{1f} = \sqrt{l_1 (l_1 \tan \theta_1 - h)^2} \tan \theta_1 \tan \theta_1, \quad b_{1f} = \frac{hl_1 \tan \theta_1 - h^2}{l_1 \tan \theta_1 - 2h}.$$ \hspace{1cm} (5.4)

Similarly for ellipse $E_{2F}$ whose equation is given by

$$\frac{x^2}{a_{2f}^2} + \frac{y^2}{b_{2f}^2} = 1$$ \hspace{1cm} (5.5)

the semi-axes lengths $a_{2f}$ and $b_{2f}$ are calculated as

$$a_{2f} = \sqrt{l_2 (l_2 \tan \theta_2 - h)^2} \tan \theta_2 \tan \theta_2, \quad b_{2f} = \frac{hl_2 \tan \theta_2 - h^2}{l_2 \tan \theta_2 - 2h}.$$ \hspace{1cm} (5.6)

Thus, if the droplet parameters $l_1$, $l_2$, $h$, $\theta_1$, $\theta_2$ are known, the equation of ellipses $E_{1F}$ and $E_{2F}$ can be derived.

### 5.3.2 Top-view parameterization

Figure 5.8 shows the geometry for parameterizing the top-view of the droplet. The droplet boundary APCQA is marked in bold lines. The droplet contact length ADC is $l_1 + l_2 = d_1$ and the droplet contact length PQ is $d_2$. The two constituent ellipses $E_{1T}$ and $E_{2T}$ are shown in dashed lines. The equation of curve QAP is given by ellipse $E_{1T}$ and the equation of curve PCQ is given by ellipse $E_{2T}$. The equations for the ellipses $E_{1T}$ and $E_{2T}$ are given, respectively, by
Thus if the droplet parameters $d_1$ and $d_2$ are known the equation of ellipses $E_{1T}$ and $E_{2T}$ can be derived.

5.3.3 3D equation of the droplet shape

Using the mathematical equations of the side view and top view, the 3D equation of the droplet is now derived. It is assumed that the ellipses $E_{1F}$ and $E_{1T}$ are a part of an ellipsoid $E_1$ given by

$$\frac{x^2}{a_1^2} + \frac{(y-y_0)^2}{b_1^2} + \frac{z^2}{c_1^2} = 1. \quad (5.8)$$

The ellipsoid $E_1$ reduces to ellipse $E_{1F}$ in the XY plane ($z=0$). Therefore,

$$a_i = a_{ij} = \sqrt{\frac{l_i (l_i \tan \theta_i - h)^2}{(l_i \tan \theta_i - 2h) \tan \theta_i}}, \quad b_i = b_{ij} = \frac{hl_i \tan \theta_i - h^2}{l_i \tan \theta_i - 2h}. \quad (5.9)$$
The ellipsoid $E_1$ reduces to ellipse $E_{1T}$ in the XZ plane ($y=y_0+b_1-h$). This yields the expression for $c_1$ as

$$c_1 = \frac{d_z/2}{\sqrt{1-(b_1-h)^2/b_1^2}}. \quad (5.10)$$

Similarly, it is assumed that the ellipses $E_{2F}$ and $E_{2T}$ are part of an ellipsoid $E_2$ given by

$$\frac{x^2}{a_2^2} + \frac{y^2}{b_2^2} + \frac{z^2}{c_2^2} = 1 \quad (5.11)$$

where,

$$a_2 = \sqrt{\frac{l_2(l_2 \tan \theta_2 - h)^2}{(l_2 \tan \theta_2 - 2h) \tan \theta_2}}, \quad b_2 = \frac{hl_2 \tan \theta_2 - h^2}{l_2 \tan \theta_2 - 2h}, \quad \text{and} \quad c_2 = \frac{d_z/2}{\sqrt{1-(b_2-h)^2/b_2^2}}. \quad (5.12)$$

Thus, if the lengths $l_1$, $l_2$, $h$, $d_2$ and contact angles $\theta_1$, $\theta_2$ are known then the 3D equation of the droplet surface is given by the ellipsoid $E_1$ for $x \geq 0$ and by ellipsoid $E_2$ for $x \leq 0$. The parameterization scheme is used to generate the 3D shape of the droplet corresponding to the conditions shown in Fig. 5.3a-b. Figures 5.9a-b depict the shape of the simulated droplets. They are comparable to the experimental images shown in Fig. 5.3a-b.
5.3.4 Validation of the droplet parameterization scheme

In order to examine the numerical accuracy of the proposed parameterization scheme, the volume of experimentally observed droplets was calculated and compared with the measured droplet volume. The side-view and top-view of the droplet was captured at the end of the spreading phase for all the 16 conditions presented in Table 5.2. The lengths $l_1$, $l_2$, $h$, $d_2$ and contact angles $\theta_1$ and $\theta_2$ were extracted from the side-view and top-view images and used to calculate the droplet volume upon impact. The volume of the ellipsoidal cap APBQA (Figs. 5.7-5.8) is given by

$$V_{11} = \frac{\pi}{6}a_1b_1c_1(1-r_1)^2(2+r_1)$$

(5.13)
where, \( r_i = (b_i - h_i) / b_i \). Using Eqs. 5.9-5.10 the expressions for \( a_1, b_1 \) and \( c_1 \) are substituted into Eq. 5.13 to give

\[
V_{11} = \frac{\pi}{12} \frac{hd_2(2l_1 \tan \theta_1 - h)}{\tan \theta_1}.
\] (5.14)

Using similar analysis, the volume of ellipsoidal cap CPBQC is given by

\[
V_{22} = \frac{\pi}{12} \frac{hd_2(2l_2 \tan \theta_2 - h)}{\tan \theta_2}.
\] (5.15)

Thus, the total volume of the droplet after impact is given by

\[
V_2 = V_{11} + V_{22} = \frac{\pi}{6} \left[ hd_2d_2 - h^2d_2 \left( \frac{1}{\tan \theta_1} + \frac{1}{\tan \theta_2} \right) \right].
\] (5.16)

Since no significant evaporation occurs the droplet volume calculated using Eq. 5.16 should be equal to the droplet volume before impact. Figure 5.10 shows the comparison of the calculated droplet volume against the experimentally observed droplet volume. The 45° line in Fig. 5.10 indicates that the droplet volume is estimated well when compared with the measured volume values. The average and maximum error between the calculated and the measured value of the droplet volume were found to be 3% and 9%, respectively, thereby confirming that the proposed parameterization accurately captures the droplet shape upon impact.
5.4 Droplet Spreading Model

The experimental results presented in Chapter 4 show that the spreading phase lasts only for a relatively short period of about 50 μs. Given the high temperatures encountered during machining, the droplet evaporation is expected to start around 50-80 μs after impact [15]. This implies that the droplet evaporation is expected to start around the time when droplet reaches its maximum spread area. For the purpose of capturing the lubrication and cooling efficiency of a droplet impinging upon a rotating surface, the initial dynamics prior to the maximum spreading is not critical, rather the contact lengths $d_1$, $d_2$ and height $h$ that the droplet achieves at the maximum spread condition. Therefore, an energy-based approach will be used to calculate the droplet parameters $d_1$, $d_2$ and $h$ at the maximum spread condition. As this system has three unknowns, three equations are required to solve the system. The equations for energy conservation and volume
conservation provide two of the required expressions. The third expression connecting $d_1$ and $d_2$ is empirically determined from the experimental data.

### 5.4.1 Energy conservation equation

The energy conservation approach assumes that the initial kinetic energy and surface energy of the droplet are partly converted into final kinetic and surface energy and partly dissipated by viscous forces. Before impact, the kinetic energy ($KE_1$) and surface energy ($SE_1$) of a spherical droplet are given by

$$KE_1 = \frac{1}{2} \left( \frac{\pi}{6} \rho d_0^3 \right) u_0^2 = \frac{\pi}{12} \rho d_0^3 u_0^2. \quad (5.17)$$

and $SE_1 = \pi d_0^2 \sigma_{fv}$ \quad (5.18)

where, $\rho$ is the density of the fluid, $u_0$ is the droplet speed, $d_0$ is the initial diameter of the droplet, and $\sigma_{fv}$ is the surface tension between the fluid and air. After impact, when the droplet is at its maximum spread, the kinetic energy is zero with respect to the rotating surface and the surface energy ($SE_2$) is given by

$$SE_2 = (A_1 + A_2) \sigma_{fv} + A_3 (\sigma_{sl} - \sigma_{sv}) \quad (5.19)$$

where, $A_1$ is the surface area of the ellipsoidal cap APBQA (Fig. 5.7-5.8), $A_2$ is the surface area of the ellipsoidal cap CPBQC (Fig. 5.7-5.8), $A_3$ is the surface area of the droplet base APCQA, $\sigma_{sl}$ is the surface tension between the fluid and the solid surface, and $\sigma_{sv}$ is the surface tension between the solid and air. The $\sigma_{sl}$ and $\sigma_{sv}$ values are the solid-fluid and fluid-air interface properties that need to be known for calculating $SE_2$. The areas $A_1$, $A_2$ and $A_3$ are given by
\[ A_1 = \frac{\pi}{\tan^{-1}\left(\frac{b}{h}\right)} \int_{\tan^{-1}\left(\frac{b}{h}\right)}^{\pi} \frac{b^2}{a^2 + c^2 + h^2} \sin \phi \cos \theta \sin \phi \, d\phi, \]

\[ A_2 = 2 \int_{\tan^{-1}\left(\frac{b}{h}\right)}^{\pi} \frac{b^2}{a^2 + c^2 + h^2} \sin \phi \cos \theta \sin \phi \, d\phi, \]

\[ A_3 = \frac{\pi}{4} \cdot d \cdot d. \]

Using Young-Laplace equation [50] the relationship between \( \sigma_{sv}, \sigma_{sl}, \sigma_{sw} \) is given by

\[ \sigma_{sv} - \sigma_{sl} = \sigma_{lw} \cos \theta_c, \quad (5.21) \]

where, \( \theta_c \) is the steady state (after the spreading and recoil phases) contact angle between the droplet and the solid surface. Substituting Eq. 5.21 into Eq. 5.19 yields

\[ SE_2 = (A_1 + A_2 - A_3 \cos \theta_c) \sigma_{lw}. \quad (5.22) \]

In the spreading phase, energy is expended in form of viscous dissipation within the droplet as it deforms to its maximum spread state. The work done in deforming the droplet against viscous forces is given by

\[ E_v = \int_0^t \int_v \psi dV dt \approx \int_v \psi dVi. \quad (5.23) \]

where \( \psi \) is the viscous dissipation function, \( V \) is the droplet volume and \( t_i \) is the time taken by the droplet to spread to its maximum spread state. In order to calculate the viscous dissipation, stagnation point flow on a moving surface by Wang [51] is used. Since the viscous dissipation occurs only in the boundary layer, it is given by

\[ \int_v \psi dV \approx \int_v \left[ 2\mu \left( \frac{\partial v}{\partial x} \right)^2 + 2\mu \left( \frac{\partial v}{\partial z} \right)^2 + \mu \left( \frac{\partial v}{\partial y} \right)^2 + \mu \left( \frac{\partial v}{\partial y} \right)^2 \right] dV \]

\[ \approx 0.2\pi d_0 d \sqrt{\frac{\mu \rho u_0}{2d_0}} \left[ \frac{u_0}{2d_0} \left( \frac{d_i^2 + d_z^2}{16} \right) + \frac{u_0 u_0}{4d_0} \right] d. \quad (5.24) \]
where, \( v_x \) and \( v_z \) are the components of fluid velocity in \( x \) and \( z \) directions, respectively, and \( u_s \) is the surface speed. The time taken by the droplet to spread on the surface is approximated as [4]

\[
t_s \approx \frac{d_0}{u_s}. 
\]  
(5.25)

Therefore, the energy lost to viscous dissipation is estimated as

\[
E_v \approx 0.2\pi d_1 d_2 \left( \frac{\mu \rho d_0}{2u_s} \right) \left[ u_i^2 + \left( \frac{u_s}{2d_0} \right)^2 \left( \frac{d_1^2 + d_2^2}{16} \right) + \left( \frac{u_s u_i}{4d_0} \right) d_1 \right]. 
\]  
(5.26)

Energy is added to the droplet by the rotating surface in form of kinetic energy given by

\[
E_r = \frac{1}{2} \left( \frac{\pi}{6} \rho d_0^3 \right) u_i^2 = \frac{\pi}{12} \rho d_0^3 u_i^2. 
\]  
(5.27)

Using energy conservation equation,

\[
KE_1 + SE_1 + E_r = SE_2 + E_v, 
\]  
(5.28)

where \( KE_1, SE_1, SE_2, E_v \) and \( E_r \) are given by Eqs. 5.18, 5.19, 5.23, 5.26 and 5.27, respectively.

### 5.4.2 Volume conservation equation

The initial volume of the spherical droplet is given by

\[
V_i = \frac{\pi}{6} d_0^3. 
\]  
(5.29)

Using volume conservation \( V_1 = V_2 \), where \( V_2 \) is given by Eq. 5.17. Thus,

\[
d_0^3 = h d_1 d_2 - \frac{h^2 d_2^2}{2} \left( \frac{1}{\tan \theta_1} + \frac{1}{\tan \theta_2} \right). 
\]  
(5.30)
Using geometry, approximate relations for $\tan \theta_1$ and $\tan \theta_2$ are given by

$$
\tan \theta_1 \approx \frac{h \sqrt{8l_1 d_z}}{l_1 d_z - 2h^2}, \quad \tan \theta_2 \approx \frac{h \sqrt{8l_2 d_z}}{l_2 d_z - 2h^2}.
$$

Equations 5.30-5.31 yield the equation for volume conservation.

### 5.4.3 Relation between $d_1$ and $d_2$

The droplet dynamics in the initial spreading phase are characterized primarily by the droplet Weber number (We) and the Ohnesorge number (Oh) defined as

$$
We = \frac{\rho u_0^2 d_0}{\sigma_n}, \quad Oh = \frac{\mu}{\sqrt{\rho \sigma_n d_0}}.
$$

Schiaffino and Sonin [38] identified two regimes of droplet spreading based on the values of We and Oh, viz., (1) almost-inviscid regime ($Oh<< We^{0.5}$); and (2) highly-viscous regime ($Oh>>We^{0.5}$). For all the experiments presented in Section 2, the range of values calculated for Oh and We show that here the droplet spreading lies in the almost-inviscid regime. Therefore, as identified by Schiaffino and Sonin [38], the spreading length of the droplet is directly proportional to We and inversely proportional to Oh. In addition, the droplet extension ($d_1/d_2$) is also expected to be proportional to the surface speed, with extension equal to unity when the surface is stationary ($u_s=0$). Therefore, the overall expression for $d_1/d_2$ is formulated as

$$
\frac{d_1}{d_2} = 1 + \beta_1 Oh^{-\beta_2} We^{\beta_3} \left(\frac{u_s}{u_0}\right)^{\beta_4}.
$$

Using least-square fit on the experimental data presented in Table 5.2, the coefficients $\beta_1$, $\beta_2$, $\beta_3$ and $\beta_4$ are estimated to be 0.16, 0.1, 0.23 and 0.11, respectively. Equations 5.28,
5.30, and 5.33 can now be solved simultaneously to find the droplet parameters $d_1$, $d_2$ and $h$.

Based on Eqs. 5.28, 5.30, and 5.33 $d_1$, $d_2$ and $h$ values are calculated for conditions listed in Table 5.2. The average and maximum errors in the model predictions are noted to be 6% and 13% for $d_1$, 8% and 20% for $d_2$, and 10% and 17% for $h$.

5.5 Chapter Summary

An energy-based approach is adopted to model the spreading behavior of a droplet impinging a rotating surface that can then be used in-conjunction with cooling and lubrication models to predict the performance of an ACF system. In particular, a parameterization scheme has been developed to characterize the 3D shape of a droplet impinging upon a rotating surface. Given the droplet contact lengths, contact angles, and height, the equation defining the droplet surface is derived. This parameterization scheme is capable of capturing droplet volume on average within 3% accuracy. An energy-based spreading model has been developed to predict the droplet contact lengths and height at the maximum spread condition. Expressions for droplet surface energy, viscous energy dissipation and relation between contact lengths have been developed. The spreading model predicts the droplet lengths and height on average within 10% accuracy. What remains is to use this spreading model to develop ways of improving the performance of ACF systems.
Chapter 6

Prediction of Cooling and Lubrication Performance of Atomization-based Cutting Fluid System

This chapter presents the approach adopted to use the droplet contact lengths and height predicted by the spreading model as input to heat transfer and lubrication equations, so as to predict the cooling and lubrication performance of the ACF system. The results of the micro-turning experiments presented in Chapter 3 are used to validate the model predictions of cooling and lubrication performance. The chapter is divided into four subsections. Section 6.1 presents the evaporative model used for predicting cooling performance of an ACF system. Section 6.2 presents the lubrication force model used to predict the lubrication performance of an ACF system. Section 6.3 presents a parametric study conducted to identify the critical factors affecting the cooling and lubrication performance of ACF systems. The chapter summary is presented in section 6.4.

6.1 Cooling performance of an ACF system

As droplets impinge upon the rotating workpiece, heat transfer occurs from the cutting zone to the impinging droplets resulting in reduction of the surface temperature.
The heat transfer from the cutting zone to the ACF system consists of two components: (1) heat transfer from the surface to the impinging droplets through conduction, and (2) heat transfer from the surface to the air through forced convection. Calculations based on the study of Li and Liang [51] show that forced convection heat transfer contributes only to about 0.1% of the total heat transferred, and is neglected for the purpose of model validation.

### 6.1.1 Calculating heat transfer from surface to the droplets

Using the analysis of Tio and Sadhal [53], the heat transferred from the surface to one droplet is given by

\[
q = \frac{k_s T_0 A^0 A}{h}
\]  

(6.1)

where, \(k_s\) is the thermal conductivity of the surface, \(T_0\) is the ambient air temperature, \(A\) is the contact area at the condition of maximum spread and \(h\) is the droplet height at the condition of maximum spread. \(A^0\) is the integral given by

\[
A^0 = 2 \int_0^\infty \frac{(k_f / k_s \text{sech}\, \pi \tau)}{[\text{tanh}\, \pi \tau \text{tanh}\, \theta_0 \tau + (k_f / k_s)]} d\tau
\]  

(6.2)

where, \(k_f\) is the thermal conductivity of the cutting fluid, and \(\theta_0\) is the equivalent contact angle given by

\[
\theta_0 = \frac{\theta_1 + \theta_2}{2}
\]  

(6.3)
where, \( \theta_1 \) and \( \theta_2 \) are the advancing and receding contact angles, respectively. The contact area of the droplet at maximum spread is given by

\[
A = \frac{\pi}{4} d_1 d_2
\]  

(6.4)

where, \( d_1 \) and \( d_2 \) are the contact lengths at the condition of maximum spread calculated for a given cutting fluid using Eqs. 5.28, 5.30, and 5.33. Once \( q \) is known from Eqs. 6.1-6.4, the total heat transferred from the cutting zone to the impinging droplets is given by

\[
Q = Nq
\]  

(6.5)

where \( N \) is the number of droplets reaching the cutting zone per second at droplet speed \( u_0 \). Higher values of \( Q \) imply better cooling performance of the ACF system.

The ability of the ACF system to carry atomized droplets to the cutting zone is a function of the penetration coefficient \( c \) given by

\[
c = \frac{n/N_0}{v_m}
\]  

(6.6)

where \( v_m \) is the velocity at which the droplets exit the atomizer, \( n \) is the number of droplets reaching the cutting zone per second measured at \( v_m \), and \( N_0 \) is the number of droplets emitted per second by the atomizer. If \( M \) is the volume flow rate specification of the atomizer, \( N_0 \) is given by

\[
N_0 = \frac{6M}{\pi d_0^3}
\]  

(6.7)

Assuming a conical flow out of the nozzle, \( n \) is given by

\[
n = \frac{r^2}{(l_0 \tan \alpha + r)^2} N_0
\]  

(6.8)
where $\alpha$ is the angle at which the flow exits the nozzle, $r$ is the nozzle radius and $l_0$ is the distance of nozzle from cutting zone. As soon as the droplets exit the atomizer, they meet with an air jet, which carries them to the cutting zone at a droplet speed $u_0$ equal to the speed of the air jet [2]. As the speed of the air jet increases, the number of droplets reaching the cutting zone reduces due to the diffusive action of the air jet [54]. The variation of $N$ with droplet speed is given by

$$N = N_0 \exp(-cu_0) \tag{6.9}$$

Equation 6.9 shows that as $c$ increases, the number of droplets reaching the cutting zone per second decreases. A higher value of $c$ characterizes an ACF system with a highly diverged droplet flow wherein the number of droplets reaching the cutting zone is reduced greatly with increase in droplet speed. The experiments of Rukosuyev et al. [25] showed that the extent of divergence of the droplet flow is dependent on both distance of atomizer from the cutting zone and the nozzle geometry. These two factors are captured in $c$.

### 6.1.2 Predicting cooling performance of an ACF system

The above cooling model is now used to predict the performance of three cutting fluids used in the micro-turning study presented in Chapter 3. The overall machining conditions for the micro-turning experiments and the values of the various parameters needed for calculating the total heat transferred from the surface to the droplets are listed in Table 6.1. Eqs. 5.28, 5.30, and 5.33 are solved simultaneously using the fluid properties and droplet characteristics listed in Table 6.1 to obtain the $d_1$, $d_2$ and $h$ values.
at maximum spread condition as presented in Table 6.2. The data in Table 6.2 is used in conjunction with the atomizer specifications and the workpiece properties (Table 6.1) in Eqs. 6.1-6.9. Thus, the heat transferred from the surface to the droplets ($Q$) for each of the three cutting fluids is calculated.

<table>
<thead>
<tr>
<th>Table 6.1 Conditions for the micro-turning tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece</td>
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<tr>
<td>Cutting Conditions</td>
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<tr>
<td></td>
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<tr>
<td>Surface Speed ($u_s$)</td>
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<tr>
<td>Droplet Speed ($u_0$)</td>
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<tr>
<td>Droplet Diameter</td>
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<td>Cutting Fluid Properties</td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>Contact angles</td>
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<tr>
<td>DI water</td>
</tr>
<tr>
<td>12.5% Castrol 6519</td>
</tr>
<tr>
<td>25% Castrol 6519</td>
</tr>
<tr>
<td>Atomizer Specifications</td>
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<tr>
<td>$A^0_i$ calculated using Eq. 6.2</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Droplet Speed (m/s)</td>
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<tr>
<td>---------------------</td>
</tr>
<tr>
<td>DI Water</td>
</tr>
<tr>
<td>12.5% Castrol 6519</td>
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<tr>
<td>25% Castrol 6519</td>
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<table>
<thead>
<tr>
<th>$d_1/d_0$</th>
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<th></th>
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<td>1.63</td>
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<table>
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<tr>
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<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
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<tbody>
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<td>DI Water</td>
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<td>0.47</td>
<td>0.35</td>
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<td>0.21</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
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<td>0.38</td>
<td>0.34</td>
<td>0.26</td>
<td>0.21</td>
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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>DI Water</td>
<td>12.5% Castrol 6519</td>
<td>0.53</td>
<td>0.36</td>
<td>0.27</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>25% Castrol 6519</td>
<td>0.5</td>
<td>0.38</td>
<td>0.34</td>
<td>0.26</td>
<td>0.21</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 6.1 is a plot of heat transferred to the droplets ($Q$) as a function of droplet speed for each of the three cutting fluids. The model predictions in Fig. 6.1 show that 12.5% Castrol 6519 is most effective whereas DI Water is least effective in providing cooling to the cutting zone. As the fluid viscosity increases for 25% Castrol 6519, the contact diameters decrease and the height increases resulting in a decrease in the amount of heat transferred from the surface to the droplet. For DI Water, the contact diameters are the smallest and height largest due to high surface tension, resulting in smallest amount of heat transferred from the surface. Even though the thermal conductivity of both 12.5% Castrol 6519 and 25% Castrol 6519 are smaller than of DI Water, the contact angles of the latter result in a smaller value of $A_1^0$ (Table 6.1) indicating reduced capability of transferring heat from the surface. Figure 6.1 further shows that for a given
fluid the heat transfer increases with increase in the droplet speed. As presented in Table 6.2, the contact diameters increase and the height decreases with increase in droplet speed resulting in increase in the heat transfer. Figure 6.1 also shows that the rate of increase of heat transfer with droplet speed is lowest for DI Water and almost comparable for 12.5% Castrol 6519 and 25% Castrol 6519.

![Figure 6.1 Model prediction of heat transfer vs. droplet speed](image)

Figure 3.6 in Chapter 3 shows the experimental cutting temperatures for the conditions used by the model in Fig. 6.1 (repeated here as Fig. 6.2). As seen by the trends in the cutting temperatures in Fig. 6.2, the minimum cutting temperature occurs when 12.5% Castrol 6519 is used. This indicates that 12.5% Castrol 6519 takes maximum amount of heat from the cutting zone, as predicted by the model results in Fig. 6.1. Figure 6.2 further shows that DI Water results in the least drop in the temperature in cutting zone (i.e., the least heat transferred to the droplet) as again confirmed by the model predictions.
in Fig. 6.1. Thus, the trends in the cutting fluid cooling performance predicted by the model match the trends seen in the cutting temperatures obtained in the experiments. Figure 6.2 further shows that the rate of decrease in temperature is only about 1.5 °C per unit increase in droplet speed for DI Water. However, for 25% Castrol 6519 and 12.5% Castrol 6519 the temperature drops by 3 °C and 2.5 °C per unit increase in droplet speed, respectively. These trends in rate of temperature drop with droplet speed match well with the trends predicted by the model for rate of increase of heat transfer with droplet speed.

![Figure 6.2 Cutting temperature data from Chapter 3](image)

### 6.2 Lubrication performance of an ACF system

Using lubrication theory [45], the lubrication force generated by one droplet is given by

$$ f = \frac{\mu d d}{h^2} u. $$

(6.10)
In order to estimate the total lubrication force generated by the fluid, $f$ should be multiplied by the number of droplets in the tool-chip interface. While it is difficult to know the exact number of droplets that are penetrating the tool-chip interface, it can be assumed that this number is proportional to the number of droplets reaching the vicinity of the cutting zone ($N$). Therefore, the total lubrication force is given by

$$F = \lambda Nf$$

where, $\lambda$ is a proportionality constant. The magnitude of the lubrication force indicates the extent to which the fluid is capable of reducing friction force in the cutting zone. High lubrication force implies large reduction in friction and thus reduced magnitude of the cutting forces. The droplet contact diameter and height values listed in Table 6.2 are used to calculate the lubrication force $F$. In order to compare the trends in the lubrication force, $F$ is normalized using the lubrication force produced by DI Water droplets at a droplet speed of $u_0=0.5$ m/s. Figure 6.3 shows the variation of normalized lubrication force with droplet speed for the three cutting fluids. Figure 6.3 shows that 25% Castrol 6519 generates the highest lubrication force whereas DI Water generates the lowest lubrication force. Due to larger oil content the viscosity of 25% Castrol 6519 is higher which results in maximum lubrication force generated as shown by Eq. 6.10. For each of three fluids, an increase in lubrication force with increase in droplet speed is observed. As the spreading increases with increase in droplet speed, higher lubrication force is generated.

Table 3.4 in Chapter 3 shows the experimental cutting forces obtained for the conditions simulated by the model in Fig. 6.3 (repeated here as Table 6.3).
shows that 25% Castrol 6519 is most effective in lubricating the cutting zone and DI Water is the least effective. This trend is same as that predicted by the lubrication model above. Note in Table 6.3, that the measured cutting force for dry machining was 1.55 N.

![Figure 6.3 Model prediction of lubrication force vs. droplet speed](image)

**Table 6.3 Cutting force data**

<table>
<thead>
<tr>
<th>Droplet Speed (m/s)</th>
<th>Cutting Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DI Water</td>
</tr>
<tr>
<td>0.5</td>
<td>1.39</td>
</tr>
<tr>
<td>2</td>
<td>1.32</td>
</tr>
<tr>
<td>4</td>
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<td>6</td>
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</tr>
<tr>
<td>8</td>
<td>1.26</td>
</tr>
<tr>
<td>10</td>
<td>1.44</td>
</tr>
</tbody>
</table>
6.3 Predicting Cooling and Lubrication for ACF-based Micro-turning Process: A Parametric Study

In this section, a parametric study is presented to identify the significant factors affecting the cooling and lubrication performance of an ACF system. The control variables of an ACF system are the cutting fluid properties (viz., surface tension and viscosity), droplet characteristics (viz., droplet diameter and droplet speed) and the number of droplets reaching the cutting zone per second (inversely proportional to the penetration coefficient). The cutting fluid properties are dependent on the type of cutting fluid used and the concentration of the base fluid used for dilution as shown in Chapter 3. The droplet characteristics are determined by the type of atomizer used for the ACF system. For a given atomizer the volume flow rate is fixed and the droplet size can be adjusted by changing the frequency of the atomizer [55]. The droplet speed can be independently adjusted by changing the speed of the air jet [54]. The penetration coefficient can be changed by changing the distance of nozzle from the cutting zone or by changing the nozzle geometry.

Table 6.4 shows the factor levels for analyzing the effect of cutting fluid surface tension, viscosity, droplet diameter, droplet speed, and penetration coefficient on the cooling and lubrication performance of an ACF system. The values chosen are the low and high levels of the typical parameters used in an ACF system [2]. A surface speed ($u_s$) of 2 m/s and ambient temperature ($T_0$) of 25°C were chosen for calculating the cooling and lubrication response.
A 2⁵ full factorial design analysis was conducted for the above listed conditions. Using Eqs. 6.5 and 6.11, heat transfer and normalized lubrication force were calculated and effect estimates were then determined. Based on the normal probability plots of the estimated effects, the significant main and interaction effects were identified and used to interpret the effect of control variables on the ACF system performance.

### 6.3.1 Cooling Performance

The analysis of the 2⁵ design reveals five main effects and two two-factor interaction effects to be significant as presented in Table 6.5. The main effects of the variables involved in the two-factor interactions should be interpreted with caution. Figures 6.4a-b show the two-way diagrams for droplet speed-penetration coefficient interaction and surface tension-droplet speed interaction.

Figure 6.4a shows that the increase in heat transfer with reduction in penetration coefficient is much larger at higher droplet speed. As presented in Section 6.1, an increase in droplet speed leads to increase in heat transfer. Furthermore for a given droplet speed, reduction in the penetration coefficient leads to increased droplet number density in the cutting zone resulting in a large overall increase in heat transfer. Figure

### Table 6.4 Factor levels for 2⁵ design

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Tension (σ)</td>
<td>42 mN/m</td>
<td>72 mN/m</td>
</tr>
<tr>
<td>Viscosity (μ)</td>
<td>1 cP</td>
<td>3 cP</td>
</tr>
<tr>
<td>Droplet Diameter (d₀)</td>
<td>12 µm</td>
<td>20 µm</td>
</tr>
<tr>
<td>Droplet Speed (u₀)</td>
<td>2 m/s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Penetration Coefficient (c)</td>
<td>0.01 (m/s)⁻¹</td>
<td>0.04 (m/s)⁻¹</td>
</tr>
</tbody>
</table>
6.4b shows that the increase in heat transfer with increase in droplet speed is larger for a fluid with lower surface tension. This is so because both high droplet speed and low surface tension promote spreading. Table 6.5 shows that an increase in droplet diameter leads to decrease in heat transfer. As shown by Eq. 6.7, increase in droplet diameter leads to reduction in number of droplets emitted per second leading to reduced heat transfer, even though the contact area per droplet increases with increase in droplet diameter. Table 6.5 further shows that the heat transfer decreases with increase in viscosity. For given surface tension and droplet characteristics, the viscous dissipation loss is higher for more viscous fluid resulting in reduced contact area upon spreading, thereby, reducing heat transferred to the droplet.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Value (kJ/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet Speed</td>
<td>1746</td>
</tr>
<tr>
<td>Penetration coefficient</td>
<td>-633</td>
</tr>
<tr>
<td>Surface Tension</td>
<td>-611</td>
</tr>
<tr>
<td>Droplet Diameter</td>
<td>-581</td>
</tr>
<tr>
<td>Droplet Speed-Penetration coefficient</td>
<td>-463</td>
</tr>
<tr>
<td>Surface Tension-Droplet Speed</td>
<td>-371</td>
</tr>
<tr>
<td>Viscosity</td>
<td>-356</td>
</tr>
</tbody>
</table>
In summary, for maximum cooling performance the ACF system should be designed such that the penetration coefficient is low, droplet speed is high, droplet diameter is small and the cutting fluid has low surface tension and low viscosity values. Penetration coefficient can be increased by decreasing the distance of the nozzle from the cutting zone and/or by changing the nozzle geometry to produce a less divergent flow.

6.3.2 Lubrication Performance

The analysis of the $2^5$ design reveals three main effects and two two-factor interaction effects to be significant as presented in Table 6.6. As all of the main effects are found to be included in significant two-factor interaction effects, their effects must be interpreted in concert with each other. Figures 6.5a-b show the two-way diagrams for viscosity-droplet speed interaction and surface tension-droplet speed interaction. As
shown by Fig. 6.5a increase in lubrication force with increase in viscosity is much larger at higher droplet speed. Increase in viscosity (attributed to larger oil content) leads to an increase in the lubrication force. As shown in Table 6.2, at higher droplet speed the contact lengths are larger and height is smaller resulting in a further increase in lubrication force. Figure 6.5b shows that the increase in lubrication force with decrease in surface tension is again greater at high droplet speed. As shown in Table 6.2, low surface tension coupled with high droplet speed leads to increased spreading resulting in higher lubrication force.

It is noted that while the number of droplets reaching the cutting zone per second is important to cooling it does not show significant effect on lubrication. This appears to reflect the fact that cooling occurs over a larger area in the general vicinity of the cutting zone while lubrication and its effect on cutting force is a much more localized phenomena, viz., at the tool-chip interface.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity</td>
<td>1.92</td>
</tr>
<tr>
<td>Droplet Speed</td>
<td>1.77</td>
</tr>
<tr>
<td>Surface Tension</td>
<td>-0.92</td>
</tr>
<tr>
<td>Viscosity-Droplet Speed</td>
<td>0.90</td>
</tr>
<tr>
<td>Surface Tension-Droplet Speed</td>
<td>-0.60</td>
</tr>
</tbody>
</table>
6.4 Chapter Summary

The output of the droplet spreading model is used as input to a system of equations to model the cooling and lubrication performance of an ACF-based micro-machining process. The quantitative results obtained from the cooling and lubrication models, when compared to the performance trends observed in the micro-turning experiments presented in Chapter 3 show good agreement lending credence to the ability of the model to predict the cooling and lubrication performance of an ACF system. Droplet speed is observed to have a dominant effect on the cooling performance of an ACF system with high droplet speed greatly increasing the heat transfer. A decrease in fluid surface tension at high droplet speed further increases the cooling performance. It is noted that the cooling performance is directly proportional to the number of droplets.
reaching the cutting zone per second and inversely proportional to the droplet diameter.

The lubrication performance of an ACF system is also greatly increased by an increase in the droplet speed. A fluid with low surface tension and high viscosity further increases the lubrication performance.
Chapter 7

Conclusions and Recommendations

7.1 Conclusions

This thesis investigates the effect atomization-based cutting fluid (ACF) system parameters and machining conditions on the cooling and lubrication performance in micro-machining processes in order to enable the design of efficient ACF systems.

The research was carried out in two phases. First, droplet behavior on a rotating surface was investigated experimentally to better understand the physics underlying the cooling and lubrication performance of ACF systems. Micro-turning experiments were conducted and the cutting performance was evaluated for cutting fluids with varying physical properties and at different droplet speeds. Single droplet impingement experiments were then conducted on a rotating surface for fluids with different surface tension and viscosity values to study the droplet spreading and evaporation behavior. The machining results were interpreted in light of results from single droplet experiments to identify the factors affecting the performance of an ACF system.

Second, model development was undertaken to predict the cooling and lubrication performance of ACF systems. Single droplet impingement experiments were conducted to capture the 3D shape of droplet upon impact on a rotating surface. A parameterization scheme was developed to define the 3D shape of a droplet and use it to model droplet spreading on a rotating surface. The output of the spreading model was used to predict
the heat transferred from the cutting zone to the droplets and the lubrication force generated by the droplets at the tool-chip interface.

7.1.1 Experimental Investigation

The following conclusions can be drawn from the experimental work conducted in this thesis:

1. Micro-turning experiments indicate that a cutting fluid with low surface tension and low viscosity generates lower cutting temperatures. Cutting temperatures are observed to decrease steadily with an increase in the droplet speed up to 6 m/s beyond which no significant reduction in temperature is seen. A fluid with low surface tension and high viscosity is observed to generate lower cutting forces.

2. The single droplet experiments show that the droplet evolution on a rotating surface occurs in four phases, viz., kinetic, spreading, relaxation and evaporation which is similar to the evolution observed in case of a stationary surface. In the spreading phase, the droplets are observed to take either the shape of a spherical cap or a deformed-ellipsoidal cap based on the resultant of the droplet impact speed and the surface velocity.

3. The droplet spreading is observed to increase with an increase in the surface speed. It is also observed to increase with a decrease in surface tension but does not appear to change with the fluid viscosity.

4. The evaporation rate of a droplet on a rotating surface is observed to be higher than that of a droplet on a stationary surface owing to increased convective heat
transfer. A fluid with low surface tension and low viscosity is observed to have higher evaporation rate than a fluid with high surface tension and/or high viscosity.

5. The micro-turning experiments and the single droplet experiments indicate that the cutting temperatures are a strong function of the droplet evaporation behavior. On the other hand, the cutting forces appear to be dependent on the fluid viscosity and do not exhibit strong dependence on the droplet contact diameter.

6. The fluid surface tension and viscosity (owing to increased oil content) values appear to result in a trade-off in the machining performance for the atomized cutting fluid application. A decrease in surface tension is observed to aid cooling in the cutting zone. However, for a given surface tension value, the fluid with higher viscosity significantly reduces the cutting force but results in a modest increase in the cutting temperatures.

### 7.1.2 Model Development and Interpretation

1. A parameterization scheme has been developed to characterize the 3D shape of a droplet impinging upon a rotating surface. Given the droplet contact lengths, contact angles, and height, the equation defining the droplet surface is derived. This parameterization scheme is capable of capturing droplet volume on average within 3% accuracy.

2. An energy-based spreading model has been developed to predict the droplet contact lengths and height at the maximum spread condition. Expressions for
droplet surface energy, viscous energy dissipation and relation between contact lengths have been developed. The spreading model predicts the droplet lengths and height on average within 10% accuracy.

3. The output of the droplet spreading model is used as input to a system of equations to model the cooling and lubrication performance of an ACF-based micro-machining process. The quantitative results obtained from the cooling and lubrication models, when compared to the performance trends observed for the micro-turning experiments show good agreement lending credence to the ability of the model to predict the cooling and lubrication performance of an ACF system.

4. Based on the model predictions, droplet speed is observed to have a dominant effect on the cooling performance of an ACF system with high droplet speed greatly increasing the heat transfer. A decrease in fluid surface tension at high droplet speed further increases the cooling performance. It is noted that the cooling performance is directly proportional to the number of droplets reaching the cutting zone per second and inversely proportional to the droplet diameter.

5. Lubrication performance of an ACF system is also greatly increased by an increase in the droplet speed. A fluid with low surface tension and high viscosity further increases the lubrication performance.
7.2 Recommendations for Future Work

Below are suggestions for extending the research in order to better understand and implement the use of ACF systems in micromachining operations.

7.2.1 Further experimentation to improve the design of ACF systems

1. Further micro-machining experiments should be carried out to examine the effect of nozzle angle and distance of nozzle from the cutting zone on the cooling and lubrication performance.

2. The study of effect of spray pattern (full cone, hollow cone, flat stream) on the machining performance should be carried out. Spray pattern that ensures maximum penetration of the droplets into the cutting zone is desired for efficient performance of ACF systems. A study of effect of spray pattern on the machining performance will yield useful information regarding the type of spray nozzles to be used for improved performance of ACF systems.

3. The effect of angle at which spray is directed with respect to the feed direction should be investigated. Some prior studies on the use of MQL in machining indicate that the angle at which the spray is injected into the cutting zone affects the machining performance. Further experimentation to understand the relation between angle at which spray is directed with respect to the feed direction will enable improved design of ACF systems.
4. The exact mechanism of lubrication in ACF systems is not very well understood. Prior studies on use of MQL in machining hypothesize that the lubrication action occurs either by capillary action of the fluid droplets into the tool-chip interface or by formation of barrier layers at the tool-chip interface to reduce friction. High-speed imaging of the micro-machining operation should be conducted to better understand the lubrication mechanism at the tool-chip interface. The knowledge can be further used to develop better models to capture the tribology of atomized cutting fluid application in micro-machining processes.

7.2.2 Further modeling studies to capture the mechanism of ACF systems

1. The spreading model should be modified to account for the surface roughness of the solid surface so that the model can be applied to micro-machining processes wherein the ridges on the surface are of the order of the diameter of the impinging droplets.

2. Further modeling studies need to be undertaken to predict the cutting temperature and cutting force for use of ACF systems in micro-machining. Models that predict the cutting temperature and cutting force can be used to determine the desired value of the design parameters (droplet diameter, droplet speed, fluid surface tension, fluid viscosity, penetration coefficient) of an ACF system for a given micro-machining operation.
7.2.3 Implementation of improved ACF system

The parametric study presented in Chapter 6 identified the design parameters that determine the cooling and lubrication performance of an ACF system. The design of an ACF system should be undertaken to test the predictions of the parametric study. This ACF system should be equipped with control of droplet characteristics (viz., droplet diameter and droplet speed), fluid properties (viz., surface tension and viscosity) and penetration coefficient so that the effect of independent parameters on the machining performance can be identified.


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