INVESTIGATING THE INFLUENCE OF FILM FORMATION ON THE MACHINING PERFORMANCE IN AN ATOMIZATION-BASED CUTTING FLUID SPRAY SYSTEM

BY

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THESIS

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Abstract

Titanium alloys are difficult to machine materials due to their poor thermal conductivity, high affinity to tool materials at cutting temperatures and production of thin chips during machining. Heat generated in the tool-chip contact region is not readily dissipated, leading to a shortened tool life. Various cooling methods have been studied for titanium machining including high pressure coolant application, minimum quantity lubrication and recently, the Atomization-based cutting fluid (ACF) delivery system to improve upon the cooling and lubrication provided by conventional flood cooling. In the ACF system, the impingement of atomized droplets of the cutting fluid on the tool surface results in the formation of a thin liquid film that penetrates the narrow tool-chip contact region and improves tool life. The characteristics of the thin film such as the film thickness and velocity influence the performance of the ACF system and are dependent on a large number
of parameters including cutting fluid properties, spray parameters, i.e., gas pressure, fluid flow rate, spray distance and spray angle, and the cutting tool surface geometry. Numerous experimental studies have been done to evaluate the effectiveness of the ACF system in titanium machining. However, these efforts fail to bring forth the mechanism of film formation and penetration of the film in the tool-chip interface.

The purpose of this thesis is to study the effect of cutting tool surface geometry, the ACF spray parameters and the physical properties of the cutting fluid on the characteristics of the thin film formed in an atomization-based cutting fluid (ACF) delivery system. A computational model is developed using three sub-models that are used to predict the carrier gas flow, droplet trajectories and the film formation, respectively. The model is validated through film thickness measurements using a laser displacement sensor. Turning inserts with chip-breaking grooves along with a conventional flat insert are used to study the effect of cutting tool surface geometry on the model-predicted film characteristics, including film thickness and velocity. Carrier gas pressure and cutting fluid flow rate are also varied to study the effect of ACF spray parameters on the film characteristics. Machining experiments are also conducted to investigate the effect of film characteristics on the machining performance in terms of tool wear, which show
that the tool wear is minimum at a particular film thickness value and large film velocity value for a particular cutting fluid using the ACF system. The effect of surface tension and viscosity on the film characteristics is also studied and it is observed through machining experiments that the composition of a cutting fluid is an important consideration in improving machining performance in addition to the film characteristics.
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Chapter 1

Introduction

1.1 Background and motivation

Titanium alloys are finding new applications in biomedical, aerospace and automotive industries due to their unique desirable properties such as high strength to weight ratio, corrosion resistance, fracture resistance and biocompatibility [1,2,3]. Their properties are also relatively unaffected by temperature. Despite the presence of many desirable qualities, titanium alloys have found limited use in these applications, primarily owing to the difficulty in machining these alloys. Properties like poor thermal conductivity, chemical affinity to tool materials at elevated temperatures and production of thin chips leads to a large cost in the machining
of titanium alloys. Temperatures as high as 1200°C can develop at the small tool-chip interface causing accelerated tool wear and reducing tool life [1,12,26]. As a result, machining of Ti alloys leads to a high cost that may not be able to justify their use. Hence, it is imperative to find methods to reduce cutting temperatures during machining of titanium.

In order to remove heat from the cutting zone and improve the performance in titanium machining, various cutting fluid application methods have been used. The most common and conventional method for coolant application is flood cooling. In a flood cooling system, a coolant is delivered through nozzles over the work zone at line water pressures using a large volume flow rate of the cutting fluid(1-10 L/min). Although flood cooling can help achieve a better machining performance as compared to dry cutting, it is associated with high costs and serious health and environmental issues [5,11]. Another method of cutting fluid delivery is the high pressure coolant application that involves the application of the cutting fluid at high pressure and large volume flow rates to the cutting zone. Application of the cutting fluids in the form of high pressure jets can also be effective at breaking chips, with the added benefit to extending tool life. [10,11,12]. An environmentally safe alternative to flood cooling is cryogenic cooling, which involves the use of a cryogen such as liquid nitrogen to cooling the cutting zone.
The use of cryogenic temperatures help to effectively cool the cutting interface and reduce wear, leading to a longer tool life [13, 14]. Another sustainable alternative to flood cooling is Minimum quantity lubrication (MQL) [15, 16, 17, 18].

With the use of very small amount of water and soluble oil, MQL utilizes the compressed air stream to form oil mist and direct it at the cutting edge. This oil mist is able to get close to the tool-chip and tool-workpiece interface, therefore reducing friction and cutting forces generated during machining. Temperature reduction at the cutting zone is achieved by its evaporation and vaporization that differ from flood cooling.

Although cooling techniques like high pressure cooling and cryogenic cooling improve tool life in comparison to flood cooling through reduction in cutting temperature and enhanced lubrication, a large amount of energy is required for their effective usage [19], in pumping large volumes of fluids at a very high pressure and production of a cryogen like liquid nitrogen, respectively. MQL has economical and environmental benefits due to its low energy consumption and low fluid usage. However, the major drawback of MQL is that the droplet size can not be easily controlled and the penetration of the droplets into the cutting zone is not guaranteed [20].
To overcome the difficulties of high energy consumption, the atomization-based cutting fluid delivery (ACF) system was developed that consumes less energy and provides effective cooling and lubrication [21]. Cutting fluid droplets are generated using an ultrasonic atomizer having droplet diameters ranging from 10-50 $\mu$m. Low velocity air is used to move the droplet with a low velocity through a droplet nozzle. High pressure gas is used to carry the cutting fluid droplets towards the cutting zone. These droplets impinge on the surface of the cutting tool and penetrate into the tool-chip contact region. The ACF system provides desirable features such as low power consumption and low volume flow rate (10-20 mL/min) of cutting fluid. The ACF system was found to reduce cutting forces, improve tool life over flood cooling and lower the cutting temperature in comparison to dry and flood cooling [21] in a micromilling operation.

Nath et al. [22] designed and evaluated an atomization-based cutting fluid spray system in macro-scale turning of titanium alloy. An experimental study was conducted to study the effect of five ACF parameters and it was concluded that the combination of low gas pressure, long spray distance, and high droplet flow rate for both gases applied in an ACF spray system results in longer tool life during titanium machining. A similar experimental study was conducted by Ganguli et al. [25] to establish the effect of spray parameters on the machining performance
in titanium milling. It was found that ACF spray system is able to extend the tool life as high as 75% over flood cooling. However, such experimental studies fail to characterize the exact mechanism of the lubrication and cooling provided by the ACF system and do not sufficiently characterize the influence of the ACF spray parameters on the machining performance.

The effectiveness of the ACF system was attributed to the formation of a thin liquid film on the surface of the cutting tool, which can penetrate effectively into the tool-chip contact region and provide effective cooling and lubrication [24, 25]. Mathews et al. [27] studied the impingement of a liquid fuel on flat surfaces. Due to the difficulty in experimentally characterizing a very thin film, numerous modeling efforts have been made to study the film formation in an ACF system. Ghai et al. [36] developed an energy-based approach to predict the spreading behavior of a droplet impinging on a rotating surface for micromachining with an ACF system. However, the dynamics of a single droplet impingement is insufficient to describe the formation of a continuous moving film with the ACF system for a machining operation. Hoyne et al. [24] developed a numerical model using boundary layer approximations of the Navier-Stokes equations to predict the thickness of the thin liquid film formed on a flat surface. However, this model leaves much scope for improvement as it fails to consider the geometry of the
spray nozzles that is essential for estimating the droplet trajectories in the carrier gas flow.

Besides the ACF spray parameters; the cutting tool surface geometry (i.e., features such as flute geometry and clearance angles on a milling tool, and chip-breaker grooves on a turning tool) could also significantly affect the film formation in the ACF system. Friedrich et al. [32] studied the film formation on a surface with a sharp corner and found that the dynamics of the film formation due to the sharp corner are different than those on a flat surface. Baxter et al. [33] investigated thin film flows over and around obstacles and found that the film flow depends on the size and shape of the obstacle considered. In addition, features like curvature of the surface are also known to alter the liquid droplet impingement and film flow characteristics [25]. Hence, cutting tools with geometries such as chip-breaking grooves that are used to improve the chip breaking capabilities of the tool, could affect the film characteristics due to their specific surface features that alter the flow path of the liquid film.

In addition to the ACF spray parameters and the tool surface geometry, the properties of the cutting fluid also play an important role in determining the machining performance in terms of both tool-life and cutting forces [11, 12]. The
characteristics of the cutting fluid film formed in the ACF system play an important role in the improvement of the machining process [24]. Physical properties of the cutting fluid such as surface tension and viscosity could affect the droplet impingement dynamics and the flow of the liquid film, and hence, influence the film formation. Hence, it is important to study the effect of using different cutting fluids on the film formation and to investigate their influence on the machining performance with the ACF system.

1.2 Research objectives and scope

1.2.1 Objectives

The objective of this research is to study the formation and the influence of the associated film characteristics on the machining of titanium alloys with grooved tools and the ACF system, and investigate the effect of using various cutting fluid in the ACF system. To accomplish this, specific research objectives are:

1. To develop and validate a numerical modeling approach to predict the film formation by the ACF system, taking into consideration the geometry of the spray nozzles as well as the tool surface, and spray parameters.
2. To study the effect of the spray parameters on the machining performance of turning titanium with grooved tools.

3. To characterize the relationship between model-predicted film characteristics and experimentally measured tool wear.

4. To study the effect of using different cutting fluids on film formation and machining performance with the ACF system.

1.2.2 Scope of research

This research focuses on investigating the film formation in an ACF system using grooved tools for titanium machining through numerical modeling and machining experiments. The model takes into consideration the geometry of the spray nozzles and the cutting insert. The trajectories of the droplets are predicted and are used to calculate the impingement positions on the tool surface. The film thickness and film velocity are calculated using the droplet impingements as mass and momentum sources. Separate models are used to predict the carrier gas flow, the droplet trajectories and film formation, respectively. Film thickness measurements conducted using a laser displacement sensor are used to validate the model.

The model is used to predict the film characteristics for varying spray param-
eters, including gas pressure (9-33 psi) and fluid flow rate (9-15 mL/min). An ultrasonic atomizer vibrating at a frequency of 40 kHz is used to atomize the cutting fluid into droplet having a median diameter of 60 µm. Properties of Hangsterfer’s 10% S-1001 in water as the cutting fluid are considered in the simulation study. Three cutting insert geometries recommended by the manufacturer for machining of titanium alloys are considered, namely TPG432, TPGF432 and TPMR432. Machining experiments are conducted using the same spray parameters as used in the simulation experiments to machine Ti-6Al-4V at a cutting speed of 80 m/min and feed rate of 0.2 mm/rev.

Simulation experiments are also conducted for cutting fluids with three levels each of surface tension (33-72 mN/m) and viscosity (1.01-2.91 cP) to study the influence of these physical properties on the fluid film. A regression model is used to investigate the effect of the surface tension and the viscosity of the cutting fluid on the film characteristics. Machining experiments are also conducted using different cutting fluids to study their influence on the machining performance.

1.2.3 Research tasks

The research objectives are accomplished in three phases:
Phase I: Focus is given on the development of a physics-based model to predict the film formation in an ACF system in terms of film thickness and film velocity, and validate the model with thin film measurements. This is achieved by the following sequence of tasks.

1. Develop a film formation model to determine the film characteristics of the film formed by the ACF system using the geometry of the spray nozzles and the tool surface;

2. Construct an experimental setup to measure the film thickness of the thin film formed by the ACF system using a laser displacement sensor; and

3. Validate the model using film thickness measurements for two different cutting fluids.

Phase II: Focus is given to conducting simulation and machining experiments with various spray parameters and cutting insert geometries and to establish the relationship between the model-predicted film characteristics and experimentally measured tool wear. This is achieved by the following sequence of tasks.

1. Conduct simulation experiments to predict the film thickness and velocity with varying spray parameters and cutting insert geometries;
2. Conduct turning experiments using the same spray parameters and cutting insert geometries as the corresponding simulation experiments;

3. Ascertain the film characteristics that affect the machining performance and the parameters used to quantify machining performance across cutting insert geometries; and

4. Develop a relationship between the film characteristics and tool wear independent of the cutting insert geometries.

**Phase III:** Focus is given to conducting simulation and machining experiments using cutting fluids with varying physical properties to study the effect of cutting fluid properties on film characteristics and machining performance. This is achieved by the following sequence of tasks..

1. Conduct simulation experiments using three levels each of surface tension and viscosity of the cutting fluid and generate a total of nine values for film characteristics;

2. Use the simulation results to fit a regression model for film thickness and film velocity with surface tension and viscosity as the independent parameters; and
3. Conduct machining experiments to study the relative machining performance for cutting fluids with varying physical properties and compositions.

1.3 Overview of thesis

Chapter 2 provides an overview of the machinability of titanium alloys along with the available literature on the application of various cutting fluids, the ACF spray system, modeling of film formation, use of grooved cutting inserts in machining, and the effect of the insert geometry and cutting fluid properties on the film formation.

In Chapter 3, the numerical model used to predict the film formation using an ACF system is presented and validated. Three sub-models are used to predict the carrier gas velocity, droplet trajectories and the film formation, respectively. Details of the computational domain and simulation setup are also provided. To validate the model, a laser displacement sensor is used to measure the thickness of the film created by the ACF system for two different fluids at various points on the surface of a cutting insert.

Chapter 4 uses the numerical model in predicting the film formation for var-
ious spray parameters and tool geometries. Two ACF spray parameters, namely gas pressure and fluid flow rate are varied to study their effect on the film characteristics for three different cutting insert geometries. Turning experiments are conducted using the same ACF spray parameters and cutting insert geometries as used in the simulations and a relationship between the film characteristics and the machining performance is established.

Chapter 5 summarizes the effect of using different cutting fluids on the film formation and the machining performance. Simulations are conducted to predict the film characteristics for varying surface tension and viscosity of the cutting fluid. For each simulation trial, an area-averaged film thickness and an area-averaged film velocity are calculated and are used to fit a regression model with surface tension and viscosity as the independent variables. Machining experiments are also conducted using cutting fluids with varying physical properties and compositions, and their influence on the machining performance is studied.

Chapter 6 summarizes the conclusions obtained as a part of this research and offers direction of future work.
Chapter 2

Literature Review

2.1 Titanium alloys and their machining

Titanium alloys are finding new applications in various industries including biomedical and aerospace. These alloys are particularly used in the aerospace industry because of their excellent combination of high strength to weight ratio, fracture resistance and corrosion resistance [1]. In addition, they maintain the aforementioned properties even at elevated temperatures. However, due to their higher cost relative to materials such as aluminum and steel, their usage is limited [2]. They are mainly used in engine parts, rotors, compressor blades and landing gears. However, their use in many applications is restricted owing to the difficulty in ma-
chining of these alloys. Specifically, the properties like poor thermal conductivity, chemical affinity to tool materials and production of thin chips leads to a large cost in the machining of titanium alloys.

2.1.1 Properties of Ti alloys

Titanium alloys have a range of desirable properties that allow them to be used in various applications. They have low density compared to steels and are also stronger than aluminum. Their properties are also relatively unaffected by temperature. This leads them to be useful in high temperature applications.

Titanium alloys are also corrosion resistant. This means that the cost associated with the use of protective coatings for other metals is generally not required for titanium alloys. This also leads to avoiding the downtime and cost that may arise due to the replacement of the corroded parts.

Titanium alloys also have a high degree of biocompatibility. Biomedical implants are required to have to be highly innocuous without any inflammatory allergic reactions in the human body. Porous Ti-based alloys are being developed as an alternative orthopedic implant material, as they can provide good biological fixation through bone tissue ingrowth into the porous network [3]. Porous ceram-
ics and polymers have also been as an orthopedic implant materials, however, they do not perform as well as Ti-alloys under load bearing conditions.

While the high strength and retention of that strength at high temperatures is a desirable quality of titanium for most applications, these properties make machining of titanium very difficult. Its high strength maintained at elevated temperatures and its low elastic modulus impairs its machinability [1]. This low elastic modulus makes it difficult to shear the material and instead, it rubs along the cutting edge of the tool, which is instrumental in increasing the friction and further increases the cutting temperature. Table 2.1 shows the comparison of the properties of titanium alloys that make them difficult to machine in comparison to a steel. It can be seen that titanium has a high strength to weight ratio compared to the steel alloy, however, its low elastic modulus and thermal conductivity make it difficult to machine.

2.1.2 Machinability of titanium alloys

Machinability of a metal refers to the ease at which a metal can be machined. The machinability of a material is generally characterized through various criteria such as tool life, tool wear, cutting forces, chip formation, cutting temperatures
Table 2.1: Properties of titanium alloys [1]

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Hardness (Hv)</th>
<th>Density (kg/m$^3$)</th>
<th>Specific heat (J/kg-K)</th>
<th>Thermal conductivity (W/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V annealed bar</td>
<td>895</td>
<td>825</td>
<td>110</td>
<td>340</td>
<td>4.43</td>
<td>580</td>
<td>7.3</td>
</tr>
<tr>
<td>Ti-6Al-4V solution treated and aged bar</td>
<td>1035</td>
<td>965</td>
<td>-</td>
<td>360</td>
<td>-</td>
<td>-</td>
<td>7.5</td>
</tr>
<tr>
<td>AISI cold drawn steel</td>
<td>1045</td>
<td>625</td>
<td>207</td>
<td>179</td>
<td>7.84</td>
<td>486</td>
<td>50.7</td>
</tr>
</tbody>
</table>

and surface finish [4].

Tool life is related to the tool wear caused during machining. According to the ISO standard, a flank wear of 0.6 mm is considered as failure of the tool. There are various types of tool wear that are classified according to the regions they affect. Different types of tool wear are shown in Fig. 2.1. Wear can occur on both the rake and the relief faces of a tool. The wear on the relief face is called flank wear. Rubbing of the worn relief faces against the machined surface of the workpiece damages the surface and produces frictional heating forces, which increase deflections and reduce dimensional accuracy. The flank wear changes with cutting time as shown in Fig. 2.2. As seen from Fig. 2.2, after an initial low wear corresponding to the rounding of the cutting edge, flank wear increases
slowly at a steady rate until a critical level of wear is reached, after which the wear accelerates and is termed as severe wear.

![Diagram of tool wear](image)

Types of wear on cutting tools: (a) flank wear; (b) crater wear; (c) notch wear; (d) nose radius wear; (e) comb (thermal) cracks; (f) parallel (mechanical) cracks; (g) built-up edge; (h) gross plastic deformation; (i) edge chipping or frittering; (j) chip hammering; (k) gross fracture.

**Figure 2.1: Types of tool wear [5]**

![Graph of tool wear over time](image)

**Figure 2.2: Tool wear with cutting time [5]**
Rake face or crater wear produces a wear crater on the tool face. Large crater wear can lead to deformation and fracture of the tool. The extent of crater wear is characterized through the crater depth. Other types of tool wear include notch wear, edge radius rounding, and edge buildup.

Tool wear can be caused through a variety of mechanisms. Abrasive or adhesive tool wear is produced at low cutting speeds when small particles of the tool adhere or weld to the chip due to friction and are removed from the tool surface. It occurs primarily on the rake face of the tool and contributes to the formation of a wear crater. Adhesive wear rates are usually low, so that this form of wear is not significant. However, significant adhesive wear may accompany built-up edge (BUE) formation, since the BUE is also caused by adhesion and can result in chipping of the tool. Abrasive wear occurs when hard particles of the tool abrade away and are removed from the tool. Abrasion occurs primarily on the flank surface of the tool. Chemical wear or corrosion, caused by chemical reactions between constituents of the tool and the workpiece or cutting fluid, produces both flank and crater wear. This wear mechanism is especially important while machining titanium due to its high chemical affinity to tool materials at elevated temperatures.
Increase in tool wear leads to an increase in cutting forces. Cutting forces are generally dependent on the machining conditions such as feed rate, cutting speed and depth of cut in the steady wear region. Experiments were conducted by Sun et al. [6] to study the variation of the cutting forces during titanium machining with feed rates and depth of cuts. It is seen that the cutting force increases with both the feed rate and the depth of cut. However, the feed and thrust forces do no vary as much. The cutting forces also increase with the depth of cut. In general, large material removal rates lead to a large cutting force.

Sun et al. [6] also studied the variation of the cutting forces as a function of cutting speeds as shown in Fig. 2.3. It was seen that the cutting forces increase with the cutting speed at very low cutting speeds. This increase is attributed to strain hardening. With further increase in the cutting speed, the cutting forces were found to reduce. This decrease is due to thermal softening of the workpiece material at higher temperatures. This leads to needing lower force to shear the material away. However, at high temperatures, the tool wear increases dramatically and hence the tool life is shortened.

Another important machinability criterion is chip morphology. Studying the characteristics of the formed chips can be used for evaluating different machining
Figure 2.3

conditions. It is desirable to have small broken chips. Chip breaking can be dependent on the method of application of cutting fluid to the machining interface. Palaniswamy et al. [7] found that the use of a high pressure coolant results in the formation of much smaller chips as compared to standard pressure coolant as shown in Fig. 2.4. In addition to coolant application, another method to form broken chips is the use of chip breaking geometry on the tool itself. Various
chip-breaking geometries that can be used in the turning process are studied by Zhou [31]. These chip breaking grooves change the forces that are applied on the chips, and result in breaking of the chips. Some typical chip breaking geometries are shown in Fig. 2.5

Figure 2.4

(a) Chips formed with standard pressure coolant [7] (b) Chips formed with high pressure coolant [7]

Figure 2.5: Various chip breaking geometries [31]

### 2.2 Cooling Techniques used in Ti Machining

In machining of titanium, a large amount of heat is generated due to the plastic
deformation of the workpiece through shear forces and due to friction at the tool-chip interface. The heat generated leads to a temperature as high as 1200°C at the cutting interface for titanium machining without the application of any coolant [9]. High temperatures lead to faster tool-wear and worse surface finish. To minimize these adverse effects of high temperature, a cutting fluid needs to be used. The cutting fluid can act as a coolant by reducing temperature, a lubricant by reducing friction and cutting forces and also help in flushing out the chips formed in the machining process. The effectiveness of cutting fluids depends to a large extent upon the method of their delivery into the cutting zone [5].

A variety of techniques have been used for the application of a cutting fluid to the cutting interface. The most common and conventional method for coolant application is flood cooling. In flood cooling systems, coolant is delivered through nozzles over the work zone at line water pressures. Coolant may be applied through either fixed or flexible piping. A large volume flow rate of the cutting fluid is generally used (1-10 L/min). Although flood cooling can help achieve a better machining performance as compared to dry cutting, it is associated with high costs and serious health and environmental issues.
2.2.1 High pressure coolant application

High pressure coolant application involves the application of the cutting fluid at high pressure and large volume flow rates to the cutting zone. Application of the cutting fluids in the form of high pressure jets can also be effective at breaking chips, with the added benefit to extending tool life. [10]. Machado et al. [10] carried out single point continuous turning tests on Ti6Al4V and Inconel 901 using various geometries of straight grade (K20) cemented carbide inserts using a high pressure coolant jet directed at the tip of the tool where the chip is formed. Trials were also carried out using a conventional coolant supply for comparison. Up to a 300% improvement in tool life was observed while machining Ti-6Al-4V. Figure 2.6 shows the improvement in tool life with high pressure coolant application for titanium at various cutting speeds. Lacalle et al. [11] studied the use of a high pressure water jet system for drilling in titanium at a pressure of 11 Mpa and a flow rate of 11 L/min. It was observed that the high pressure system lead to almost double the cutting speeds compared to conventional speeds with a good drill life.

Nandy et al. [12] undertook high-pressure cooling using a neat oil and a water-soluble oil and evaluated its effects on machining evaluation parameters.
Figure 2.6: Tool life improvement with High pressure coolant application for machining Ti alloy [10]

such as chip form, chip breakability, cutting forces, coefficient of friction, contact length, tool life and surface finish of the finished workpiece were evaluated in comparison with those from the conventional cooling method. High-pressure cooling also provided desirable chip breaking and lead to reduction in cutting forces. Figures 2.7a and 2.7b show the chips formed and the tool wear while using high pressure coolant, respectively.

2.2.2 Cryogenic cooling

Cryogenic cooling involves the use of a cryogen such as liquid nitrogen to cooling the cutting zone. The use of cryogenic temperatures help to effectively cool the cutting interface and reduce wear, leading to a longer tool life. Cryogenic ma-
chining is an environmentally safe alternative to flood cooling. Hong et al. [13] developed a new economical cryogenic machining approach. This approach uses a chip breaker that helps to lift the chip and liquid nitrogen is released through a nozzle between the chip breaker and the rake face of the tool insert. Figure 2.8 show the schematic of the application of the liquid nitrogen on the cutting interface. As the nitrogen evaporates, a nitrogen cushion formed by evaporating
nitrogen lowers the coefficient of friction between the chip and the tool. These
cryogenic machining tests show that tool life increases up to five times the state-
of-the-art emulsion cooling, outperforming other machining approaches.

Figure 2.8: A schematic of the cryogenic machining approach [13]

Venugopal et al. [14] studied the effects of cryogenic cooling on growth and
nature of the tool wear while turning Ti-6Al-4V alloy bars with microcrystalline
uncoated carbide inserts under dry, wet and cryogenic cooling environments in the
cutting velocity range of 70-100 m/min. It was found that cryogenic cooling by
liquid nitrogen jets enabled substantial improvement in tool life through reduction
in adhesion-dissolution-diffusion tool wear through control of machining temper-
ature desirably at the cutting zone. Figure 2.9 shows the tool wear comparison of
dry, wet and cryogenic cooling conditions for different cutting speeds.
2.2.3 Minimum quantity lubrication

Minimum quantity lubrication (MQL) has been explored as a sustainable alternative to flood cooling. With the use of very small amount of water and soluble oil, MQL utilizes the compressed air stream to form oil mist and direct it at the cutting edge. This oil mist is able to get close to the tool-chip and tool-workpiece interface, therefore reducing friction and cutting forces generated during machining. Temperature reduction at the cutting zone is achieved by its evaporation and vaporization that differ from flood cooling [15].

Sadeghi et al. [16] investigated the use of vegetable and ester oils with the
MQL cooling technique and evaluated the cutting performance in comparison to flood cooling. Aluminum oxide grinding wheels were used to evaluate the use of MQL in grinding of titanium alloys. It was shown that the MQL technique can achieve similar or better grinding performance as with conventional lubrication methods. However, it was found that the surface roughness in MQL grinding was larger than in conventional grinding due to retained sharpness of grits and less temperature. Quantity of lubricant 60 ml/h and delivery pressure 4 (bar) were found to be the most appropriate quantity of lubricant and delivery pressure in MQL grinding of titanium alloy, Ti-6Al-4V that minimized grinding forces.

Zeilmann et al. [17] studied the temperature rise during drilling of Ti-6Al-4V using MQL. Two different types of MQL cooling were used, namely, internal MQL for drills with an internal cooling hole and external MQL for drills without holes through an external nozzle. The results showed potential for drilling with MQL applied internally through the tool. For drilling with MQL applied with an external nozzle, the process was restricted to small depths and limited with reference to the requirements of the surface quality of the hole. Figure 2.10 shows the maximum temperatures reached during the drilling processes using different cooling methods.
Rahman et al. [18] used a two-dimensional steady-state incompressible analysis for the minimum quantity of lubricant flow in milling operations using a computational fluid dynamics (CFD) approach. The analysis of flow and heat transfer in a four-teeth milling cutter operation was undertaken. A steady-state, pressure-based, planar analysis was performed with a viscous, realizable k- model. A mixture of oils and air were sprayed on the tool, which is considered to be rotating and is at a temperature near the melting temperature of the workpiece. Figure 2.11 shows the computational domain used.

The CFD analysis showed that the flow penetration into the cutting zone is dependent upon the flow velocity and the number of nozzles. A single nozzle with a very small flow velocity cannot achieve complete lubrication using MQL fluid. The issue of uneven distribution can be solved by increasing the number of
nozzles, thus distributing the incoming lubricant evenly on the cutter’s periphery which can result in the improved lubrication of the cutting surface. The MQL flow in the study in [18] is inefficient in high-speed milling, because it is not able to reach the inner zones of the tool teeth. Figures 2.12 and 2.13 show the velocity contours and MQL particle paths, respectively, from the CFD analysis.

### 2.2.4 Limitations of the discussed cooling methods

Although cooling techniques like high pressure cooling and cryogenic cooling improve tool life in comparison to flood cooling through reduction in cutting temperature and enhanced lubrication, a large amount of energy is required for their effective usage [19]. High pressure cooling required pumping of large volumes of
fluids at very high pressure, increasing the energy input. For cryogenic cooling, the production of a cryogen such as liquid nitrogen can be a costly and energy intensive process. Due to these concerns there is a need for a low energy cooling system that can provide comparable machining performance.
In contrast to high pressure cooling and cryogenic cooling, MQL has economical and environmental benefits due to its low energy consumption and low fluid usage. It also has been shown to have a machining performance at par with conventional flood cooling. However, the major drawback of MQL is that the droplet size cannot be easily controlled and the penetration of the droplets into the cutting zone is not guaranteed [20].

To overcome the difficulties of high energy consumption, the atomization-based cutting fluid delivery system was developed that consumes less energy and provides effective cooling and lubrication [21]. The ACF system has shown improvement in machining performance by increasing tool life, reducing cutting temperatures. Details of the principle and working of the ACF system are discussed in subsequent sections.

2.3 Atomization-based cutting fluid (ACF) Spray system

Since effective penetration of the cutting fluid at the interface is important during machining, Jun et al. [21] proposed an atomization-based cutting fluid (ACF) spray system to deliver significantly small amount of cutting fluid in the form of small separated fluid droplets. The ACF system consists of an ultrasonic atomizer.
The ultrasonic atomizer is used to atomize cutting fluid droplet to sizes ranging from 10-50 \( \mu \text{m} \). Low velocity air is used to move the droplet with a low velocity through a droplet nozzle. High pressure gas is used to carry the cutting fluid droplets towards the cutting zone. Figure 2.14 shows the schematic of the experimental setup used in [21]. The droplet velocity is assumed to be equal to the velocity of the carrier gas and is chosen such that the droplet impingement lies in the spreading regime.

Through experiments conducted by Jun et al. [21], it was found that the ACF system performed much better in micromilling in comparison to flood cooling. Figure 2.15 shows the cutting edge wear after cutting 30 slots with the flood coolant method and 45 slots with the atomization-based cutting fluid application system. It was found that the tool wear in flood cooling method was much higher
than with the ACF system. The wear with the ACF system was found to be uniform. These results suggested that the ACF system leads to better machining performance through efficient lubrication, cooling and chip evacuation. It was also found that the ACF system lead to much lower tool temperatures in comparison to flood cooling and dry cutting conditions as shown in Fig. 2.16.

Figure 2.15: Tool wear using (a) flood cooling and (b) ACF cooling [21]

Nath et al. [22] designed and evaluated an atomization-based cutting fluid spray system in macro-scale turning of titanium alloy. Figure 2.17 shows the ACF spray unit used. Nath et al. [22] conducted experiments to study the effects of 5 ACF parameters on the tool life and forces in titanium turning, namely, spray
Figure 2.16: Tool temperatures [21]

distance, spray angle, gas pressure, fluid flow rate and carrier gas type.

Figure 2.17: Schematic of the ACF system designed by Nath et al. [22]

It was observed that the ACF system could increase tool life by approximately 1.5 times over flood cooling. Figure 2.18 shows the chips formed in the machining experiments. It was observed that the ACF system leads to the formation of small broken chips in comparison to flood cooling. Hence, it was concluded that the ACF system lead to effective cooling and lubrication of the cutting zone, leading to the formation of broken chips and increasing machining perfor-
mance. The effectiveness of the ACF system was attributed to formation of a thin liquid film of cutting fluid on the tool surface that could penetrate effectively in the tool-chip contact area and provide cooling. This penetration of the cutting fluid in the tool chip contact region is absent in flood cooling.

![Figure 2.18: Chip formed during machining with (a), (b) ACF system; and (c), (d) Flood cooling [22]](image)

Nath et al. [22] also conducted a $2^{5-1}$ partial factorial design of experiment to study the effect of the 5 ACF spray parameters. The two-way diagrams showing the interactive effects is shown in Fig. 2.19. It was found that the tool-life depends on higher-order effects of all the 5 spray parameters. For the machining conditions
that were considered, it was concluded that the combination of low gas pressure, long spray distance, and high droplet flow rate for both gases applied in an ACF spray system results in longer tool life during titanium machining.

Figure 2.19: Two way diagram for tool-life [22]

Hoyne et al. [23] studied the temperature distributions on the cutting tool using an ACF system. The temperatures were obtained both by inserting thermocouples in the contact region and the tool-work thermocouple technique. The
friction coefficients are also estimated from the force data to confirm the temperature reduction due to effective penetration of cutting fluid, thereby providing lubrication at the cutting interface. Electro-discharge machining was used to drill holes in the tools. Figure 2.20 shows the inserted thermocouple setup used to tool temperature measurements.

![Figure 2.20: Inserted thermocouple measurement setup [23]](image)

Figure 2.21 shows the temperature measurements conducted by Hoyne et al. [23]. The tool-work thermocouple measurements indicated that the ACF spray system reduces average cutting temperatures by 7-13%, whereas flood cooling reduces it by only 1-3% as compared to dry machining. Tool life experiments revealed that, after 4 min of machining, the ACF spray system with air-CO$_2$ mixture has a lower friction coefficient than flood cooling, and thereby enhances tool life. The significantly lower temperatures at the tool-chip interface measured by the inserted thermocouple technique indicated that the ACF spray system actively
penetrates cutting fluid in the form of a thin fluid film (microscale) into the tool-chip interface to extend tool life. This was confirmed by using a camera during the machining operation to study the penetration of the fluid film into the tool chip contact region. The results of this study are shown in Fig. 2.22.

Figure 2.21: Inserted thermocouple temperature measurements [23]

Hoyne et al. [24] also studied the film formation by an ACF system. An experimental apparatus was constructed to observe and measure the film at various distances from the impingement point (DIP) and various perpendicular offset distances (POD) from the centerline of the spreading film. Figure 2.23 shows the setup used by Hoyne et al. in film thickness measurements. Using a camera,
Figure 2.22: Chip lifting-falling cycle during titanium machining: (a) Chip lifting allows thin film to penetrate (less fluid excretes) and (b) chip falling causes more fluid excretion from the interface [23]

film thickness was measured at different distance from impingement points and perpendicular offset distance from the centerline of the tool.

The top view and the side view of the fluid film from the experimental observation by Hoyne et al. are shown in Figures 2.24 and 2.25, respectively. It was seen that the film shows long, evenly spaced streaks that extend radially away from the spray impingement point. A radial symmetry in the spreading film is seen. Close to the impingement point, there exists an “impingement zone”, where the focused high velocity gas introduces strong shear forces on the film driving the fluid away from this zone. Outside the impingement zone, the film is less
disturbed by the high-velocity gas, allowing the fluid film to slow and thicken revealing illuminated streaks that spread radially outward from the impingement point. Measurements of film thickness were conducted by visual inspection of the camera pictures. It was found that other ACF spray parameters, including fluid properties, gas pressure, and droplet velocity, also have profound impact on the formation of the thin fluid film.

Tanveer et al. [26] developed a thermal model to predict tool temperature in machining of Ti-6Al-4V with the ACF spray system. A numerical model based on FEM using COMSOL Multiphysics was developed to estimate the temperature profile near the tool-chip interface. A 2D approximation of the 3D machining
Figure 2.24: Top view of spreading film [24]

Figure 2.25: Side view of spreading film [24]

process was used. The heat generated due to the cutting action in machining was represented as a surface heat flux at the tool chip-interface. Experiments were conducted to establish that the heat transfer mechanism from the tool in film
boiling. Figure 2.26 shows the geometry used in the modeling and the boundary condition used. An energy based approach was used to determine the droplet spreading and then is used as the area over which the film boiling heat transfer occurs.

Figure 2.26: Geometry of the tool with boundary conditions. [26]

Turning experiments were conducted thermocouples inserted in the tool to measure the temperature along the tool during the machining operations. The temperature values predicted by the model were used to compare with the experimental values. Comparisons were also made with the experimental temperature measurements for dry cutting and flood cooling. Figure 2.27 and 2.28 show the contour plot of the tool temperature and the comparison of the predicted temperature values with the experimental results, respectively. It was found that the
cutting temperature at the cutting edge was as high as 1200 °C for dry cutting and the use of the ACF system lead to a significant decrease in the cutting temperature (600 °C).

Figure 2.27: Predicted temperature contour plot of the tool [26]

Figure 2.28: Comparison between numerical and experimental results. [26]

Ganguli et al. [25] investigated the effectiveness of the atomization-based
cutting fluid (ACF) spray system in end-milling of titanium alloy, Ti-6Al-4V. Figure 2.29 shows the schematic of the use of the ACF system in milling operations. Milling experiments were conducted in two phases. In the first phase, different ACF spray parameters were studied and the best combination of spray parameters was established that lead to the best machining performance. In the second phase, machining experiments were conducted, using the spray parameters selected in phase one, to assess the machinability of titanium alloy for different cutting fluid application methods, viz., ACF system, flood cooling and dry cutting, as well as for different machining conditions.

![Figure 2.29: ACF spray system in milling setup. [25](image)](image)

In the first phase of experiments conducted by Ganguli et al. [25], two ACF parameters, namely, spray distance and gas pressure were varied at two levels each. Average peak to valley forces were measured and it was found that the low
spray distance low gas pressure combination and the high spray distance high gas pressure combination resulted in machining with minimum forces. In the second phase, experiments were conducted using the spray parameters determined from the first phase and machining performance in milling of titanium was evaluated by measuring forces, flank wear and surface roughness. It was found that ACF spray system is able to extend the tool life as high as 75% over flood cooling. Figure 2.30 shows the wear progress of the tool flank with machining for different cutting fluid application methods. It was also observed that with the application of the ACF system, the tool wear is uniform, without any abrupt chipping and notch formation.

Figure 2.30: Wear progress of the tool flank with machining for different cutting fluid application methods. [25]

In addition to better wear characteristics, Ganguli et al. [25] found that using the ACF also resulted in lower cutting forces, better surface finish and production
of smaller chips as compared to flood cooling. It was concluded that enhanced cooling and lubrication capabilities of ACF spray system, due to thin film formation on the cutting edge was instrumental in reducing the tool flank wear and hence the cutting forces and surface finish.

From the above mentioned studies with the ACF system, it is clear that the ACF system is a low energy consuming, environmental friendly alternative to flood cooling that can provide better machining performance with the optimum spray parameters. The ACF system is particularly effective in machining of difficult-to-cut materials such as titanium alloys. Hence, to maximize its effectiveness many physics-based modeling studies have been conducted to study the effect of various parameters on the ACF system. Some of the studies conducted are discussed in the following section.

2.4 Thin film formation and modeling

The effectiveness of the ACF system is attributed to the formation of a thin film of cutting fluid on the tool surface. Hence, numerous studies have been conducted to study the film formation through various spray systems, including the ACF system. Mathews et al. [27] studied the impingement of a liquid fuel on flat surfaces.
The film formation and evolution in time was studied. Three separate angles of impingement were considered. Features like film thickness, width and spreading distances were considered. Figure 2.31 shows the evolution of a film with an impingement angle of 30°. From the experiments of Mathews et al. [27], it was also concluded that for a lower impingement angle, the film front displaced to a larger distance from the impingement point as compared to a higher impingement angle. A similar trend was also seen for the film width. From film thickness measurements, it was concluded that, a trend of increasing film thickness with increasing distance from the impingement point was seen. However, it the differences of film thickness for different impingement angles did not show any particular trend. Figure 2.32 shows the film thickness along the centerline of the surface for different impingement angles.

Lee et al. [28] presented a numerical and analytic study of film formation and evolution during spray impingement. At impingement points the source terms for mass and energy are calculated based on conservation principles. It was shown that during the period where most of the film evolution takes place, the effect of gas shear and surface tension are negligible. Three different impingement angles of 30°, 45° and 60° were considered. Features such as film front displacement, film width and film thickness were compared with experimental results. Figure
Figure 2.31: Evolution of a film due to spray impingement [27]

2.33 shows the predicted film front displacement and film width as a function of time and its comparison to measured values. Figure 2.34 shows the predicted film thickness along the centerline of the surface for three different impingement angles and comparisons to measured values. It was confirmed from experimental measurements that the film front displacement is larger for a larger impingement
Figure 2.32: Film thickness along the centerline [27]

angle. This was because the impinging spray has a larger momentum tangential to the surface at larger impingement angles. The film width was found to be very slightly vary with the impingement angle. From the film thickness measurements, the model predictions were found to be close to the experimental measurements.

Hoyne et al. [24] developed an analytical 3-D model based on mass and momentum conservation to characterize the thin fluid film produced by the ACF spray system to better understand the penetration mechanism that improves tool life during machining. This model used the boundary layer approximation to the Navier-Stokes mass and momentum equations to estimate the thickness and the
Figure 2.33: Film front and width displacement with time [28]

Figure 2.34: Film thickness along the centerline [28]
velocity of the thin fluid film for various locations in 3D space and in time. The
modeling approach and the associated computational domain is shown in Fig.
2.35.

Figure 2.35: (a) Fluid film described with mesh and coordinates and (b) an arbi-
trary fluid cell [24]

The continuity of mass and momentum equations are discretized and then
solved within fluid cells individually to determine the fluid film development in
space and in time. Boundary layer approximations are used to simplify the mass
and momentum equations. The governing film flow equation for mass continuity
is derived as [24]

\[
\frac{\nabla h}{\nabla t} + \frac{1}{A_w} \sum (u_r \bar{n}) h_i l_i = \frac{1}{A_w} \left[ \frac{\pi}{6} \left( N_d N(r) \bar{N} \partial \right) \right] ,
\]

The first term on the left hand side of Eq. 2.1 shows the dependence of the film
thickness on time. The second term represents the volume of fluid flowing in and
out of a cell. The term on the right side represents the mass source in the fluid
film mass due to impinging droplets. The droplet impingement is simplified to an empirical function of the position of the fluid cell in the domain with respect to the spray impingement point. The governing equation for film momentum is derived as [24]

$$\nabla \left( hu_r \right) \nabla t = \frac{1}{\rho A_w} \sum \left[ P(r, \theta) \bar{n} \right] h_i l_i + \frac{M(r, \theta)}{\rho A_w} - \frac{1}{A_w} \sum \left[ u_r^2 \bar{n} \right] h_i l_i \beta + \frac{1}{\rho A_w} F_s + \frac{1}{\rho A_w} F_b , \tag{2.2}$$

where the term on the left side of Eq. 2.2 is the rate change of momentum. The terms on the right hand side represent the pressure force, the tangential momentum input due to droplet impingement, the convective momentum loss, the viscous shear and the body forces, respectively.

Hoyne et al. [24] used the numerical model to compared the film thickness values with experimental measurements. Figure 2.36 shows the results of these measurements. The simulated film thickness values were found to be within one standard deviation of the experimental values. The prediction of fluid film velocity resulting from the thin fluid film model was used to determine how readily the fluid film will penetrate the toolchip interface during machining for a given set of ACF spray parameters. It was concluded that the film velocity predicted by the
model was more than 20 times greater than the value required to fully penetrate the tool-chip contact region.

Ganguli et al. [25] conducted numerical simulations using a CFD approach to predict the film thickness of a film formed by the ACF system on a rotating surface. Figure 2.37 shows the geometry used in these simulations. The rotating end-mill tool was modeled as a cylinder. The wall of the cylinder was assumed to be smooth and the cylinder has a fixed angular velocity. The liquid film thickness was characterized for 4 different combination of spray parameters.

Figure 2.38 shows a 3D plot of film thickness with angular position for all the conditions considered in [25]. It was seen that the liquid film thickness varies considerably near the point of impact of the spray but stabilizes at distances farther away from it. It was also concluded that higher droplet velocities lead to the formation of thinner fluid films and lower velocities lead to thicker fluid film. It was predicted that very thin films and very thick films do not provide effective cooling because thin films may evaporate before reaching the cutting zone and thick films may not penetrate effectively in the cutting zone.
Figure 2.36: Experimental and predicted film thickness values over POD and DIP [24]
2.5 Effect of Surface geometry on machining performance and film formation

With advances in cutting tool design, tool geometries with chip breaking grooves are being used to improve the machining performance by breaking the formed
chips and reducing machining forces. Kim et al. [29] developed a chip breaking system for mild steel in turning. Chip control in turning is difficult in the case of mild steel because chips are continuous. Thus the development of a chip breaker for mild steel is an important subject for the automation of turning operations. Experiments were conducted with various chip breaker geometries such as side-curl chip breaker and up-curl chip breaker. It was concluded that a side-curl chip breaker is particularly useful in a finish turning operation using mild steel. Figure 2.39 shows the schematic of the two chip breakers used.

Efforts have also been made into investigating the use of grooved tools for machining of titanium. Xie et al. [30] studied the use of various non-coated micro-grooved tools on tool rake surfaces in dry cutting of titanium alloy. Dry turning experiments of titanium alloy were performed using micro-grooved tools and cutting temperature, cutting force, chip formation and tool wear were investigated in connection with the micro-groove depth and material removal rate. Figure 2.40 shows the grooved rake face of a turning insert.

Xie et al. concluded from their study that the use of grooved tools could lead to a reduction in cutting temperature of up to 103 °C in comparison to a traditional plane tool. Figure 2.41 shows the cutting temperatures measured for
turning with various tool geometries. It was also concluded that the depth of the groove on the tool rake face also influences the cutting temperatures, tool wear and the cutting forces. Xie et al. also found that in order to decrease cutting chip frictions and exclude cutting heat, the micro-groove depth needs to be large enough to maintain the air space between chip back surface and tool rake surface. Moreover, the micro-groove width needs to be less than cutting chip width so as to produce cutting chip sliding on tool rake surface.
In addition to breaking of chips, the tool geometry also affects the film formation and film flow on the surface, which is an important consideration of the ACF system. Friedrich et al. [32] studied the film formation on a surface with a sharp corner and found that the dynamics of the film due the sharp corner are different than those on a flat surface. Figure 2.42 shows the schematic of the film separation phenomenon studied. The ability to measure the liquid mass that stays
attached to the wall after the corner was built into the test section. An analytical force balance was developed and a film separation criterion was proposed on the basis of gas velocity over the film and the Reynold number of the film as shown in Fig. 2.43.

Figure 2.42: Schematic of film separation [32]

Figure 2.43: Film separation criterion [32]

Baxter et al. [33] studied the film motion around an obstacle on an inclined
plane. The effects of the obstacle were examined for various flow configurations and results produced for flow over hemispherical obstacles. It was concluded that the flow profiles are governed by the obstacle geometry. Flow around large hemispheres and cylinders was also studied. Figure 2.44 shows the free surface and the contour lines for a flow around a large cylinder. Malamataris et al. [34] also used a computer aided analysis to study the flow of a viscous film along an inclined wavy wall. A complete description of viscous flow along an inclined wall with infinitesimal and finite wall indentations was given in the whole range of laminar regime. Figure 2.45 show the streamlines in a flow along a wavy wall. Clearly, the surface geometry affects the film motion. Tool geometries, such as, chip breaking grooves are also expected to affect the film formation in a similar way, which is an important concern regarding the ACF system.

2.6 Effect of cutting fluid on machining

It has been well established that the use of a cutting fluid increases the machining performance of titanium machining for various coolant application methods. However, the cutting fluid also plays an important role in determining the cooling performance [?, 12]. Nandy et al. [12] conducted experimental studies on turning
of titanium with different cutting fluids and concluded that the properties of the
cutting fluid is an important consideration in machining processes. A neat oil and
a water soluble oil were used as the cutting fluids and it was concluded that the
high pressure water soluble oil was much more effective in enhancing tool life as
compared to high pressure neat oil. Figure 2.46 shows the tool wear comparison with different cutting fluids used.

Nath et al. [19] conducted turning experiments on titanium with a varying concentration of the cutting fluid. Five different concentrations from 5 to 15% of a water-soluble metalworking fluid (MWF) were applied during turning of a titanium alloy, Ti-6Al-4V. It was clear that the change in concentration of the cutting fluid would also change the physical properties of the cutting fluid. It was
observed that the tool life increases with increasing concentration and then drops as the concentration is further increased. This was attributed to a lack of lubrication effect at low concentrations that lead to an increase in the friction forces resulting in severe chipping of the tool. At high concentration, it was concluded that the cooling effect is less. A good balance was found at a concentration of 10% cutting fluid in water. Figure 2.47 shows the tool wear progress for different concentrations of the cutting fluid.

![Figure 2.47: Wear progress of the tool flank with machining][19]

### 2.7 Research Gaps

Review of the previous literature shows that the ACF system is effective in cooling and lubricating the cutting zone in titanium machining, resulting in significant
improvement in the machining performance while consuming very low amount of cutting fluid and energy. It is known that the film formation and penetration is the primary reason for the effectiveness of the ACF system. However, there is a lack of understanding of the exact effects of the film characteristics that lead to an improved machining performance.

There are numerous modeling efforts made in literature to predict the film formation through many spray systems. A previous study used to model the film formation in an ACF system reduces the droplet impingement to an empirical relationship [24]. However, for the ACF system it is important to consider the droplet impingement on the tool surface from the exact nozzle geometry and the spray parameters. The nozzle geometry and position is also an important consideration because the spray parameters like spray distance and spray angle are determined by the nozzle position and are known to control the film formation and thus the machining performance in an ACF spray system [22]. The film formation model must also consider the geometry of the surface as it has been established that the surface properties play a significant role in the film formation phenomenon. The film formation in an ACF system depends on a large number of parameters that are difficult to study experimentally. Thus, a numerical model that considers all the above mentioned effects is required to study and maximize the effectiveness
of the ACF system

In addition to modeling efforts, there is a need for a film thickness measurement technique to validate the model. Most previous efforts made into measurement of the film thickness in an ACF system involve optical measurements using cameras [24,37]. However, only a 2D visualization of the film is possible through this method and hence, a different method that can be used to measure the film thickness over the complete extent of the tool surface is required.

The ACF has only been used for turning operations using a conventional flat tool [22, 24, 26, 35]. As mentioned, chip breaking grooves on turning inserts can be useful in improving machining performance and reducing forces. However, for the ACF system, the film formation on the tool is an important consideration and hence, there is a need to study the film formation by the ACF system on grooved cutting inserts to establish its applicability and study its effectiveness in improving the machining performance.

Despite a number of experimental studies on the ACF system [22, 35], the exact effect of varying the ACF spray parameters on the machining performance has not been established. Furthermore, The effect of these parameters on the film characteristics has also not been studied. Since the fluid film formation is believed
to be the primary reason for the effectiveness of the ACF system, there is a need to investigate the effect of the ACF spray parameters on the machining performance and to relate the observations to the film characteristics through modeling efforts.

Most previous studies using the ACF have considered the same cutting fluid (S-1001). The effect of concentration of this cutting fluid has also been studied [35], however, a study on the effect of using cutting fluids with different physical and chemical properties with the ACF system on the machining performance is missing. In addition, the properties of the cutting fluid also affect the film formation and hence, there is a need to study the effect of these properties on the film characteristics and explore the influence of these film characteristics on the machining performance.
Chapter 3

Thin Film Model Formulation

In an ACF spray system, a thin, moving film of cutting fluid is delivered at the tool-chip interface during the turning operation [22] as shown in Fig. 3.1. An ultrasonic atomizer is used to generate a spray of atomized droplets of the cutting fluid, which is impinged onto the surface of the turning insert to form a thin film. This thin film penetrates the tool-chip interface and provides essential cooling and lubrication that has been shown to improve the machining performance during a turning operation [22, 26, 35]. The formation of the cutting fluid film in an ACF system is governed by the droplet-surface interaction and the physical properties of the cutting fluid [24, 36]. Therefore, the geometry of the impinged surface and the type of cutting fluid used in the turning operation play a critical role in
the effectiveness of the ACF system. The characteristics of the fluid film such as film thickness and velocity profile are also affected by the ACF spray parameters such as fluid flow rate, gas pressure, spray distance and spray angle (refer to Fig. 3.1) and therefore, it is critical to choose the right combination of the ACF spray parameters that will ensure a desired performance of the ACF system. The ACF system has been shown to improve tool life by 1.5 times over flood cooling in turning operations [22]. Furthermore, the ACF system is known to provide desirable features like low power input for the atomizer, no requirement for the pumping of high volume flow rates of the cutting fluid and usage of very low volumes of cutting fluid, making it environment friendly.

Many experimental studies have been conducted on the ACF system. [22, 25, 35]. However, such experimental efforts are often inadequate in obtaining quantitative understanding of the effect of all the parameters as there exists a large number of parameters that affect the film formation by the ACF system. Furthermore, the experiments fail to bring forth the detailed mechanism of the film formation in the ACF system and penetration of the film in the tool-chip interface. In order to effectively use the ACF system for machining, it is imperative to understand the mechanism of the cooling and lubrication effect. It is believed that the thin liquid film formed in the ACF system is the primary difference compared
to flood cooling that lead to increased machining performance. To understand the effect of the fluid film on the machining performance, a numerical modeling study needs to be used due to the large number of variables present in the ACF system, including, spray parameters (gas pressure, flow rate, spray distance, angle), surface properties (chip-breaking grooves, tool shapes), fluid properties (surface tension, viscosity) and droplet parameters (diameter, injection velocity). Each one of these parameters can affect the fluid film characteristics and in turn, the machining performance. Hence, a numerical model is developed to predict the film formation in an ACF system and is evaluated using ANSYS Fluent computational solver. The details of the model are described in the rest of the chapter.

Figure 3.1: Schematic of the ACF spray system in a turning setup showing ACF spray parameters, i.e., fluid flow rate, gas pressure, spray distance and spray angle.
3.1 Modeling approach

Figure 3.2 shows a schematic of the modeling approach adopted in this work. The approach is similar to the one used by Pattabhiraman et al. [37] in describing dielectric film formation in spray EDM. Three different models, namely, the carrier gas model, the discrete phase model (DPM) and the Eulerian wall film model (EWF) are used to simulate ACF spray and the resulting fluid film formation on a cutting tool. The carrier gas model is used to model flow of the carrier gas throughout the domain using the equations of conservation of mass and momentum. The discrete phase model (DPM) is used to model the movement of atomized droplets of a cutting fluid in the carrier gas flow using the Euler-Lagrange approach. The carrier gas is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase (atomized droplets) is modeled by tracking a large number of droplets through the calculated gas flow field. The dispersed phase can exchange momentum, mass, and energy with the fluid phase [38]. The trajectory of a discrete phase particle (or droplet or bubble) is predicted by integrating the force balance on the droplets, which is written in a Lagrangian reference frame. Finally, the Eulerian wall film (EWF) model is used to study the film formation on the surface of the cutting insert.
The present model also includes the nozzle geometry including the nozzle walls as well as the geometry of the spray-impinged turning insert (both flat and the grooved-type) that was missing from the earlier work [25, 37]. In addition, the droplet injection parameters from the atomizer outlet that serve as an input to the discrete phase model (DPM) are chosen from experimental measurements in order to calculate the droplet trajectories with better accuracy. The loss of cutting fluid due to impingement on the nozzle walls is also considered in the model.

The physical properties of the cutting fluid and the surface geometry of the turning insert on which the cutting fluid film is formed act as inputs to the Eulerian Wall Film Model and therefore, significantly influence the formation and charac-
teristics of the fluid film. The surface geometry of the impinged surface affects the boundary conditions for the gas and fluid flow, while the physical properties of the cutting fluid appear in the mass and momentum conservation equations. The nozzle geometry and the ACF spray parameters act as inputs to the carrier gas model that predicts the carrier gas velocity profile. The specific ACF spray parameters that are taken into consideration in this model are the spray distance, the spray angle and the gas pressure. Using the combination of three models i.e., Carrier Gas Model, Discrete Phase Model and the Eulerian Wall Film Model, spatial profiles of thickness and velocity of the cutting fluid film formed by the ACF system on a turning insert can be obtained. Detailed description of each of these models along with governing equations used is given in rest of the chapter.

3.2 Carrier gas model

The Carrier Gas Model uses equations of conservation of mass and momentum to model flow of the carrier gas thorough the computational domain. The carrier gas is treated as a steady, compressible fluid. The mass conservation equation is given as [38]:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m ,
\]  

(3.1)
where, $\rho$, $t$, $\vec{v}$, and $S_m$ are the fluid density, time, fluid velocity and mass source term, respectively. The momentum conservation equation is given as \[38\],
\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla . (\rho \vec{v} \vec{v}) = -\nabla p + \nabla . (\bar{\tau}) + \rho \bar{g} + \bar{F},
\] (3.2)

where, $p$ is the static pressure, $\bar{\tau}$ is the stress tensor, $\rho \bar{g}$ is the gravitational body force and $\bar{F}$ is the external body force (e.g., that arises from interaction with the dispersed phase).

From previous measurements of the carrier gas velocity for the ACF system [25], it is seen that the velocity of the carrier gas at the outlet of the gas nozzle reaches values more than 200 m/s. Using the diameter of the gas nozzle (2 mm), the density and the viscosity of air, the Reynolds number inside the gas nozzle tube can be as high as $4.8 \times 10^5$, which is much larger than the critical Reynolds number required for the transition to turbulent flows in pipes(2300). Similar turbulent behavior is expected from the high velocity jet coming out of the gas nozzle due to the imbalance between the fluid velocity in the jet and the quiescent ambient fluid and the creation of an unstable shear layer. Hence, to model the convection and diffusion of turbulence energy, the shear stress transport (SST) $k-\omega$ model has been used. This formulation makes the model usable
all the way down to the wall through the viscous sublayer, in the inner parts of the boundary layer. The most widely used k-\( \epsilon \) model of turbulence is known to show numerical stiffness for a flow around complex geometries like the chip-breaking grooves of cutting inserts [39] but a common problem of the k-\( \omega \) model is that it too sensitive to the inlet free stream turbulence properties [38]. The SST formulation of the k-\( \omega \) model, however, allows for a switch to k-\( \epsilon \) behavior in the free stream and retain the k-\( \omega \) behavior in the viscous sublayer near the surface of walls. This formulations allows for avoiding the weaknesses of both these models. A pressure-based solver with the SIMPLE algorithm for the pressure velocity coupling is chosen for the numerical simulations due to its fast convergence properties. The pressure-based solver is used as an alternative to density-based solver in ANSYS fluent for problems involving high-speed jets, such as the high pressure gas flow in the ACF system.

The computational domain is shown in Fig. 3.3. As shown in the figure, the domain is divided into three parts namely, the nozzle unit, the cutting insert and the intermediate air. The nozzle unit consists of two coaxial nozzles. Cavities are introduced in the fluid domain in the shape of the nozzle walls. The intermediate air is modeled as a cuboidal domain with cavities in the shape of the nozzle unit and the cutting tool, i.e., a turning insert. The position and the orientation
of these cavities are adjusted according to the required spray distance and spray angle. The domain is made large enough so that the gas flow in the domain is not influenced by the boundaries of the domain. The turning insert is modeled as a triangular prism with the cutting edge having a radius of 1/32 inch. Additional modifications in the geometry of the domain are made for simulating the film formation on grooved inserts by including the chip-breaker geometry on the surface of the triangular prism. In order to reduce the computational time, only a half of the computational domain is used in the model evaluation by exploiting symmetry boundary condition. The domain is meshed with an unstructured mesh with about 800,000 elements having a maximum size of 3 mm. Spatial variations in properties like film thickness and gas velocity are likely be present over a smaller length scale in regions such as the insert tip and the gas nozzle outlet, respectively, because of the small radius of the insert tip and the small diameter of the gas nozzle outlet. Therefore, a mesh refinement is introduced in these regions.

The least-squares gradient method is used to calculate gradients due to its less expensive computational time and comparable accuracy to other methods such as the node-based gradient method. Discretization of pressure and momentum is accomplished through second order and second order upwind method, respectively. Higher order methods provide a greater accuracy and are expected to
be closer to the exact solution as compared to first order methods. The transient terms of the model equations are included because the flow of the cutting fluid droplets and the formation of the fluid film are expected to evolve with time. The simulations are carried out for a time of 300 ms with a time step of 0.1 ms.

The fluid domain is assigned as air and the physical properties of air are used in the simulations. The gas nozzle inlet is modeled as a ‘pressure-inlet’ with
the required pressure. The domain boundaries are set as ’pressure-outlets’ with atmospheric pressure to model the quiescent air. ’No-slip’ boundary conditions are used at the nozzle walls and the surface of the cutting insert.

Figure 3.4: Velocity contour for a gas pressure of 15 psi

Figures 3.4, 3.5 and 3.6 show the velocity and pressure contours calculated using the carrier gas model for a gas pressure of 15 psi at the inlet of the gas nozzle and a flat turning insert. From Fig. 3.4, it can be seen that the gas velocity just outside the nozzle domain has a very large value of about 100 m/s. The gas flow over the surface of the insert provides the shear force for the film that is formed on the insert surface. This leads to large film velocities and is expected to provide
effective penetration into the tool-chip contact region during a machining process.

Figure 3.5 shows the velocity contours inside the gas nozzle. It can be seen that the gas velocity inside the nozzle is much larger than the velocity outside the nozzle.
Figure 3.7: Pressure contour for a gas pressure of 15 psi in the nozzle unit geometry. This is due to the small radius of the gas nozzle and its converging geometry, which leads to a large velocity to maintain the mass out flow rate equal to the mass flow rate into the nozzle. Figure 3.6 shows the pressure contour in the intermediate air due to the high pressure flow from the gas nozzle. It can be seen that a high pressure region is developed on the surface of the cutting insert because of the no-slip boundary condition on the insert surface, which causes the gas velocity to be zero. The drop in the gas velocity is converted into pressure according to the Bernoulli equation. Figure 3.7 shows the pressure contour in the nozzle unit separately, as the pressure values inside the ACF nozzles are much larger compared to the pressure in the surrounding air. Note that the scale used in the legend is different for the two figures. It is seen that the pressure from the gas
nozzle inlet is about $10^5$ Pa (15 psi) and starts dropping close to the outlet where the gas velocity is the largest.

### 3.3 Discrete phase model (DPM)

The Discrete Phase Model (DPM) uses velocity profile of the carrier gas to determine the trajectory of the atomized cutting fluid droplets. The droplets are generated and introduced into the spray nozzle according to the injection parameters such as droplet diameter, droplet mass and the fluid flow rate. The DPM model is applicable for problems where the dispersed phase has a volume fraction less than 10%, which is the case for the ACF system. The trajectory of each droplet is predicted by integrating the force balance on the droplet, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle due to drag and gravity [38].

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{v} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}\;,$$

(3.3)

where, $\vec{F}$ is the additional acceleration term accounting for forces like Saffmann lift force, virtual mass force or thermophoretic force. $F_D(\vec{v} - \vec{u}_p)$ is the drag force
per unit particle mass and is given by,

\[ F_D = \frac{18\mu C_D Re}{24\rho_p d_0^2} . \]  

(3.4)

In equations 3.3 and 3.4, \( \vec{v} \) is the carrier gas velocity, \( \vec{u}_p \) is the liquid particle velocity, \( \mu \) is the molecular viscosity of the fluid, \( \rho \) is the density of the carrier gas, \( d_0 \) is the particle diameter and \( Re \) is the relative Reynolds number. Note that the physical properties of the cutting fluid such as density and viscosity affect the forces on each droplet and hence, the trajectories of the fluid droplets could be different for cutting fluids with different physical properties.

The droplet injection is set as a cone at the inlet of the droplet nozzle with a cone angle of 20°. This value is chosen from experimental measurements using an atomizer (as shown in Figure 3.8) without the high pressure carrier gas. The ACF system includes an ultrasonic atomizer (Model VC5040AT from Sonic and Materials, Inc., CT [40]) with a frequency of 40 kHz that can generate atomized cutting fluid droplets with a median diameter of 60 \( \mu \)m. Hence, the droplet size is set to 60 \( \mu \)m in the simulations. The properties of the cutting fluid are assigned to the droplets. The mass flow rate of the droplets is set according to the fluid flow rate used in the ACF system.
Figure 3.8: ACF spray from an atomizer

The domain boundaries are assigned a boundary condition of 'escape' for the DPM particle to allow the particles of exit the computational domain. The DPM particles are allowed to be impinged on the cutting insert surface as well as the nozzle walls by setting a boundary condition of 'trap' at these boundaries for the DPM particles. The Eulerian wall film model (described in Section 3.4) is also enabled on the cutting insert surface to model the film formation. Mass and momentum of the impinged droplets appear as the source terms in the film mass and momentum equations of the EWF model. The 'trap' boundary condition at the nozzle walls allows accounting for the loss of cutting fluid due to droplet impinge-
Table 3.1: Boundary conditions for the numerical model

<table>
<thead>
<tr>
<th>Boundary name</th>
<th>Carrier gas BC</th>
<th>Discrete phase particle (droplet) BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain boundaries</td>
<td>Pressure Outlet (Atmospheric Pressure)</td>
<td>Escape</td>
</tr>
<tr>
<td>Gas nozzle inlet</td>
<td>Pressure Inlet</td>
<td>Escape</td>
</tr>
<tr>
<td>Nozzle walls</td>
<td>No-slip</td>
<td>Trap</td>
</tr>
<tr>
<td>Insert surface</td>
<td>No-slip</td>
<td>Trap (EWF model enabled)</td>
</tr>
</tbody>
</table>

The boundary conditions on the various boundaries of the computational domain are summarized in Table 3.1.

Figure 3.9: Simulated droplet spray for 15 psi gas pressure

Figure 3.9 shows the droplet spray out of the ACF spray system for a gas pressure of 15 psi. The particles are colored according to the particle velocity. It can be seen that some DPM particles are originating from the insert surface.
These droplets are formed due to film stripping caused by the shear force exerted by the carrier as on the surface of the thin liquid film formed on the insert surface.

### 3.4 Eulerian wall film model (EWF)

Using the trajectory of the droplets, both the impingement points and impingement velocities of the droplets on the cutting tool surface are determined. These droplet impingements are treated as mass and momentum source terms in the governing equations for the Eulerian Wall Film (EWF) model. The magnitudes of these terms are determined by calculating the fraction of the droplet mass that is added to the film, which is a function of the droplet velocities, the physical properties of the fluid and the instantaneous film thickness at the impingement location [38]. The cutting fluid film is modeled as a two dimensional thin film. The thin film assumption implies that the thickness of the fluid film is small compared to the radius of curvature of the surface and therefore, the variation of the film properties across the thickness of the film can be ignored. In addition, the motion of the liquid in a film is allowed only parallel to the surface on which it is formed. The assumption is valid because: (i) the film is formed on a flat surface, which can be assumed to have an infinite radius of curvature, and (ii) the film thickness
values reported for typical atomized/spray fluid delivery systems [24] are in the order of tens of microns. The film thickness distribution is obtained by solving equations for mass and momentum conservation for the cutting fluid [38]. The mass conservation equation is given as:

$$\frac{\partial h}{\partial t} + \nabla_s [h \vec{V}_f] = \frac{\dot{m}_s}{\rho_l},$$

(3.5)

where, $\rho_l$ is the liquid density, $h$ is the film height, $\nabla_s$ is the surface gradient operator, $\vec{V}_f$ is the mean film velocity and $\dot{m}_s$ is the mass source per unit wall area due to droplet collection, film separation or other phenomena.

Momentum conservation equation for the film is given as:

$$\frac{\partial}{\partial t} (h \vec{V}_f) + \nabla_s (h \vec{V}_f \vec{V}_f) = -\frac{h \nabla_s P_l}{\rho_l} + \vec{g}_n h + \frac{3}{2 \rho_l} \vec{\tau}_s - \frac{3 \nu_l}{h} \vec{V}_f + \frac{\dot{q}}{\rho_l},$$

(3.6)

where, $P_l = P_{gas} - \rho h (\vec{n} \cdot \vec{g}) - \sigma \nabla_s \cdot (\nabla_s h)$. The terms on the left hand side of Eq. (3.6) represent the material derivative of the film momentum. On the right hand side, the first term includes the forces due to the gas-flow pressure, the gravity component normal to the wall surface and surface tension; the second term represents the effect of gravity in the direction parallel to the film; the third term
represents the shear force on the surface of the film due to the gas flow outside the film; the fourth term represents the viscous dissipation in the film; and the last term is associated with droplet collection or separation [38]. Note that the Weber number, i.e., the ratio of inertial forces on the film to surface tension forces, for the film formed by the ACF system is of the order of $10^{-2}$. As a result, it is assumed that the flowing film does not have enough inertia to be separated into droplets at the sharp edges of the turning insert [32] and instead flows along the insert surface as a continuous film. Figures 3.10 and 3.11 velocity show the film thickness and velocity contours obtained for a flat turning insert, with a gas pressure of 15 psi and a fluid flow rate of 15 mL/min.

Figure 3.10: Film thickness contour for a flat insert. (gas pressure = 15 psi, fluid flow rate = 15 mL/min, spray distance = 30 mm, spray angle = 30°)
3.5 Experimental Validation

The model was validated by comparing the experimental measurements of ACF film thickness to the corresponding model predictions. A schematic of the experimental setup used for film thickness measurements is shown in Fig. 3.12. It consists of a standalone ACF system and a laser displacement sensor. The ACF system includes an ultrasonic atomizer (Model VC5040AT from Sonic and Materials, Inc., CT [40]) with a frequency of 40 kHz that can generate atomized cutting fluid droplets with a median diameter of 60 µm. The fluid flow rate at the outlet of the atomizer is 5.9 mL/min. The carrier gas used is air, at a pressure of 10 psi.

Figure 3.11: Film velocity contour for a flat insert. (gas pressure = 15 psi, fluid flow rate = 15 mL/min, spray distance = 30 mm, spray angle = 30°)
The spray angle and the spray distance used are 30° and 30 mm, respectively. The impingement point is set at a distance of 14 mm from the cutting edge of the insert so that the maximum area near the cutting edge of the insert falls in the steady zone of the film where measurements can be made [24].

Figure 3.12: Schematic of the experimental setup for ACF film thickness measurement using a laser displacement sensor

The laser displacement sensor consists of a vibrating objective lens that focuses a converging beam of light on the target surface. With the vibration of the lens, the focal point of the laser changes in time. This creates a variation in the intensity of the light reflected back into the instrument and the position of the surface is located by sensing the peaks in the reflected light intensity, which is maximum when the focal point lies exactly on the surface. This instrument can also be used to detect the interface between air and a thin liquid film. Thus, the film thickness can be measured by locating the surface of the liquid film and the
solid surface on which it is formed [41].

A Keyence LT-9010M laser displacement sensor was used to obtain film thickness measurement at various points on the surface of a flat turning insert as shown in Fig. 3.13. Here, X represents the distance from the impingement point along the centerline of the tool and Y represents the perpendicular offset distance from the centerline of the insert. The model was evaluated for two different cutting fluids, i.e., 10% S-1001 and deionized (DI) water using the same ACF spray parameters used in experiments. Table 3.2 lists the physical properties of the two fluids used. During the experiments, it was observed that the film thickness value at a given measurement point on the insert surface fluctuates with time due to transient nature of the film and shear instabilities of the fluid. Therefore, film thickness measurements were conducted for a period of 30 seconds and a single time-averaged film thickness value with a standard deviation is obtained at each measurement point. Figures 3.14 and 3.15 show the film thickness contours obtained for the two fluid that are used for validation of the model.

Table 3.2: Physical properties of the liquids

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface tension</th>
<th>Viscosity</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1001</td>
<td>0.041 N/m</td>
<td>1.22 cP</td>
<td>1003 kg/m³</td>
</tr>
<tr>
<td>Water</td>
<td>0.072 N/m</td>
<td>1.01 cP</td>
<td>1000 kg/m³</td>
</tr>
</tbody>
</table>
Figures 3.16 and 3.17 show comparison of the experimental time-averaged film thickness values and model-predicted values for S-1001 and DI water, respectively. The experimental errorbars are placed at ± standard deviation. From Fig. 3.16 and 3.17, it is observed that the model predictions are accurate within one standard deviation of the experimental measurements of the time-averaged
film thickness across the surface of the insert for both the cutting fluids. The model also captures the trend of the film thickness with the distance from the impingement point fairly well for both the fluids used. The figures show that the experimental film thickness values remain almost constant with an increasing distance from the impingement point (i.e., along X) in the region where the measurement are made. A similar trend is also found in the model predictions. However, the model predicts a drop in the film thickness as the distance from impingement decreases in the region close to the impingement point where the experimental measurement could not be made due to the obstruction caused to the spray by the laser sensor. However, the low film thickness values near the impingement point were confirmed by the experiments conducted by Hoyne et al. [24]. Note
Figure 3.16: Comparison of the simulated film thickness values with measurements for S-1001

that the experimental measurement for DI water at Y=3 mm is not available as the DI water does not readily spread to the edges of the turning insert due to its high surface tension, thus, making it difficult to obtain a continuous film thickness measurement.
Figure 3.17: Comparison of the simulated film thickness values with measurements for DI Water

3.6 Chapter Summary

This chapter describes a numerical model for the ACF system to predict the film characteristics, including film thickness and film velocity, of the film formed by the ACF system. The model uses three separate sub-models, namely, the carrier gas model, the discrete phase model and the Eulerian wall film model to predict the flow of the carrier gas, the liquid droplets and the thin liquid film, respec-
tively. Validation of the numerical model is provided using experimental thin film measurements for two different fluids using a laser focus displacement sensor.

The carrier gas model involves solving the continuity and Navier-Stokes equations to predict the flow of the carrier gas by using the spray geometry and the spray parameters as inputs. The discrete phase model solves the force balance on each cutting fluid droplet in a Lagrangian reference frame to predict the trajectories of the droplets using the carrier gas flow and the droplet injection parameters as inputs. The Eulerian wall film model solves for the mass and momentum conservation of the fluid in a thin film using the impinging droplets from the DPM as the mass and momentum sources. ANSYS fluent is used to evaluate the model.

Thin film measurements are carried out using a laser focus displacement sensor to validate the model. Two cutting fluids with different physical properties are used to compared the measured film thickness values to the ones predicted by the model. It was observed that both the simulated film thickness values and the trends of film thickness across the surface of the insert are close to the measured values for both the fluids considered.
Chapter 4

Evaluation of the ACF system for grooved cutting inserts

4.1 Introduction

With advances in the cutting tool design, new tool geometries such as turning inserts with chip-breaking grooves are being employed to improve the machining performance by breaking the formed chips and reducing machining forces [29,31]. It has been shown that the surface geometry of the impinged surface affects the film formation when the ACF system is used [25,32,33]. Therefore, in order to assess the applicability and effectiveness of the ACF system with grooved turning
inserts, the ACF film formation model described in section 3 was used to study the film characteristics, i.e., film thickness and velocity with two specific geometries as shown in Fig. 4.1. The flat insert (Kennametal TPG432 K313 Grade) without any chip-breaker geometry and two grooved inserts with geometries as shown in Fig. 4.1, i.e., Kennametal TPGF432 KCU10 Grade and Interstate TPMR432 TCN55 Grade were chosen due to their recommended use by the tool manufacturer [42] for turning of high temperature alloys including titanium alloys. For each insert, the ACF parameters were varied to further understand how the film characteristics vary with the spray parameters for a given chip-breaking geometry. To study how the ACF film characteristics on different insert geometries translate to improvements in the machining performance, turning experiments were also carried out using the same insert and ACF spray parameters as used in the model. Tool flank wear was considered as the measure of machining performance and was correlated with the model predictions of film thickness and film velocity for different tools across a range of ACF spray parameters. Section 4.2 discusses the effect of cutting tool geometry and ACF spray parameters on the film formation using the model followed by Section 4.3 that describes experimental investigation of the effect of cutting tool geometry and ACF spray parameters on the machining performance.
4.2 Film Formation on grooved inserts

Figures 4.2 and 4.3 compare the model-predicted film thickness and film velocity contours, respectively, on three different tool geometries, i.e., a flat insert and two grooved inserts using same ACF spray parameters (fluid flow rate = 15 mL/min, gas pressure = 15 psi, spray distance = 30 mm and spray angle = 30°). It is seen from Fig. 4.2 that, the film thickness values near the cutting edge of the flat insert are around 5-6 µm, while for the grooved inserts, the film thickness near the cutting edge is closer to 10 µm. The elevated surface present on the grooved inserts lowers the gas pressure over the cutting edge and reduces the forces exerted on the fluid film by the carrier gas flow. As a result, the film thickness in the tool-chip contact region near the cutting edge is higher for the grooved insert compared to the flat insert. The specific chip-breaker geometry also affects the
distribution of film velocity on the insert surface as seen from Fig. 4.3. The film velocity near the cutting edge for the grooved inserts is higher in comparison to the flat insert. Clearly, the film characteristics depend strongly on the surface geometry. Therefore, it is expected that, even with the same spray parameters, the ACF system would result in a different machining performance for different cutting tool geometries.

As mentioned earlier, the ACF spray parameters also affect the film formation on the impinged surface. In order to study the effect of ACF spray parameters on the film formation for different tool geometries, simulation experiments were performed. The figure below shows the film thickness contour comparison between the flat and the grooved inserts. (gas pressure = 15 psi, fluid flow rate = 15 mL/min, spray distance = 30 mm, spray angle = 30°)

Figure 4.2: Film thickness contour comparison between the flat and the grooved inserts. (gas pressure = 15 psi, fluid flow rate = 15 mL/min, spray distance = 30 mm, spray angle = 30°)
conducted using the model for the three turning insert geometries with varying gas pressure and fluid flow rate. Since, during a machining operation, chips move along the rake face of the tool and the cutting fluid in the tool-chip contact region provides cooling and lubrications [24], it is believed that the machining performance is primarily influenced by the film characteristics in the tool-chip contact region. Hence, the area-averaged film thickness and area-averaged film velocity in the tool-chip contact region were calculated and used for comparison. The area of the tool-chip contact region considered here is the maximum area of the insert that can be in contact with the chip for a given tool-chip contact length as shown.
in Fig. 4.3. Typical tool-chip contact lengths reported for turning of titanium al-
loys range from 0.5 mm [22] to 3 mm [24] and the tool-chip contact length in
this study is assumed to be equal to the depth of cut (1 mm) used in machining
experiments. The values of the ACF spray parameters, i.e., gas pressure and
fluid flow rate are chosen from based on studies [25, 26]. Figures 4.4 - 4.18 show
the film thickness and velocity contours used for area-averaging for all the values
of the spray parameters that are considered.

From Figs. 4.4 - 4.18, it can be observed that the film thickness values are
seen to be generally lower for higher gas pressures and higher for larger fluid flow
rates. The film velocities are seen to increase with both increasing gas pressure
and increasing fluid flow rate. However, all the contours for a particular cutting
insert look similar, in terms of the location of the maximum film thickness and the
film thickness trends on the insert surface. It is seen that the flat insert and grooved
insert 2 show maximum film thicknesses at similar positions on the insert surface
but grooved insert 1 has a significantly different trend and shows maximum film
thickness near the cutting edge. This is because grooved insert 2 has a geometry
that is closer to the flat insert compared to grooved insert 1, which has an abrupt
step on its surface. It is also seen that the large film velocity appears close to
the regions of large film thickness for all three insert geometries, and all the ACF
spray parameters considered.

(a) Film thickness on the flat insert (gas pressure = 9 psi, fluid flow rate = 9 mL/min)

(b) Film velocity on the flat insert (gas pressure = 9 psi, fluid flow rate = 9 mL/min)

Figure 4.4
(a) Film thickness on the flat insert (gas pressure = 9 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on the flat insert (gas pressure = 9 psi, fluid flow rate = 15 mL/min)

Figure 4.5
(a) Film thickness on the flat insert (gas pressure = 15 psi, fluid flow rate = 9 mL/min)

(b) Film velocity on the flat insert (gas pressure = 15 psi, fluid flow rate = 9 mL/min)

Figure 4.6
(a) Film thickness on the flat insert (gas pressure = 24 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on the flat insert (gas pressure = 24 psi, fluid flow rate = 15 mL/min)

Figure 4.7
(a) Film thickness on the flat insert (gas pressure = 33 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on the flat insert (gas pressure = 33 psi, fluid flow rate = 15 mL/min)

Figure 4.8
(a) Film thickness on grooved insert 1 (gas pressure = 9 psi, fluid flow rate = 9 mL/min)

(b) Film velocity on grooved insert 1 (gas pressure = 9 psi, fluid flow rate = 9 mL/min)

Figure 4.9
(a) Film thickness on grooved insert 1 (gas pressure = 9 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on grooved insert 1 (gas pressure = 9 psi, fluid flow rate = 15 mL/min)

Figure 4.10
(a) Film thickness on grooved insert 1 (gas pressure = 15 psi, fluid flow rate = 9 mL/min)

(b) Film velocity on grooved insert 1 (gas pressure = 15 psi, fluid flow rate = 9 mL/min)

Figure 4.11
(a) Film thickness on grooved insert 1 (gas pressure = 24 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on grooved insert 1 (gas pressure = 24 psi, fluid flow rate = 15 mL/min)

Figure 4.12
(a) Film thickness on grooved insert 1 (gas pressure = 33 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on grooved insert 1 (gas pressure = 33 psi, fluid flow rate = 15 mL/min)

Figure 4.13
(a) Film thickness on grooved insert 2 (gas pressure = 9 psi, fluid flow rate = 9 mL/min)

(b) Film velocity on grooved insert 2 (gas pressure = 9 psi, fluid flow rate = 9 mL/min)

Figure 4.14
(a) Film thickness on grooved insert 2 (gas pressure = 9 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on grooved insert 2 (gas pressure = 9 psi, fluid flow rate = 15 mL/min)

Figure 4.15

114
(a) Film thickness on grooved insert 2 (gas pressure = 15 psi, fluid flow rate = 9 mL/min)

(b) Film velocity on grooved insert 2 (gas pressure = 15 psi, fluid flow rate = 9 mL/min)

Figure 4.16
(a) Film thickness on grooved insert 2 (gas pressure = 24 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on grooved insert 2 (gas pressure = 24 psi, fluid flow rate = 15 mL/min)

Figure 4.17
(a) Film thickness on grooved insert 2 (gas pressure = 33 psi, fluid flow rate = 15 mL/min)

(b) Film velocity on grooved insert 2 (gas pressure = 33 psi, fluid flow rate = 15 mL/min)

Figure 4.18
The area-averaged film thickness and area-averaged film velocity, respectively, were obtained from the respective contours (Figs. 4.4 - 4.18) using the procedure described earlier for varying gas pressure and fluid flow rate for each insert geometry, and are shown in Figs. 4.19 and 4.20. From the simulations, it is observed that the film thickness and velocity contours become steady after a flow time of \( \approx 300 \) ms. Therefore, the area-averaging for film thickness and velocity is done at a flow time of 300 ms. It can be seen from the figures that the area-averaged film thickness decreases, while the area-averaged film velocity increases with an increase in the gas pressure for all three insert geometries. At higher gas pressures, the droplets impinge on the surface with a larger momentum that results in the formation of a high velocity film, in general. At higher velocity, the mass flow rate of the liquid exiting the insert surface from the edges is also higher, resulting in a thinner film. However, for flat and grooved insert 1 it is seen that the film velocity decreases when the gas pressure is increased from 9 psi to 15 psi. Similarly, for grooved insert 2 the film velocity decreases marginally when pressure increases from 15 psi to 24 psi. One of the reasons for this observation be may be that, for the specific insert geometry, the additional film momentum due to increase in the gas pressure gets transferred to regions on the insert surface that are outside the area considered for averaging. For example, in Fig. 4.3, the
film velocity contour for grooved insert 2 shows large film velocities in regions that are not considered for area-averaging. Another reason could be due to the phenomenon of droplet splashing that counters the momentum of the impinged droplets added to the film. At higher gas pressure, the atomized cutting fluid droplet impact the surface with a higher impact energy, which increases the fraction of impinging droplets being splashed and reduces the fraction being spread to form the film [38]. With a lower fraction of impinging droplets in the spreading regime, the effective momentum that is transferred to the film is reduced resulting in the drop of area-averaged film velocity. However, as the pressure is increased further, the increase in the momentum of the droplets in the spreading regime compensates for the loss of the momentum due to splashing, thus, increasing the film velocity.

![Graphs showing model-prediction of ACF spray parameters](image)

Figure 4.19: Model-prediction of the effect of ACF spray parameters, i.e., fluid flow rate and the gas pressure on the area-averaged film thickness for various tool geometries

Figures 4.19 and 4.20 also show that with an increase in the fluid flow rate,
both the film thickness and film velocity are found to increase for all three insert geometries. This is because, at a high flow rate, there is a large mass and momentum addition to the film from the impinging droplets, resulting in the formation of thick films with large velocities. The results of area-averaged film thickness and film velocity are tabulated in Table 4.1. It is also observed from Fig. 4.19 and 4.20 that, for the same spray parameters, the area-averaged film thickness and film velocity values are different across the three different insert geometries. Changes in the groove geometry directly affect the film motion by changing the fluid flow path. As the film motion is only allowed parallel to the surface of the insert, the presence of the chip-breaking grooves alter the flow of the film from the horizontal motion on the flat insert. In addition, the gravity term also acts differently because the film velocity has components in the vertical direction as it moves along the corners present on the surface of the two grooved inserts. The
groove geometry also indirectly affect the film formation by altering the flow of the carrier gas over the cutting inserts (demonstrated by Figs. 4.21 - 4.23). The carrier gas velocity and pressure terms appear in the film momentum equation and thus affect the film characteristics.

It can be seen from Fig. 4.21 that a high pressure region is developed on the surface of the flat insert due to the slowing down of the carrier gas velocity, according to the Bernoulli principle. The highest pressure is seen close the the impingement point because the gas jet has the largest momentum at this point on the surface of the insert, which gets converted into pressure. Similar phenomena are observed for the other two insert geometries in Figs. 4.22 and 4.23. For the flat insert, the high pressure seen at the impingement point drops off monotonically near the cutting edge, however, for the grooved inserts, a second high pressure region is seen just after the chip-breaker geometry. The presence of the chip breaking groove results in a low carrier gas velocity near the cutting edge that manifests as the high pressure region. It can also be seen that the pressure value near the cutting edge is the largest for grooved insert 1, followed by grooved insert 2 and the flat insert, respectively. Conversely, the carrier gas velocity near the cutting edge is the least for grooved insert 1 and the largest for the flat insert. Hence, it is seen that grooved insert 1 shows the largest film thickness near the cutting edge,
Figure 4.21

(a) Pressure contour near the flat insert surface (gas pressure = 15 psi)

(b) Velocity contour near the flat insert surface (gas pressure = 15 psi)
(a) Pressure contour near Grooved insert 1 (gas pressure = 15 psi)

(b) Velocity contour near Grooved insert 1 (gas pressure = 15 psi)

Figure 4.22
(a) Pressure contour near Grooved insert 2 (gas pressure = 15 psi)

(b) Velocity contour near Grooved insert 2 (gas pressure = 15 psi)

Figure 4.23
followed by grooved insert 2 and then the flat insert.

As mentioned, for grooved insert 1, the area-averaged film thickness and film velocity values are larger than those for the other two inserts for almost all of the spray parameters considered and a fairly large film thickness is maintained even at high gas pressure. It is believed that the effect of large gas velocity is diminished for grooved insert 1 due to an abrupt change in the form of a sharp corner on the surface of this insert (refer to Fig. 4.22). Grooved insert 2, on the other hand, has a gradual change in the surface geometry. Therefore, it exhibits area-averaged film thickness and velocity values closer to the flat insert. As a result of higher film thickness, grooved insert 1 is also found to consistently form films with larger velocity compared to the other two inserts. A large film thickness value allows the film to have a large surface velocity due to a presence of a velocity gradient along the film thickness as demonstrated in Fig. 4.24.

4.3 Machining Performance with grooved inserts

Since the cutting tool geometry and the ACF spray parameters are seen to affect the thickness and velocity of the film formed by the ACF system, they would also influence the machining performance because the penetration of the fluid film
Figure 4.24: Velocity gradients in the liquid film

into the tool-chip contact region depends on these film characteristics. To study the effect of film characteristics on the machining performance using ACF system, tool wear measurements were carried out using turning experiments with the same insert geometries and ACF spray parameters as used to study the film formation (refer to Table 4.1). A flat insert (Kennametal TPG432 K313 Grade) without any chip-breaker geometry and two grooved inserts with a geometries as shown in Fig. 4.1, i.e., Kennametal TPGF432 KCU10 Grade and Interstate TPMR432 TCN55 Grade were used. The machining parameters were fixed for all the exper-
Table 4.1: Results of model-predicted film characteristics and experimental measurements of tool wear

<table>
<thead>
<tr>
<th>Insert type</th>
<th>Cutting condition</th>
<th>Fluid flow rate (mL/min)</th>
<th>Carrier gas pressure (psi)</th>
<th>Area-averaged film thickness (µm)</th>
<th>Area-averaged film velocity (m/s)</th>
<th>Normalized flank wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>Dry</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.00 (0.46 mm)*</td>
</tr>
<tr>
<td>Flat</td>
<td>Flood</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.73</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 9</td>
<td>9</td>
<td>9</td>
<td>4.09</td>
<td>0.063</td>
<td>0.73</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 9</td>
<td>9</td>
<td>15</td>
<td>3.15</td>
<td>0.070</td>
<td>0.73</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 15</td>
<td>9</td>
<td>9</td>
<td>7.72</td>
<td>0.110</td>
<td>0.73</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 15</td>
<td>15</td>
<td>15</td>
<td>4.10</td>
<td>0.091</td>
<td>0.58</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 15</td>
<td>15</td>
<td>24</td>
<td>3.60</td>
<td>0.117</td>
<td>0.64</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 15</td>
<td>15</td>
<td>33</td>
<td>3.40</td>
<td>0.144</td>
<td>0.63</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>Dry</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.00 (0.61 mm)*</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>Flood</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.83</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 9</td>
<td>9</td>
<td>9</td>
<td>5.44</td>
<td>0.070</td>
<td>0.81</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 9</td>
<td>9</td>
<td>15</td>
<td>4.82</td>
<td>0.092</td>
<td>0.62</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 15</td>
<td>9</td>
<td>9</td>
<td>10.56</td>
<td>0.145</td>
<td>0.69</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 15</td>
<td>15</td>
<td>15</td>
<td>6.96</td>
<td>0.118</td>
<td>0.53</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 15</td>
<td>15</td>
<td>24</td>
<td>5.33</td>
<td>0.189</td>
<td>0.40</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 15</td>
<td>15</td>
<td>33</td>
<td>5.37</td>
<td>0.208</td>
<td>0.41</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>Dry</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.00 (0.43 mm)*</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>Flood</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.75</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 9</td>
<td>9</td>
<td>9</td>
<td>5.47</td>
<td>0.076</td>
<td>0.63</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 9</td>
<td>9</td>
<td>15</td>
<td>4.26</td>
<td>0.090</td>
<td>0.67</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 15</td>
<td>9</td>
<td>9</td>
<td>7.93</td>
<td>0.099</td>
<td>0.67</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 15</td>
<td>15</td>
<td>15</td>
<td>5.79</td>
<td>0.120</td>
<td>0.67</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 15</td>
<td>15</td>
<td>24</td>
<td>3.57</td>
<td>0.110</td>
<td>0.64</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 15</td>
<td>15</td>
<td>33</td>
<td>3.33</td>
<td>0.151</td>
<td>0.58</td>
</tr>
</tbody>
</table>

*Absolute value of flank wear
imental trials and are listed in Table 4.2. Turning experiments with dry cutting conditions (no cutting fluid) and with conventional flood delivery of the cutting fluid were also conducted to obtain baseline data. A mixture of 33% CO₂ and air was used as the carrier gas for the ACF as the CO₂ is shown to provide additional cooling to the tool-chip contact region as it cools to a lower temperature when sprayed out of a pressurized tank in comparison to air [22]. A Mori Seiki Frontier L-1 CNC lathe was used for conducting the turning experiments. A machining time of 140 s (corresponding to a cutting length of 186.4 m) was chosen because a substantial difference in tool wear was observed between different cutting conditions after 140 s of machining without causing tool failure according to the ISO standard [22]. The impingement point of the ACF spray is set at a distance of 8.4 mm from the cutting edge of the insert so that the tool-chip contact region is in the steady zone of the film [24]. Figure 4.25 shows the setup used for the turning experiments.

Table 4.2: Cutting conditions

<table>
<thead>
<tr>
<th>Cutting speed</th>
<th>Feed rate</th>
<th>Depth of cut</th>
<th>Spray distance</th>
<th>Spray angle</th>
<th>Carrier gas</th>
<th>Cutting fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 m/min</td>
<td>0.2 mm/rev</td>
<td>1 mm</td>
<td>30 mm</td>
<td>30°</td>
<td>33% CO₂ + 67% air</td>
<td>10% S-1001</td>
</tr>
</tbody>
</table>

Typical flank wear on the turning inserts after dry cutting is shown in Fig. 4.26.
Using the flank wear for dry cutting with a given tool geometry as a reference, a ‘normalized flank wear’ was calculated for each experimental trial as the ratio of flank wear measured for the particular trial to the flank wear for dry cutting. The normalized flank wear can be viewed as a quantification of the improvement of a cooling condition over dry cutting for a given tool geometry and therefore, allows for the comparison of tool wear across different tool geometries. Model predictions of the area-averaged film thickness and the area-averaged film velocity value for each trial were also calculated. Table 4.1 shows the results of the film characteristics and normalized flank wear obtained from the simulations and machining experiments, respectively. The absolute value of flank wear measured after dry cutting for a given tool geometry is shown in parentheses in the Table.
Figure 4.26: Tool wear in dry cutting

A contour plot of normalized flank wear across all three tool geometries as a function of area-averaged film thickness and film velocity is shown in Fig. 4.27. A
linear interpolation scheme is used to estimate the flank wear values between the experimental data-points. From Fig. 4.27, it is observed that the normalized flank wear is dependent on both the film thickness and the film velocity. The normalized flank wear shows a minimum value at film thickness of $\approx 5.5 \ \mu m$ and is seen to increase with film thickness that is both larger and smaller than this value. The reason for this trend may be that films having a thickness larger than $\approx 5.5 \ \mu m$ do not effectively penetrate in the tool-chip contact region, while thinner films evaporate before they can provide effective cooling, resulting in film boiling [43]. With increase in the film velocity, however, the normalized flank wear is seen to decrease monotonically as the higher velocity films have a higher heat transfer coefficient that enhances the cooling at the tool-chip interface.

Note that for grooved insert 1, the film having a high velocity and a large enough thickness results in the minimum normalized flank wear for the range of spray parameters considered (refer to Table 4.1). For a flat insert, on the other hand, the film thickness reduces significantly at high pressures, which hinders further reduction in tool wear and produces a large value of normalized flank wear. The improvement shown by the ACF system over dry cutting for grooved insert 2 is not as substantial as seen for grooved insert 1 as the film velocity for grooved insert 2 is lower in general as compared to the film velocity for grooved insert 1.
The general trend of the effect of the film characteristics on the tool wear is found to be similar for all the three insert geometries considered. Note that the present model does not consider the effect of temperature of the cutting insert on the film characteristics. The high temperature of the cutting insert during a machining operation is expected to alter the film characteristics due to evaporation of the liquid in the film. However, the trends of the film thickness and film velocity with the spray parameters and chip-breaker geometries are expected to be similar.

In addition to the tool wear, the cutting forces are also measured during the turning operation for various ACF spray parameters and each of the three inserts.

Figure 4.27: Normalized tool wear as a function of area-averaged film thickness and film velocity
Table 4.3: Forces measured from turning experiments

<table>
<thead>
<tr>
<th>Insert type</th>
<th>Cutting condition</th>
<th>Fluid flow rate (mL/min)</th>
<th>Carrier gas pressure (psi)</th>
<th>Cutting force (N)</th>
<th>Feed force (N)</th>
<th>Thrust force (N)</th>
<th>Resultant force (N)</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat*</td>
<td>Dry</td>
<td>-</td>
<td>-</td>
<td>416.40</td>
<td>143.35</td>
<td>224.68</td>
<td>494.39</td>
<td>0.50</td>
</tr>
<tr>
<td>Flat</td>
<td>Flood</td>
<td>-</td>
<td>-</td>
<td>393.65</td>
<td>146.98</td>
<td>127.84</td>
<td>439.22</td>
<td>0.54</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 9</td>
<td>9</td>
<td>9</td>
<td>416.98</td>
<td>138.90</td>
<td>122.35</td>
<td>456.22</td>
<td>0.49</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 9</td>
<td>15</td>
<td>15</td>
<td>415.18</td>
<td>137.72</td>
<td>120.18</td>
<td>453.63</td>
<td>0.49</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 15</td>
<td>9</td>
<td>9</td>
<td>408.79</td>
<td>140.99</td>
<td>121.13</td>
<td>449.07</td>
<td>0.50</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 15</td>
<td>15</td>
<td>15</td>
<td>415.86</td>
<td>138.85</td>
<td>122.46</td>
<td>455.21</td>
<td>0.49</td>
</tr>
<tr>
<td>Flat</td>
<td>ACF 15</td>
<td>24</td>
<td>33</td>
<td>395.08</td>
<td>114.18</td>
<td>104.43</td>
<td>424.30</td>
<td>0.43</td>
</tr>
<tr>
<td>Grooved 1**</td>
<td>Dry</td>
<td>-</td>
<td>-</td>
<td>473.55</td>
<td>281.11</td>
<td>229.17</td>
<td>596.48</td>
<td>0.82</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>Flood</td>
<td>-</td>
<td>-</td>
<td>407.98</td>
<td>160.91</td>
<td>137.24</td>
<td>459.54</td>
<td>0.57</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 9</td>
<td>9</td>
<td>9</td>
<td>414.03</td>
<td>161.23</td>
<td>143.75</td>
<td>466.99</td>
<td>0.56</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 9</td>
<td>15</td>
<td>15</td>
<td>447.27</td>
<td>195.81</td>
<td>172.42</td>
<td>517.80</td>
<td>0.62</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 15</td>
<td>9</td>
<td>9</td>
<td>419.34</td>
<td>190.83</td>
<td>164.68</td>
<td>489.27</td>
<td>0.64</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 15</td>
<td>15</td>
<td>15</td>
<td>425.04</td>
<td>204.37</td>
<td>190.39</td>
<td>508.60</td>
<td>0.68</td>
</tr>
<tr>
<td>Grooved 1</td>
<td>ACF 15</td>
<td>24</td>
<td>33</td>
<td>456.95</td>
<td>210.59</td>
<td>190.14</td>
<td>537.87</td>
<td>0.65</td>
</tr>
<tr>
<td>Grooved 2***</td>
<td>Dry</td>
<td>-</td>
<td>-</td>
<td>485.44</td>
<td>201.22</td>
<td>173.61</td>
<td>553.43</td>
<td>0.59</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>Flood</td>
<td>-</td>
<td>-</td>
<td>507.00</td>
<td>253.46</td>
<td>228.30</td>
<td>611.08</td>
<td>0.70</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 9</td>
<td>9</td>
<td>9</td>
<td>484.71</td>
<td>230.60</td>
<td>183.61</td>
<td>567.31</td>
<td>0.67</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 9</td>
<td>15</td>
<td>15</td>
<td>485.84</td>
<td>210.21</td>
<td>178.70</td>
<td>558.71</td>
<td>0.61</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 15</td>
<td>9</td>
<td>9</td>
<td>483.52</td>
<td>209.09</td>
<td>184.80</td>
<td>558.27</td>
<td>0.61</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 15</td>
<td>15</td>
<td>15</td>
<td>458.44</td>
<td>204.87</td>
<td>182.30</td>
<td>534.20</td>
<td>0.63</td>
</tr>
<tr>
<td>Grooved 2</td>
<td>ACF 15</td>
<td>24</td>
<td>33</td>
<td>479.58</td>
<td>205.85</td>
<td>178.67</td>
<td>551.63</td>
<td>0.61</td>
</tr>
</tbody>
</table>

*TPG432 K313 grade, **TPGF432 KCU10 grade, ***TPMR432 TCN55 grade
considered. The cutting force, feed force and the thrust force (refer to Fig. 4.25) are measured using a *Kistler* dynamometer for the entire duration of the machining process. The average force values in the last 10 s of the machining process for each of the machining experiments is tabulated in Table 4.3. The cutting force and the feed force are used to calculate a friction coefficient as described in [12].

From Table 4.3, it is seen that the forces in the turning process depend on the type of insert used. However, note that the inserts considered are of different manufacturing grade, which also may influence the cutting forces. Forces for grooved insert 2 are larger than the forces for the other two inserts for every cutting condition. It can also be seen that the feed force for the flat insert is smaller than the feed force for the grooved inserts for almost all the cutting conditions. This increase in the feed force for the grooved inserts may be due to the presence of the chip-breaker grooves, which aid is breaking of the chips by application of a force along the feed direction. This chip breaking action is responsible for the additional feed force and is absent in the flat insert.

For the flat insert it is seen that the largest resultant force is exerted in the dry cutting condition. The thrust force for this condition is significantly larger than the flood cooling condition and all the ACF system runs. The reason for a
large values of the forces is that the cutting insert undergoes a large amount of wear in the dry cutting condition as compared to other cutting conditions where a cutting fluid is used. A cutting insert with a large amount of wear requires larger forces to machine the workpiece material. This is also evident for the 24 psi, 15 mL/min ACF condition, which has the lowest resultant force. From Table 4.1, this condition is also seen to have a lower amount of wear compared to the dry cutting. The lowest friction factor out of all experiments with the flat insert is also observed at this particular condition.

Similar observations are made for grooved insert 1. The maximum forces are seen at the dry cutting condition, which also corresponds to the largest amount of tool wear. The minimum value of the resultant force is seen for the 9 psi, 9 mL/min and the 15 psi, 15 mL/min ACF condition. 15 psi, 15 mL/min also shows one of the lowers of tool wear out of all the cutting conditions. Grooved insert 2 also shows a similar trend, where the minimum forces are seen for the 15 psi, 15 mL/min ACF condition. It can be seen that both flat insert and grooved insert 2 show minimum cutting forces and friction factor for the high flow rate and large gas pressure conditions. However, grooved insert 1 shows a different trend where the minimum cutting force for that insert is observed at the low pressure low flow rate condition. From Fig. 4.1, it can be seen that grooved insert 2 has a gradual
variation in the surface and has a geometry closer to the flat insert compared to
grooved insert 1, which has an abrupt step on its surface. This may be the reason
for grooved insert 1 to show different trends as compared to the other two inserts.
In general, the minimum cutting forces for all the inserts is observed for one of
the ACF conditions showing that the ACF system does aid in reducing the cutting
forces over dry and flood cooling.

4.4 Chapter summary

The model developed in Chapter 3 is used to study the effect of film character-
istics, i.e., the film thickness and velocity on the machining performance in this
chapter. Three different turning inserts are considered, each having a different
surface geometry. Area-averaged film thickness and area-averaged film velocity
are used to represent the film characteristics. For each of the three turning inserts,
it is seen that the area-averaged film thickness and the area-averaged film veloc-
ity both increase with increasing fluid flow rate. With increasing gas pressure,
the area-averaged film thickness is seen to decrease and the area-averaged film
velocity is found to increase.

The insert geometry also has an effect on the film characteristics. It is ob-
served that grooved insert 1 results in the formation of films that have large film thickness and film velocity values. Conversely, the flat insert results in the formation of the thinnest films. Grooved insert 2 forms films with thickness and velocity values that are intermediate between the flat insert and grooved insert 1. The groove geometry for groove insert 2 has a gradual change compared to grooved insert 1, which has an abrupt corner on its surface.

To evaluate the machining performance, normalized flank wear values are used. From the machining experiments, it is concluded that the tool wear for each of the three inserts is minimum for a certain film thickness value. Large film velocity values lead to reducing the tool wear. It is seen that grooved insert 1 results in the formation of films that have the film thickness in the range for minimizing wear and large film velocities and thus, result in the minimum normalized flank wear. It is also seen that the film characteristics have a similar effect on the normalized flank wear for each of the three cutting inserts.

It is seen that the cutting forces are influenced by different insert geometries. The chip breaking action for the grooved inserts results in some additional feed force being applied on the insert in comparison to the flat insert. However, note that the inserts considered are of different manufacturing grade, which also may
influence the cutting forces. It is seen that the cutting forces are maximum for the dry cutting condition due to the faster rate of wear seen in dry cutting. In general, the minimum cutting forces for all the inserts is observed for one of the ACF conditions showing that the ACF system does aid in reducing the cutting forces over dry and flood cooling.
Chapter 5

Effect of cutting fluid

It is well established that the type of cutting fluid is an important consideration that can maximize the performance for titanium machining. For the ACF system, the characteristics of the formed film control the penetration of the cutting fluid into the tool-chip contact region. Physical properties of the cutting fluid are particularly important in an ACF system as they too affect the film characteristics along with tool geometry and ACF parameters and therefore, can be used to improve machining performance. Use of a variety of cutting fluids in ACF systems has been investigated experimentally for micro-milling [36] and turning [35] applications. However, the quantitative understanding of the effect of specific fluid properties such as density, viscosity and surface tension etc. on the thickness and
velocity of the film formed by the ACF system is missing. Therefore, the model developed in this work is used to study the effect of physical properties of cutting fluid on the film formation. The physical properties of the cutting fluid such as density and viscosity affect the forces on each droplet through the drag force (refer Eq. 3.3) and hence, the trajectories of the fluid droplets could be different for cutting fluids with different physical properties. The properties of the cutting fluid also affect the droplet impingement dynamics, including the tendency to spread or splash [38], in the numerical model. In addition, these properties also appear in the film momentum conservation equation (Eq. 3.6) and hence, directly affect the film formation.

5.1 Effect of surface tension and viscosity on the film characteristics

The specific fluids used in this work are listed in Table 5.1 along with their properties, i.e. surface tension and viscosity. Five of these fluids have been previously used by Ganguli et al. [25] and Ghai et al. [36]. As shown in Chapter 4, the trends of film characteristics with respect to the ACF spray parameters as well as the trend of normalized flank wear with respect to the film characteristics remain sim-
ilar across the specific tool geometries considered in the study. It is, therefore, assumed that the trends of the film characteristics with respect to the surface tension and viscosity of the cutting fluid would be similar across tool geometries too. Hence, only the flat insert geometry is considered for the simulation experiments with varying cutting fluid properties. For all the simulation trials, the gas pressure and the fluid flow rate are fixed at 15 psi and 15 mL/min, respectively. The spray impingement point is set at a distance of 8.4 mm from the cutting edge of the insert as discussed in Chapter 4.

To evaluate the effect of viscosity on the film thickness and velocity contours, two particular fluids are considered, namely, 10% S-1001 and 25% Castrol Clearedge 6519. From Table 5.1, it can be seen that both these fluids have approximately similar values of surface tension at about 0.041 N/m but have different viscosities of 1.22 cP and 2.91 cP, respectively. From Fig. 5.1, it can be seen that the film thickness values for 25% Castrol Clearedge are generally larger than those for S-1001. This is because of its large value of viscosity, which opposes the spreading of the film over the insert surface. Hence, the film does not flow to the same extent resulting in a large film thickness values. To study the effect of viscosity on the film velocity, the film velocity contours for these two fluids are shown in Fig. 5.2. It is observed that due the large viscosity of 25% Castrol
Clearedge, the film velocities for this fluid are lower close to the cutting edge of insert. The large viscosity hinders the motion of the fluid in the film, resulting in a smaller film velocity. There does exist a small local region of large velocity for Castrol Clearedge, which is seen due to the transient nature of the simulations that show such fluctuations in velocity. However, the area-averaged film velocity near the cutting edge is much lower for Castrol Clearedge as compared to S-1001.

To study the effect of surface tension on the film characteristics, the film thickness and film velocity contours are plotted for 0.01% Neodol-6 and DI Water, and are shown in Figs. 5.3 and 5.4, respectively. These two fluids have a similar viscosity of 1.01 cP but different surface tensions of 0.033 N/m and 0.072 N/m, respectively. From Fig. 5.3, it can be seen that the film thickness for DI Water is higher than Neodol over the complete range of the insert surface. This is due to its large surface tension, which hinders the formation of films. Large surface tension decreases the tendency of spreading of the liquid as this results in an increase in the surface area of the fluid. Hence, DI water does not spread as much as Neodol-6 and forms thicker films. To study the effect of surface tension on the film velocity, film velocity contours for these two fluids are shown in Fig. 5.4. It is seen that larger surface tension results in larger film velocities. This happens because both fluids have a similar viscosity and hence, similar velocity gradients are expected to
Figure 5.1: Film thickness contours for (a) 10% S-1001 and (b) 25% Castrol Clearedge 6519
Figure 5.2: Film velocity contours for (a) 10\% S-1001 and (b) 25\% Castrol Clearedge 6519
Figure 5.3: Film thickness contours for (a) 0.01% Neodol-6 and (b) DI Water
Figure 5.4: Film velocity contours for (a) 0.01% Neodol-6 and (b) DI Water
be present across the film thickness at identical ACF spray parameters. However, DI water films are thicker and hence reach a larger velocity values at the surface for the same velocity gradients. This effect was also illustrated previously in Fig. 4.24.

Table 5.1: Physical properties of fluids

<table>
<thead>
<tr>
<th>Surface tension (N/m)</th>
<th>Viscosity (cP)</th>
<th>Fluid</th>
<th>Area-averaged film thickness (µm)</th>
<th>Area averaged film velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.033</td>
<td>1.03</td>
<td>0.01% Neodol-6</td>
<td>3.94</td>
<td>0.102</td>
</tr>
<tr>
<td>0.033</td>
<td>1.22</td>
<td>-</td>
<td>4.29</td>
<td>0.094</td>
</tr>
<tr>
<td>0.033</td>
<td>2.91</td>
<td>-</td>
<td>5.59</td>
<td>0.052</td>
</tr>
<tr>
<td>0.043</td>
<td>1.07</td>
<td>2% Pluronic L-64</td>
<td>3.80</td>
<td>0.095</td>
</tr>
<tr>
<td>0.041</td>
<td>1.22</td>
<td>10% S-1001</td>
<td>4.10</td>
<td>0.090</td>
</tr>
<tr>
<td>0.042</td>
<td>2.91</td>
<td>25% Castrol Clearedge 6519</td>
<td>7.25</td>
<td>0.063</td>
</tr>
<tr>
<td>0.072</td>
<td>1.01</td>
<td>DI Water</td>
<td>5.33</td>
<td>0.117</td>
</tr>
<tr>
<td>0.072</td>
<td>1.22</td>
<td>-</td>
<td>5.85</td>
<td>0.110</td>
</tr>
<tr>
<td>0.072</td>
<td>2.91</td>
<td>-</td>
<td>10.5</td>
<td>0.090</td>
</tr>
</tbody>
</table>

5.2 Regression model

To study the interaction effects between the surface tension and the viscosity of the cutting fluids, a regression modeling approach has been used. Simulations are conducted using all the fluids listed in Table 5.1. Three levels each of surface tension and viscosity are chosen and a total of nine tests are conducted. For all the
simulation trials, the gas pressure and the fluid flow rate are fixed at 15 psi and 15 mL/min, respectively. The spray impingement point is set at a distance of 8.4 mm from the cutting edge of the insert. For each simulation trial, an area-averaged film thickness and an area-averaged film velocity are calculated and are used to fit a regression model with surface tension and viscosity as the independent variables.

\[
\bar{f} = a_0 + a_1 \gamma + a_2 \mu + a_3 \gamma^2 + a_4 \gamma \mu + a_5 \mu^2 + \epsilon. \tag{5.1}
\]

In Eq. 5.1, \( \bar{f} \) is the area-averaged film thickness or area-averaged film velocity, \( \gamma \) is the surface tension of the liquid, \( \mu \) is the viscosity of the liquid and \( \epsilon \) is the error due to higher order terms. The constants \( a_0 - a_5 \) are determined using the film thickness/film velocity values from simulation trials. The area-averaged film thickness and area-averaged film velocity values are also listed in Table 5.1 and the values of the constants obtained by fitting the regression model are tabulated in Table 5.2.
Table 5.2: Constant values calculated from the regression model

<table>
<thead>
<tr>
<th>Constant</th>
<th>Values of the constants for film thickness</th>
<th>Values of the constants for film velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>4.4501</td>
<td>0.1912</td>
</tr>
<tr>
<td>$a_1$</td>
<td>-81.5154</td>
<td>-1.5909</td>
</tr>
<tr>
<td>$a_2$</td>
<td>-0.1173</td>
<td>-0.0742</td>
</tr>
<tr>
<td>$a_3$</td>
<td>43.7129</td>
<td>0.2813</td>
</tr>
<tr>
<td>$a_4$</td>
<td>704.0287</td>
<td>16.1537</td>
</tr>
<tr>
<td>$a_5$</td>
<td>-0.0536</td>
<td>0.0104</td>
</tr>
</tbody>
</table>

5.3 Effect of fluid properties on film formation

Figure 5.5 shows the contours of area-averaged film thickness and area-averaged film velocity given by the regression model as a function of surface tension and viscosity. It can be seen from the Figure 5.5a that the area-averaged film thickness in the tool-chip contact region increases with both surface tension and viscosity. A large value of viscosity hinders the flow of the liquid film along the insert surface resulting in less spreading and higher film thickness. Similarly, an increase in the surface tension of a cutting fluid reduces its tendency to spread on a solid surface and therefore, results in a thicker film. In general, thinner liquid films are expected to penetrate more effectively into the narrow tool-chip interface and provide effective cooling [25] during machining, thereby, resulting in reduced tool wear. However, as mentioned earlier, below a certain film thickness the cutting fluid
also has a risk of evaporating even before reaching the tool-chip interface. Hence, a certain film thickness is required in the tool-chip contact area to maximize the effectiveness of the ACF system.

Figure 5.5: (a) Film thickness and (b) film velocity as a function of fluid properties
The area-averaged film velocity decreases with an increase in the viscosity of the cutting fluid, while increases with an increase in the surface tension as seen from Fig. 5.5b. It is seen that the effect of increasing surface tension on the film velocity is more prominent at higher viscosity because at higher viscosity, the low film velocity and low velocity gradients reduce the magnitude of the inertial and the viscous terms in the film momentum equation. This results in an increase in the relative magnitude of the terms containing surface tension. From Fig. 4.27, it is seen that large film velocities would result in low tool wear. Thus, the film formation model can be used to select a combination of these fluid properties that can result in a film formation with appropriate thickness and high velocity for the given spray parameters to improve the machining performance. Note that the chemical composition of the cutting fluid could also play a role in the cooling and lubrication during machining, which is not considered in this study.

5.4 Machining results

Section 5.3 presents the effect of the physical properties of a cutting fluid on the characteristics of the formed film. However, it is important to investigate if these changes in the film characteristics translate into improving the machining per-
formance. Therefore, machining experiments are conducted using four different fluids as the cutting fluid using the ACF system. Physical properties including surface tension and viscosity are measured for each fluid by measuring the capillary rise between two parallel glass plates and a DHR-3 rheometer, respectively. The setup for surface tension measurement is shown in Figure 5.6. Two glass slides are clamped close to each other with a uniform distance between them. As the glass slides are brought in contact with the fluid in the reservoir, the fluid rises into the gap due to the capillary effect. The height to which the fluid rises is measured and compared to the height to which distilled water rises. A surface tension value is calculated for each of the fluids assuming negligible differences in contact angles for each. The physical properties of the cutting fluids used in this study are listed in Table 5.3. The area-averaged film thickness and velocity values calculated using the regression model described in Section 5.2 are also tabulated in Table 5.3. A description of the four fluids used in this study is given below.

1. **10% S-1001**: S-1001 is a semi-synthetic water soluble cutting fluid that is recommended by the manufacturer for use in cutting and grinding processes for aerospace and biomedical materials, including titanium. Numerous previous studies on the ACF system have employed this particular cutting fluid [22, 25, 26, 35] and have found it to be effective in improving
Table 5.3: Physical properties of the cutting fluids

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface Tension (N/m)</th>
<th>Viscosity (cP)</th>
<th>Area-averaged film thickness calculated using the regression model (µm)</th>
<th>Area-averaged film velocity calculated using the regression model (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% S-787</td>
<td>0.045</td>
<td>1.21</td>
<td>4.36</td>
<td>0.093</td>
</tr>
<tr>
<td>10% S-500CF</td>
<td>0.051</td>
<td>1.04</td>
<td>4.26</td>
<td>0.101</td>
</tr>
<tr>
<td>10% S-1001</td>
<td>0.041</td>
<td>1.22</td>
<td>4.25</td>
<td>0.092</td>
</tr>
<tr>
<td>DI Water</td>
<td>0.072</td>
<td>1.01</td>
<td>5.23</td>
<td>0.116</td>
</tr>
</tbody>
</table>

Figure 5.6: Surface tension measurement using two glass plates

machining performance. This fluid is used in evaluating the machining performance of grooved inserts as discussed in Section 4.3 and can be viewed as a benchmark to compare the machining performances of other fluids. This cutting fluid has low surface tension and comparatively high viscosity, which is found to provide good lubricity [36]. However, from Figure 5.5, this fluid is expected to form film with thickness slightly lower than the
value that was seen to provide minimum wear in Chapter 4 ($\approx 5.5\mu m$) but with low velocity.

2. **10% S-787**: S-787 is a chlorine-free vegetable based semi-synthetic coolant. S-787 is recommended for high-pressure applications with exotic aerospace and medical alloys. S-787 also has a low surface tension and high viscosity, similar to that of S-1001 and hence, is expected to form films having low velocity and thickness that is lower than $\approx 5.5\mu m$.

3. **10% S-500CF**: S-500CF is an emulsifiable oil that is not soluble in water. It is recommended for the general machining of all metals. This fluid has a moderate surface tension value and a very low viscosity value. From Figure 5.5, this fluid is expected to form a film with thickness very close to $\approx 5.5\mu m$ and having large velocity. These film characteristics are expected to provide low wear from Section 4.3. However, it is possible that the composition of each of the cutting fluid could play an important role in the machining performance.

4. **Deionized water**: Deionized water is also used as a cutting fluid to investigate the importance of the chemical composition of a cutting fluid. DI water has a large surface tension and a low viscosity and is expected to form films
with both desirable thickness and large velocity values. However, DI water does not contain any additional chemicals that provide lubrication during the machining process as compared to the other three fluids used in this study. Hence, using the results of this study, it would be possible to gauge the importance of the chemical composition of the fluids in comparison to the characteristics of the formed film using the ACF system.

Turning experiments are conducted using the ACF systems with each of the fluids mentioned previously for a machining time of 140 s. A turning test with a dry cutting condition is done to benchmark the tool wear value. A flat insert Kenametal K313 TPG432 is used in the turning experiments. The cutting conditions are the same as those listed in Table 4.2. The ACF spray parameters are held constant at values of 15 psi and 15 mL/min for the carrier gas pressure and the fluid flow rate, respectively. In each of the experiments, the cutting forces are measured using a Kistler dynamometer. The flank wear of each turning insert is measured after the turning experiment is completed and are used to calculate the normalized flank wear. A friction coefficient is calculated using the procedure used in [12]. The results from the turning experiments are listed in Table 5.4.

From Table 5.4, it can be seen that even though DI water has the largest sur-
Table 5.4: Results of turning experiments with different cutting fluids

<table>
<thead>
<tr>
<th>Cutting Fluid Used</th>
<th>Cutting Force (N)</th>
<th>Feed Force (N)</th>
<th>Thrust Force (N)</th>
<th>Resultant Force (N)</th>
<th>Friction coefficient</th>
<th>Normalized Flank Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>423.72</td>
<td>140.93</td>
<td>123.11</td>
<td>463.20</td>
<td>0.87</td>
<td>1.00 (0.21 mm)*</td>
</tr>
<tr>
<td>10% S-787</td>
<td>397.13</td>
<td>121.48</td>
<td>114.15</td>
<td>430.70</td>
<td>0.76</td>
<td>0.58</td>
</tr>
<tr>
<td>10% S-500CF</td>
<td>392.77</td>
<td>116.86</td>
<td>115.95</td>
<td>425.87</td>
<td>0.73</td>
<td>0.69</td>
</tr>
<tr>
<td>10% S-1001</td>
<td>408.41</td>
<td>132.66</td>
<td>117.28</td>
<td>445.15</td>
<td>0.84</td>
<td>0.69</td>
</tr>
<tr>
<td>DI Water</td>
<td>397.60</td>
<td>129.85</td>
<td>122.83</td>
<td>435.93</td>
<td>0.84</td>
<td>0.73</td>
</tr>
</tbody>
</table>

*Absolute value of flank wear

Face tension and lowest viscosity and from the previous analysis, it should form a film with thickness close to the value that was seen to minimize the wear in Chapter 4 and large film velocity, it does not result in the lowest tool wear. Clearly, the composition and the chemical properties of a cutting fluid are important for minimizing tool wear. Of the other three cutting fluids, S-500CF has the lowest viscosity and forms high velocity films. However, it also does not provide the best machining performance. S-787 gives a better performance than S-1001, but it is not clear if that is attributed to having a larger surface tension or a better composition. Both these fluids are recommended for cutting of aerospace and medical alloys such as titanium. This may suggest that in spite of better penetration by the DI water film, the lubrication effect provided by it is not as significant as the lubrication effect shown by S-787 film even with a lower extent of penetration. Hence, the chemical composition of the cutting fluid is the dominant factor in improving...
machining performance compared to the physical properties of the cutting fluid. It is more appropriate to use the present model to select spray parameters for a particular insert geometry for a particular cutting fluid. This also suggests that the analysis provided in Chapter 4 only applies to the cutting fluid used in that analysis and can not be extended to other fluids without considering the effect of the composition of the cutting fluid.

Tables 5.4 also shows that the cutting forces and the friction coefficient are maximum for the dry cutting operation as expected. These parameters also have a large value for DI water, which confirms the fact that the lubrication effect provided by the cutting fluid is strongly governed by the chemical composition of the fluid in comparison the the film characteristics. S-500CF and S-787 show lower values of the forces and friction coefficient involved in the machining process. S-1001 and DI water show a similar friction factor, which may be explained by a large cooling effect provided by DI water. In general, a low value of the friction coefficient does correspond to a lower value of tool wear as the friction forces responsible for the tool wear are lower.
5.5 Chapter summary

In this chapter, the model developed in Chapter 3 is used to study the effect of cutting fluids with varying physical properties on the characteristics of the film formed by the ACF system. The effect of surface tension and viscosity of a fluid on the area-averaged film thickness and the area-averaged film velocity is studied. Three levels of each of these parameters are considered and simulations are conducted to calculate an area-averaged film thickness and velocity value for each case. A total of nine values of each film thickness and velocity are used to fit a regression model through the predicted data with the surface tension and the viscosity of the fluid as the independent parameters.

Using the regression model, it is seen that the area-averaged film thickness increases with both increasing surface tension and increasing viscosity. A large value of viscosity hinders the flow of the liquid film along the insert surface resulting in less spreading and higher film thickness. Similarly, an increase in the surface tension of a cutting fluid reduces its tendency to spread on a solid surface and therefore, results in a thicker film. The area-averaged film velocity is found to be maximum for a fluid with large surface tension and low viscosity. A large viscosity hinders the flow of the liquid film, resulting in a low velocity. A film with
a particular film thickness value and high velocity is expected penetrate into the tool-chip contact region, however, note that the chemical composition of the cutting fluid could also play a role in the cooling and lubrication during machining, which is not considered in this study.

To investigate if the changes in the film characteristics for different cutting fluids translate into improving the machining performance, turning experiments are conducted using a total of four different cutting fluids. The surface tension and the viscosity for each of these fluids are also measured. It is seen that the fluid (DI water) that is expected to form films with the desirable characteristics (i.e. optimum thickness and high velocity) does not result in the best machining performance compared to other fluids, which form films that do not have the most desirable film characteristics. This suggests that, even though a cutting fluid film may penetrate effectively into the cutting zone, it must have a chemical composition that provides effective lubrication to improve the machining performance.
Chapter 6

Conclusions and future work

6.1 Summary

This thesis investigates the effects of ACF spray parameters, insert geometry and cutting fluid properties on the characteristics of the formed film and its influence on the machining performance during the turning of titanium alloy.

This research is carried out in three phases. In the first phase, focus is given to develop a physics-based numerical model to predict the film formation in an ACF system. The numerical model consists of three sub-models that each predict the carrier gas flow, droplet trajectories and the film formation, respectively. The carrier gas model uses mass and momentum conservation to predict the carrier gas
velocity profile. The discrete phase model is used to calculate droplet trajectories using a force balance on each droplet in an Lagrangian frame of reference. The Eulerian wall film model uses mass and momentum conservation for the film to predict film thickness and velocity. It uses the droplet impingements on the insert surface as mass and momentum sources. The model is an improvement to previous modeling efforts [24, 36] as it takes important parameters such as nozzle geometry, insert geometry, cutting fluid loss and droplet injection parameters into consideration. Appropriate assumptions including small volume fraction of cutting fluid droplets and small thickness of the film are made. A test bed was constructed to measure film thickness using a laser displacement sensor for the purpose of validating the model. The model was validated for two different cutting fluids.

In the second phase, the numerical model was used to predict the film formation on the surface of turning inserts with two types of chip breaking grooves (TPGF432 and TPMR432) as well as a conventional flat insert. The effect of ACF spray parameters including gas pressure and fluid flow rate on the film thickness and film velocity was studied. Area-averaged film thickness and area-averaged film velocity were determined to be the appropriate characteristics for studying the influence of the film formation on the machining performance. The effect of
the ACF spray parameters on the area-averaged parameters was studied of each of the three insert geometries. Turning experiments were conducted to determine the values of the film thickness and film velocity that would minimize tool wear. A normalized flank wear after 140 s of machining was calculated and used to compare machining performance across different cutting insert geometries.

In the third phase, focus was given to investigate the effect of using different cutting fluids on the film formation and the machining performance. To this effect, simulations were conducted using three levels of surface tension and viscosity of the cutting fluid. Nine values each of area-averaged film thickness and velocity were obtained and used to fit a regression model to predict the film thickness and velocity with surface tension and viscosity as the independent variables. To investigate the effect of using cutting fluids with different physical properties on the machining performance, machining experiments were conducted using four different cutting fluids. Surface tension and viscosity for each fluid was also measured. Normalized flank wear was used to compare the machining performance for the ACF system using each of the four fluids. Specific conclusions from this study are detailed in Section 6.2.
6.2 Conclusions

6.2.1 Film formation modeling and validation

1. The film thickness values predicted by the numerical model developed in this thesis are within one standard deviation of the measured film thickness values for both DI water and 10% S-1001. Large fluctuations are seen in the film thickness with time, and hence, a time-averaged value is reported from measurements conducted over 30 s.

2. For 10% S-1001, it is seen that the film thickness has a low value (≈3-5 μm) close to the impingement point and rises to a uniform value of about 10 μm for a distance of 5-10 mm from the impingement point along the centerline of the insert. The film thickness is observed to drop sharply close to the edge of the insert. For 1-3 mm of perpendicular offset distances (Y), similar trends are seen but with a lower film thickness value. The drops in film thickness near the edge are more gradual for larger values of Y.

3. DI water also shows similar trends as S-1001, but with a larger film thickness value due to its large surface tension and lower tendency to spread. It also does not spread easily to the edges of the insert, and hence, no mea-
surement was possible for Y=3mm.

6.2.2 Film formation on grooved inserts

1. For each of the three turning inserts geometries studied, the area-averaged film thickness and the area-averaged film velocity both increase with increasing fluid flow rate. With increasing gas pressure, the area-averaged film thickness is seen to decrease and the area-averaged film velocity is found to increase.

2. Grooved insert 1 results in the formation of films that have large film thickness and film velocity values, followed by grooved insert 2, and then by the flat insert, which forms films with the least thickness and velocities. This is because the groove geometry for groove insert 2 has a gradual change compared to grooved insert 1, which has an abrupt corner on its surface.

6.2.3 Machining performance on grooved inserts

1. The normalized flank wear shows a minimum value at film thickness of \( \approx 5.5 \, \mu m \) and is seen to increase with film thickness that is both larger and smaller than this value. The reason for this trend may be that films having
a thickness larger than $\approx 5.5 \mu m$ do not effectively penetrate in the tool-chip contact region, while thinner films evaporate before they can provide effective cooling, resulting in film boiling.

2. With increase in the film velocity, the normalized flank wear is seen to decrease monotonically as the higher velocity films have a higher heat transfer coefficient that enhances the cooling at the tool-chip interface.

3. Grooved insert 1 shows the minimum normalized flank wear because using grooved insert 1 results in the formation of films that have the film thickness in the desirable range and large film velocities.

4. The forces in the turning process depend on the type of insert used. Forces for grooved insert 2 are larger than the forces for the other two inserts for every cutting condition. However, note that the inserts used are of different manufacturing grades, which may also affect the forces.

5. For the flat insert and grooved insert 1, the dry cutting condition is seen to have the largest cutting forces at the end of 140 s of machining. As the forces reported are at the end of the machining process, the inserts have already gone under considerable wear in the dry cutting run, leading to large cutting forces. For all the inserts, the minimum value of the resultant force
is seen for cutting with the ACF system.

6.2.4 Effect of cutting fluid properties

1. The area-averaged film thickness increases with both increasing surface tension and increasing viscosity. A large value of viscosity hinders the flow of the liquid film along the insert surface resulting in less spreading and higher film thickness. Similarly, an increase in the surface tension of a cutting fluid reduces its tendency to spread on a solid surface and therefore, results in a thicker film.

2. The area-averaged film velocity is found to be maximum for a fluid with large surface tension and low viscosity. A large viscosity hinders the flow of the liquid film, resulting in a low velocity.

3. The fluid (DI water) that is expected to form films with the desirable characteristics (i.e. optimum thickness and high velocity) does not result in the best machining performance compared to other fluids, which form films that do not have the most desirable film characteristics.

4. Even though a cutting fluid film may penetrate effectively into the cutting zone, it must have a chemical composition that provides effective lubrica-
tion in order to improve the machining performance.

6.3 Recommendations for future work

Below are suggestions for extending this research to better understand and evaluate the performance of the ACF system for the turning of titanium using grooved tools

1. The model developed in this study is a cold wall model that does not consider the effect of temperature changes. The model can be improved by incorporating the energy equation into it and taking the evaporation of the liquid film into consideration. This would lead to a better understanding of the penetration effect of the fluid film.

2. The present model assumes that the fluid film does not have enough inertia to separate into droplets at the sharp corners on the surface of the grooved inserts. However, this may not be true for some ACF spray conditions, particularly at large carrier gas pressure. A critical Weber number can be defined at these sharp edges, above which the film can start separating into droplets [38] instead of flowing along the insert surface as a continuous
film. This addition would help in a better prediction of the film thickness on grooved inserts.

3. The model should be extended to account for micro level surface properties including surface roughness as it also affects the film formation and droplet impingement dynamics. An empirical modification to the surface tension of the liquid as a function of the surface roughness could be used. Film thickness measurements and machining experiments can be used to investigate the effect of surface finish on the film formation and the machining performance.

4. The film thickness measurements conducted in this research using the laser displacement sensor show a large value of standard deviation. In addition, the entire extent of the insert surface is not covered because the operating range of the sensor used was very low, resulting in it causing a hindrance to the ACF spray. To avoid these problems, a better model for such a sensor can be used with a better resolution and a larger operating distance, which would give more accurate measurements of film thickness.

5. Efforts can be made to measure the film velocity for the films formed by the ACF system through optical measurements. This would provide a better
validation of the present model and also help to determine the relationship between the film velocity and the penetration shown by the cutting fluid film into the tool-chip contact region.

6. This research focuses only on grooved inserts with a relatively simple 2-dimensional chip breaker geometry. A similar study on more complex groove geometries can help in further improving the effectiveness of the ACF system. Focus would have to be on reducing the computational time as such geometries result in a large number of elements in the computational mesh.

7. Cutting temperatures for the grooved cutting inserts can be measured to study the cooling effect of the ACF system on such inserts. Grooved insert geometries pose a difficulty in measuring temperature as the holes in the insert, which are used for inserting the thermocouples [26], were found to weaken the insert to an extent where it would fail catastrophically during the machining process. A better method to insert the thermocouples needs to be developed that does not disturb the groove geometry on the rake face of the cutting insert.

8. The film formation model can be extended to predict the film formation during the end milling of titanium alloys. An end mill geometry can be
incorporated into the computational domain and the sliding mesh option in ANSYS fluent can be used to predict the effect of the rotation of the end mill on the film formation. Corresponding milling experiments would help in establishing the relationship between the film characteristics and machining performance for end milling.

9. Turning experiments can be conducted using more cutting fluids to investigate if there exists an optimum value for the surface tension and the viscosity of the cutting fluid that would maximize the machining performance. Low viscosity fluids form fast moving films with a better penetration, but conversely, higher viscosity has been shown to provide a better lubrication effect [36]. Fluids with similar compositions can be used to study the effect of these physical properties.
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