ABSTRACT

LOWRIE, JAMES BALLANFONTE. Integration of Metal Forming Process and Real Time Lubricant Formulation Utilizing Hydrodynamic Cavitation. (Under the direction of Dr. Gracious Ngaile.)

A more robust and cost efficient metal forming manufacturing process chain could be realized if inefficiencies due to the separation between the metal forming plants and the lubricant formulators could be reduced or eliminated. This can be accomplished by combining the fields of metal working lubricant formulation and sonochemistry to achieve real time formulation of the lubricant at the point of use via cavitation. In addition to reducing the number of steps in the process chain, this type of real time formulation would allow for the creation of entirely new lubricants, potentially, with superior characteristics. Furthermore, this strategy can result in process enhancements, such as imparting cost effective surface texturing on the workpiece or improving mixing and dispersion of the lubricant. A mathematical model has been derived that shows how this type of cavitation may be produced at the workpiece surface during a hydrodynamic drawing process. Additionally, equipment has been developed so that the chemical and physical effects of hydrodynamic cavitation on the lubricant can be determined for various cavitation conditions. This device was used to test the dispersive and particle break up effects of hydrodynamic cavitation on water and canola oil with suspended nano and micro particles. The results of these tests were evaluated using SEM, ring compression tests, and ball penetration tests and were compared to the traditional method of formulating these lubricants (i.e. ultrasonic irradiation). It was found that cavitation that was produced by hydrodynamic cavitation in the developed equipment could be an effective substitute for ultrasonic cavitation produced in an ultrasonic bath, while at the same time being a much more cost effective means of producing nano-lubricants on the industrial scale.
Integration of Metal Forming Process and Real Time Lubricant Formulation Utilizing Hydrodynamic Cavitation

by
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DEDICATION

To my parents, Bruce and Sara, for all of the support and guidance. Your encouragement and dedication have been instrumental in all my achievements.
BIOGRAPHY

James Lowrie is a North Carolina native and grew up in a rural area outside of Winston-Salem where he began to love learning about math, science, and the natural world. He graduated from the mechanical engineering program at North Carolina State University (NCSU) in December 2012 and joined the Advanced Metal Forming and Tribology Laboratory at NCSU in January of the following year. Here he learned about the analytical, numerical, and experimental techniques used to investigate metal forming processes such as forging, extrusion, and hydroforming. James has had the opportunity to give talks at several international conferences, including the Japan Society for Technology of Plasticity’s (JSTP) International Seminar on Precision Forging, the International Conference on Micro Manufacturing (ICOMM), the North American Manufacturing Research Conference (NAMRC), and the Manufacturing Science and Engineering Conference (MSEC). Additionally, he has published six full-length articles in journals including the Journal of Manufacturing Processes, the Journal of Engineering Manufacture, and the Journal of Micro and Nano Manufacturing. James is also an author of a chapter in the ASM handbook dedicated to the metal forming technique known as drawing. James is committed to advancing the science of manufacturing to raise standards of living and protect the integrity of the natural world.
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CHAPTER 1
INTRODUCTION, MOTIVATION, AND OBJECTIVES

1.1 Background and Motivation

Lubrication is a critical part of the metal forming process. It extends the life of tools, reduces the cost in energy, and helps ensure proper material flow. There are numerous types of lubricants available to the metal forming industry, but in most cases they are supplied by outside lubrication formulation companies. These companies buy the raw ingredients and mix them in house for sale to the metal formers. This requires them to ensure that the shelf life of their products is sufficient to allow the lubricant to be formulated, shipped, and stored in preparation for being in service. This increases the cost of the lubricant and may require the lubricant formulator to add chemicals that may harm the lubricating properties of the product in favor of anti-microbial properties or long-term emulsion stability. In also prevents the lubricant formulator from taking advantage of beneficial, but short lived chemical species to improve the performance of their product. These compromises could be avoided if the lubricant was formulated in real time, at the point of use.

The research that will be the subject of the dissertation will investigate strategies for utilizing hydrodynamic cavitation to alter the lubricant and workpiece surface chemically and physically at the point of use. Numerous studies from the field of sonochemistry have shown that cavitation allows chemical reactions to take place under relatively mild conditions compared to conventional processing techniques. Additionally, cavitation is known to create powerful micro-jets that can break up suspended solids and modify the surfaces of larger materials. The dissertation will utilize analytical, numerical, and experimental analyses to investigate the possibility of applying hydrodynamic cavitation to a metal forming process to formulate the lubricant in real time and improve the tribological conditions at the die workpiece interface.

1.2 Objectives

The main goal of this research is to improve the lubrication characteristics of metal forming processes by investigating the potential to use hydrodynamic cavitation to
processes the lubricant and workpiece surface in real time. This is done by investigating relevant technologies, applying analytical and numerical models to the analysis of lubrication in the metal forming process, and experimenting to improve the current understanding of the techniques which are likely to be beneficial in the pursuit of this endeavor. As such, the specific objectives of the study are as follows:

1. Identify useful technologies that could be adapted to serve the goal of the project and determine how they could be applied to improve lubricant performance.
2. Develop an analytical model that describes hydrodynamic lubrication in a drawing process, especially in regards to a specialized die set that appears to produce cavitation under certain conditions.
3. Develop flexible equipment to test effects of hydrodynamic cavitation on a lubricant independently from the plastic deformation of the workpiece in the drawing process.
   a. Determine conditions that cause cavitation in a lubricant.
   b. Determine useful operations that can be performed on the lubricant using hydrodynamic cavitation.
4. Draw conclusions about the feasibility of applying this process to mass production scales and other operations.

1.3 Organization

The dissertation is divided into seven parts including the first chapter, which serves as a quick introduction into the motivation and objectives of the study. Chapter 2 covers a literature review that is undertaken in order to determine the state of the art in the fields of metal forming lubrication, sonochemistry, and the mathematical models that describe both phenomena. Chapter 3 uses the information presented in Chapter 2 to posit several opportunities in which cavitation and sonochemistry may be used to benefit the tribological performance of metal forming operations. Chapter 4 describes an analytical model whose goal is to provide a more in depth view of how cavitation may be created in a metal forming process. The analytical model describes the hydrodynamic lubrication film that is created by a hydrostatic drawing die and can account for a variety of workpiece properties, lubricant properties, inlet conditions, die geometries, and thermal boundary conditions. As an output the model provides the pressure, temperature, and thickness of the lubricant film at any point in the die, which can be
combined with the Rayleigh – Plesset equation to determine cavitation conditions that arise in the die. Chapter 5 describes the development device designed to create hydrodynamic cavitation so that the ideas proposed in the third chapter can be examined. The development of the device is carried out, and numerical and visual analyses of the fluid flow through the system are described. The device is then employed to test the effects of hydrodynamic cavitation on graphite particles suspended in water to show that the device can indeed create the conditions necessary to test the concepts laid out in Chapter 3. Chapter 6 focuses on ring compression and ball penetration tests used to evaluate nano-lubricants formulated with both an ultrasonic bath and the external cavitation device. The goal of these tests is to show that hydrodynamic cavitation can be used in place of acoustic cavitation to disperse nano-particles into a lubricant. The last chapter of the dissertation states the conclusions that can be drawn from the study and gives an outlook for the potential benefits to the metal forming industry that could be achieved by adopting hydrodynamic cavitation to physically and chemically modify the lubricant and workpiece surface in real time. Additionally, some further avenues for study are identified to help guide future research into this field.
CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Before any work can be done in investigating the possibility of utilizing cavitation to perform real time lubricant formulation and surface modifications, it is first important to establish the state of the art in the fields of metal forming lubrication and sonochemistry. This gives insight into what lubricants are in use and what makes them effective, as well as helping to determine what the possible effects of cavitation are on the lubricant and the surface of the workpiece. This information is collected and summarized in the literature review in this chapter so that it can serve as the foundation for the research carried out in the rest of the dissertation.

2.2 Metal Forming Lubrication

Metal forming operations typically involve using a hard tool to push or shape a softer metal workpiece, causing the two surfaces to slide over each other as the workpiece is deformed into its final shape. While necessary to create the desired part, the sliding motion of the workpiece results in a few negative effects. These include wear of the tools, increased energy costs, damage to the surface of the workpiece, and reduction in the formability of the material. The field of science that deals with the effects of interacting surfaces is known as tribology and has been of great interest to metal formers seeking to improve the quality of their processes.

In a microscopic sense, smooth surfaces do not exist. The surfaces of the tools and workpieces in the metal forming process will always consist of microscopic peaks and valleys, or asperities. When two surfaces come into contact, it is always the peaks of these asperities that come into contact first. As the forces between the surfaces increase, the surface asperities break and deform to allow for a greater number of asperities to touch and share the load. When the two surfaces slide across each other, the asperities must plow into each other, resulting in wear of the tools and poor surface finish of the final product. Additionally, because of the high shear strength of metals, it takes a great deal of energy to carry out this process, resulting in high frictional losses.
Metal forming lubricants act as an intermediary between the die and the workpiece. They help to reduce die wear, decrease frictional losses, and ensure proper material flow. There are two main lubrication regimes that lubricants are designed to operate in, the boundary layer lubrication regime and the hydrodynamic lubrication regime. In the boundary layer regime, the load between the two bodies is carried mainly by the asperities of the two surfaces. As the surfaces slide across each other the asperities in contact can plow into each other, which can generate a great deal of stress and heat leading to softening and damage of the tools and welding of the two materials. The hydrodynamic lubrication regime differs from this by completely eliminating contact between the two bodies through the establishment of a thick fluid film. The creation of the fluid film generally requires high relative speeds between the two surfaces and a low contact load. It is important to note that if the fluid film is not thick enough to separate the two surfaces entirely there will be some contact of the surfaces asperities resulting in a ‘mixed lubrication regime’. This mixed lubrication regime generally results in conditions which are superior to the boundary layer regime because an increased portion of the load is carried by the lubricant, resulting in lower shear stresses on the metal surface. Examples of these lubrication regimes can be seen in Figure 1.

![Figure 1: Three Main Types of Lubrication in Bulk Metal Forming Processes [1]](image)

Metal forming lubricants are designed based on the conditions that they are expected to be operating in, i.e. a lubricant that is good for one operation is not necessarily good for others. The factors which play into lubricant formulation include the temperature range that they are expected to operate in, the pressures between the two surfaces, the amount of surface expansion that the workpiece undergoes, and the chemical affinity between the lubricant and surfaces. Additionally, lubrication engineers must consider the cost, lubricity, shelf life, and environmental impact of the products they choose to employ. In order to better establish the types of lubricants that are currently being used in the metal forming process and the conditions
in which they operate, a quick survey of the boundary layer and hydrodynamic lubrication schemes is carried out.

2.2.1 Boundary Layer Lubricants

When the die and workpiece come into direct contact, the die is typically much smoother and harder than the workpiece. The normal pressure between the two surfaces results in the asperities of the workpiece being flattened against the surface of the die. This flattening increases until the area in contact is sufficient to resist the normal load without further yielding of the asperities. When the two surfaces begin to slide over each other the very small asperities on the die plow into the newly flattened workpiece material creating shear stress and further increasing the flattening of the surface asperities on the workpiece. This is done in two ways, first, motion of the workpiece causes only the front of the asperities on the die to be in contact with the workpiece, reducing the contact area and increasing the normal pressure at the interface. The second reason for the increased flattening of the workpiece is that the shear stress created by the relative motion between the two parts increases the total stress at the surface leading to an increased yielding of the workpiece material [2]. It is important to note that, while the previously mentioned factors tend to flatten the workpiece asperities, the plastic deformation of the workpiece can cause surface roughening [3].

Boundary layer lubricants reduce the severity of metal-to-metal contact without preventing the surfaces asperities of the two surfaces from coming into contact. This lubrication regime is common in the metal forming industry because of the high pressures and temperatures that are observed during the deformation process. The lubricants that are employed for these purposes can be either solid or liquid and some even make use of both states to form low friction conversion layers. Typically, only the solid lubricants are used in hot forming operations, while both the liquid and solid lubricants can be used in cold forming operations. The main goal of the lubricant in boundary layer lubrication is to provide an intermediate surface which can alleviate some of the harsh conditions at the interface between the two metals.

One of the main strategies for improving the contact between the two surfaces is to create an intermediate layer between them that can be sheared instead of the surface asperities of the die or workpiece. The lubricant generally has a much lower shear strength than either of the
two metals, which greatly reduces the stresses at the interface. This leads to a reduction in the frictional forces, temperature, and amount of metal to metal contact. The reduction in frictional forces makes the metal forming process more energy efficient and also reduces the tendency for the workpiece to resist sliding along the die, reducing the chances of an under filling defect. The reduction in interface temperature can prevent the two surface from welding together as they slide across each other and will help reduce wear on the dies caused by softening of the surface as it is heated. The degree of metal to metal contact is reduced because the lubricant will fill the gaps between the asperities and generate static pressure as it is compressed and forced to move during the flattening of the workpiece asperities [4]. This phenomenon was demonstrated experimentally by Le et. al. in their study into the electrical resistance between the tool and workpiece during the plane strain compression of an aluminum strip [5]. This pressure will carry some of the load exerted between the two surfaces, reducing the area in contact and the amount of friction as the surfaces slide over each other, as shown in Figure 2 [6].

![Figure 2: Effects of Lubricant Being Trapped in Asperity Valleys](image)

For this strategy to work, it is imperative that the lubricant avoid being pushed out of the region between the contacting asperities. Furthermore, the lubricant must be able to adequately compensate for the generation of new workpiece surfaces as the deformation process is carried out [7]. Because the new surfaces have not been exposed to the lubricant at the time of their creation, they act like unlubricated surfaces when brought into contact with the die, unless the lubricant is adequately spread to the new surfaces as they are created. The degree to which each of these factors matters to the lubricant depends on the conditions encountered during the deformation process. For example, Figure 3 indicates that the choice of lubricant for an aluminum forging process depends on the level of surface expansion that the particular process
undergoes and the pressures that will be encountered during the process, which is related to the hardness of the material [8].

Figure 3: Lubrication System Required for Various Aluminum Alloys and Forming Processes [8]

Solid lubricants which adhere heavily to the workpiece are very good at staying in place, but are not as good at being distributed to the virgin surfaces created as they are created. They are also useful for high temperature applications, where oil and water based lubricants would break down. The most commonly used solid lubricants are molybdenum disulfide and graphite based lubricants. These lubricants have chemical structures that consists of layers of strongly bonded sheets with weak van der waals bonds between layers that allow the layers to slide over each other with very little resistance, as shown in Figure 4. New environmentally friendly solid lubricants are also being developed, most notably boric acid [9, 10].
Liquid lubricants employed as boundary layer lubricants must have a high viscosity and/or a high physical or chemical attraction to the workpiece in order to avoid being pushed out of the contact area and are, in general, easier to remove from the contact area than solid lubricants because of this. Unlike solid lubricants, however, they are much more likely to be redistributed to the newly generated surfaces created as the workpiece is deformed. Additionally, it is much easier to reapply liquid lubricant systems between forming steps than it would be to reapply solid lubricants. The most commonly used liquid lubricants are mineral oils with extreme pressure additives (generally chlorine, phosphorous, and sulfur compounds), though water emulsions are becoming increasingly common.

One major downside to liquid lubrication is that it can form an ideal environment for microbial life, which feeds by breaking down the chemicals that make up the lubricant base and additives. Generally, these microbes require water in order to live and breed, so oil based lubricants are more resistant to biological infestations than water emulsions. However, it is difficult to keep all water out of the lubricant and, over time, some will find its way into the mix. As the number of microbes in the lubricant increases, slimes, sludges, and foul smells develop in addition to the degradation of the lubricant performance, requiring the lubricant to be replaced [11]. In order to increase the life of the lubricant, formulators generally add biocidal agents to the lubricant to inhibit the growth of these harmful microorganisms.

Another classification of lubricants in this regime is the conversion coating, which makes use of chemical surface modifications to the workpiece to create a lubricant carrier that will
cause the lubricant to strongly adhere to the workpiece [8]. Conversion coatings are applied in a number of steps, but there are two main stages. The first stage is to chemically modify the workpiece surface so that it has a high chemical attraction to the potential lubricant. The second process is to apply a lubricant to the workpiece that is both very attracted to the modified surfaces and has excellent lubricating properties. The modified surface is thus strongly bonded to both the base metal and the lubricant allowing the lubricant to withstand much higher pressures than it ordinarily would be able to. Lubricants that are commonly used as part of this lubrication strategy are oils with extreme pressure additives, soaps, and molybdenum disulfide. The types of chemical coatings that are applied to the surface of the workpiece are the zinc phosphate coating for steels and the aluminum fluoride coating for aluminum alloys [8].

While the conversion coatings are attractive due to their ability to withstand a great deal of surface expansion and pressure, they come with some serious downsides as well. For example, the large number of steps required to prepare the surface, apply the chemical coating, and lubricate the coat require a significant amount of time and add cost to the process. Additionally, the baths used to clean and chemically alter the workpiece surface can be hazardous and can become contaminated with heavy metal sludge [12]. Because of this, there has been a large push in the last two decades to create more environmentally friendly high performance lubricants. For example, in 2001 Sheljaskow presented a study which had been carried out to reduce the environmental consequences of warm forging steel products by replacing traditional oil-graphite emulsions and water graphite suspensions with a graphite based billet coating and graphite free oil based die lubricant [13]. Other researchers have shown that environmentally friendly double layered lubricants could have lubricating performance that was at least as good as the traditional conversion coatings in both steel [14-16] and aluminum alloys [17].

Another way to improve lubrication in the boundary layer regime is to modify the contacting surfaces. For example, laser surface texturing has been used to create arrays of micro dimples on the surfaces of parts, which has proved useful in increasing their life and reducing frictional loads [18, 19]. It is thought that these geometric surface modifications improve lubrication transport and entrap contaminants and wear particles. Surface coatings also offer an
opportunity to improve the properties of the mating surfaces by increasing the resistance to cold welding and softening due to high temperatures at the interface. For example, a study carried out in Germany in 1996 by Vetter et. al. showed that a chromium nitride (CrN) coating could significantly increase the life of the tools while at the same time reducing the amount of lubrication required [20]. More complex super-lattice coatings like Ti-Hf-Cr-N have also been experimented with to improve on the anti-wear characteristics of the simpler coatings [21]. Other studies showed that surface coatings could be combined with much more environmentally friendly lubricants to replace traditional lubricant systems [22, 23]. The factors which affect the successfulness of a particular coating pertain to the particular conditions encountered in the process, as the coating must withstand the pressures and temperatures generated by the contact. Of particular interest are the Young’s Modulus, brittleness, and adhesion of the coating [24].

2.2.2 Hydrodynamic Lubrication

Hydrodynamic lubrication occurs when an uninterrupted liquid lubricant film is established between the tools and workpiece, which results in the entire deformation load being carried by the lubricant. The total separation of the workpiece and die completely eliminates the contact between the die and workpiece and, thus, the damage to the surfaces that result for this contact. Additionally, the fluid separating the surfaces has a much lower resistance to shear stress than either of the surfaces, so the frictional forces which must be overcome and the energy wasted by friction are greatly reduced. The process makes use of viscosity driven flow, which is dependent on the relative motion between the die and workpiece and the viscosity of the lubricant. The downside to this type of lubrication is that it generally only occurs in high speed and low temperature applications. This is because low speeds are not able to drag the fluid into the contact zone because the viscous forces on the fluid are not great enough to counteract the extreme pressures generated at the die workpiece interface. High temperatures have a similar effect by greatly reducing the viscosity of the lubricant and even causing it to break down chemically. Despite these limitations, the hydrodynamic lubrication regime is highly attractive to designers of metal forming processes hoping to reduce friction, increase tool life, and improve material flow [25].
The occurrence of the hydrodynamic lubrication regime in the near net shape forming of metal parts is well known and has been widely studied. In the 1950’s and 60’s it was discovered that the hydrodynamic lubrication regime was present, or could be achieved in numerous metal forming processes. Christopherson and Naylor discovered how to encourage the formation of a hydrodynamic film in the wire drawing process by pressurizing the lubricant at the die inlet to near the yield point of the wire and derived relationships between the various parameters in the fluid film [26]. Once it was established that hydrodynamic lubrication was achievable in the drawing process, other researchers attempted to improve the equations describing the hydrodynamic film by re-deriving them using varying assumptions and solution strategies [27 – 29]. Other continuous processes, such as extrusion [30 – 32], strip rolling [33 – 35], and even strip drawing [36], were also examined under hydrodynamic lubrication conditions. In general, the film thickness is affected by the surface speeds, the viscosity of the lubricant, and the geometry of the interface. Increasing the viscosity of lubricant results in an increase in the lubricant thickness. Additionally, the thickness of the film can be increased by adjusting the surface velocity of the workpiece into an optimal range.

2.3 Cavitation

2.3.1 Basic Theory

Cavitation occurs when bubbles are formed in a liquid due to a drop in the pressure in the fluid. The bubbles are filled with vapor from the base liquid and contaminant gases that have been entrained in the fluid. As the pressure in the liquid drops to approach its vapor pressure, small gas filled imperfections on solid surfaces in contact with the fluid and suspended in the lubricant begin to grow in size. These nucleation sites continue to grow until the pressure in the fluid is returned, causing the bubbles to shrink back to their original size. In some cases the momentum of the bubble as it shrinks is so great that it collapses violently causing a sudden and local release of energy. This collapse can create extreme pressures and temperatures, as well as high velocity fluid jets and suspended particles. It is estimated that the pressures inside a collapsing bubble may reach pressures of up to 100 MPa and temperature may become as high as 5000 K [37].

It is obvious that these events within the fluid may lead to damaging effects, for example, amongst many engineers, cavitation is seen as a detrimental and destructive phenomenon due
to its tendency to destroy pumps, propellers, and other submerged solid structures. However, in the proper conditions, the energy released during cavitation may be harnessed in beneficial ways. Some chemists have sought to do just this by using cavitation to do everything from reduce reaction times, create radical species, and improve the mixing process to assist in numerous chemical and physical processes. This field of chemistry is called sonochemistry and is becoming increasingly important as scientists seek to improve efficiency and reduce the environmental impact of chemical processes.

One of the major benefits of utilizing cavitation to carry out reactions is that the intense temperatures and pressures inside the collapsing bubble create miniaturized reaction chambers. These reaction chambers have three zones, i) the hot, high pressure, gaseous interior of the bubble, ii) the liquid – gas boundary, and iii) the liquid surrounding the bubble. Inside the bubble radical species are created, which can cause oxidation reactions inside the bubble and diffuse into the surrounding liquid to cause reactions at the bubble surface and, to a more limited degree, the surrounding liquid [38, 39]. Oxidation reactions are not the only reactions that can be carried out inside a cavitation bubble. Reactions that take place in compressed gases inside the shrinking bubble are also encouraged by the high pressures in the bubble. This happens because the reactivity of chemicals in the gaseous phase are dictated by the partial pressure of the gases and when the total pressure in the bubble rises so do the partial pressures of the trapped gas. This allows for the formation of chemical species that normally require complex chemical reactors to pressurize and heat the reagents. Additionally, cavitation allows for the formulation of chemical species that are unattainable in conventional thermal reactions because of the new reaction pathways created by the high degree of radicals created during the bubble collapse [39, 40]. This change in reaction pathways is known as ‘sonochemical switching’.

Cavitation also has distinct and important effects on polymers and polymerization. The radical species produced inside the bubble can cause the initiation of polymerization by stripping an atom off of a mer, making it chemically active and attracted to surrounding mers [39]. This process can also affect developed polymers causing cross-linking between the individual chains, which greatly affects the properties of the polymer [37]. It is interesting to note that cavitation is capable of building these types of polymer structures without the addition
of initiator compounds [41]. Additionally, cavitation has the ability to break apart polymer chains, resulting in the preferential removal of long chains and refining the molecular weights of the polymer chains in the solution [37].

Furthermore, these reactions are carried out without greatly affecting the bulk properties of liquid due to the highly localized nature of the cavitation event. This allows chemical reactions to take place without having a high degree of undesirable thermal reactions in the solvent. Furthermore, the short lived nature of cavitation makes it possible for temperature sensitive reaction products that are created in the bubble to survive long term in the cooler surrounding liquid. The short lived and localized nature of the reactions caused by the collapsing bubble is the potential to create particles on the nano-scale from precipitation reactions [42]. The rapid cooling rates in the aftermath of a bubble collapse are also responsible for the creation of amorphous metallic glasses from the decomposition of volatile metal containing compounds inside the bubble [43].

Reactions carried out using cavitation also benefit from the physical effects of collapsing bubbles on the surrounding environment. For example, the shockwaves and turbulence created during bubble collapse create improved mixing. This increases the likelihood that a reaction will occur by ensuring that reactants are evenly and rapidly distributed in the medium [39]. Solid-liquid reactions are also encouraged by exposure to cavitation. In media that consist of solid particles suspended in liquid, the collapsing bubbles have a pronounced effect on solid surfaces in the liquid. For example, smaller solid particles are propelled at high speed by the shockwaves created by collapse. This results in energetic impacts between the suspended solids that can break protective oxide layers off of the surface and remove reaction products, leaving a much more reactive body suspended in the liquid [39, 40]. Larger solids particles and solid surfaces cause the collapse of the bubble to occur in an asymmetric way that results in a jet of fluid pushing through the center of the bubble. This micro-jet is the cause of the destructive properties of cavitation that are feared by the designers of underwater propellers and turbo machinery. However, this destructive tendency can be harnessed to encourage chemical reactions by breaking up large particles into smaller particles, revealing new reaction sites [39, 42]. Additionally, the jets themselves can break the brittle surface oxides off of solid structures leaving virgin material to react with the surrounding liquid [39].
Cavitation can also be used to modify the shapes of suspended solid particles. It has already been mentioned that larger particles can be broken up into smaller ones, but cavitation can also cause particles to group together to form larger structures. This occurs when the collisions of the suspended particles creates temperatures large enough to weld the particles together [44]. This is increasingly likely when the particles make direct impacts; glancing blows tend break surface asperities and generally smooth the particle surface [45]. The topology of solid surfaces can be modified by cavitation if the shockwaves and micro-jets created by collapsing bubbles at the solid surface create a pressure large enough to yield or erode the surface. This could be used to create residual stresses on the solid surface in addition to the potential benefits of a modified topology.

![Image of two micro-particles fused together and before/after images of smoothed particles](image)

**Figure 5:** a) Two Micro-Particles Fused together by a Collision in an Ultrasonic Cavitation Recator [45], b) Before and After Images of Micro-Particles Smoothed by Ultrasonic Induced Cavitation [46]

Liquid droplets suspended in the bulk medium are also affected by the collapse of cavitation bubbles. The main effect is that the shockwaves and large shear stresses created by cavitation events can lead to the breakup of large droplets into smaller droplets [47, 48]. This leads to an
increase in the stability of the emulsion and is responsible for allowing a greater amount of the secondary liquid to be held in the emulsion at a given time [47]. Reduced bubble size leads to increased stability of the emulsion because they have a higher surface area to volume ratio than large bubbles. This means that the drag forces, which are proportional to the surface area of the droplets and prevent the bubbles from sinking or rising to separate from the base liquid, dominate the buoyancy forces, which are proportional to the displaced volume [49]. This is illustrated in Stokes Law, shown in Equation 1, which shows that the motion due to the buoyancy of the droplet is proportional to the square of the droplet diameter. Note, $U_T$ is the terminal velocity of the droplet, $g$ is the acceleration due to gravity, $d$ is the diameter of a spherical droplet, $\Delta \rho$ is the difference in density between the droplet and base liquid, and $\mu$ it the dynamic viscosity. Bubble collapse can also lead to collisions between individual droplets, which can cause them to combine into larger droplets, though this effect is less pronounced when cavitation intensity is high.

$$U_T = \frac{gd^2\Delta \rho}{18\mu}$$

Equation 1.

Living organisms in the cavitating medium are also subjected to the large shockwaves and impacts created by the collapsing bubble. This causes clumped groups of microorganisms that take the form of slimes or films to be broken up. It is also capable of causing a great deal of damage to the cells themselves, rupturing the cell walls and interfering with the functions carried out on the cell membranes [50, 51]. This effect is most pronounced when the microorganisms are growing, giving cavitating liquids a biocidal property [52].

In order to design equipment to take advantage of these features of cavitation and sonochemistry, a good theoretical background of the cavitation process is necessary. This allows the designer to understand the interactions between the various process parameters and the effects of varying them. This understanding starts with an understanding of the creation of the cavitation bubbles in the form of nucleation theory [53, 54]. After establishing how the bubbles come to be in a cavitating liquid, the bubbles’ behavior in the liquid must be determined. This is done by employing the Rayleigh – Plasset equation, which combines the equations describing fluid dynamics with the equations of state for the inside of the bubble. There are numerous assumptions that can be used in the derivation of this equation, each with
various applications, depending on the particular conditions affecting the bubble. This analysis is used to determine if a bubble grows or shrinks and what the internal conditions of the bubble are for any given pressure field and thermal and fluid factors [53, 55]. The establishment of bubble behavior and internal conditions allows the designer to predict the chemical and physical effects that the presence of bubbles may have on the solids and liquids exposed to cavitation.

It is very likely that some of the numerous benefits of cavitation based chemistry may be applied to the field of lubrication technology to improve the lubricants’ effectiveness or reduce its cost. Thus, a review of the technologies and capabilities that have been created to harness the power of cavitation must be reviewed. The two main methods for producing cavitation based reactions and physical modifications are ultrasonic and hydrodynamic reactors, which are reviewed separately in order to compare and contrast the techniques. Particular attention is given to the types of processes that are carried out with each process and the chemical and physical phenomena on which they operate.

2.3.2 Ultrasonic Sonochemistry

The defining feature of ultrasonic sonochemistry is that vibrations of between 20 KHz and several MHz [40] are used to produce cavitation in liquid media to conduct cavitation assisted reactions. The liquid medium can be anything from reactants mixed in a solvent to a slurry of solid particles in a reactive liquid, so long as cavitation can be induced in the liquid. There are two types of ultrasonic cavitation devices, a bath type device (Figure 6a) and a probe type device (Figure 6b). In practice the probe type device is much more popular than the bath type device because it is easier to deliver large amounts of energy to the reactants. Typically bath type reactors can produce powers of 1 W/cm² while probe type reactors typically produce 50 – 500 W/cm² [37]. The majority of the studies mentioned in this section were carried out using ultrasonic probes.
Ultrasound is able to produce a large number of cavitation events in the fluid due to its ability to produce rapid vibrations which create rapid pressure changes in the fluid. The cavitation event always starts with a liquid being exposed to a low pressure event, which causes the rarefication of the medium at certain nucleation sites. These nucleation sites can be anything from dissolved gases in the liquid to the surfaces of suspended particles. Once the rarefaction occurs, a bubble is created in the liquid matrix and begins to grow. When the liquid is again exposed to high pressure the bubble begins to contract and if the bubble is beyond some critical size the collapsing will lead to the complete collapse of the bubble. This process may occur over the application of several pressure waves and is illustrated in Figure 7 [40]. The collapse of the bubble can lead to the immense pressures and temperatures mentioned previously. These collapsing events are highly localized and the bulk temperature of the fluid is not greatly affected, though the collapse does trigger the release of shockwaves in the fluid that can assist in mixing, cleaning surfaces, and causing particle collisions [37]. In cases where the collapse of the bubble is asymmetric, such as is the case when the bubble is near a solid surface a powerful jet of fluid is created which can remove oxides, or even fragment brittle solids [37].
The vast majority of the beneficial phenomena of cavitation that were discussed in section 2.3.1 were discovered through the use of ultrasonic sonochemistry. This is mainly because it is easy to control the process variables in an ultrasonic sonochemical reactor. The main variables to control are the concentrations of the various chemical components of the system, the frequency of the emitter, and the intensity of the waves produced. These variables are easy for researchers to replicate so that repeatable experiments can be carried out. It should be noted that bath type reactors do not produce results that are as repeatable as the probe type reactors because the intensity of cavitation depends on the positioning of the reaction vessel and any equipment in the bath.

Some examples of the types of reactions that have been undertaken using ultrasonic sonochemistry are listed here to give an idea for the wide range of chemical processes that can be accomplished with this technology. The creation of particles with high surface area to volume ratios is important to increase reaction rates for numerous liquid-solid phase reactions and cavitation is capable of producing both sheets and particles that meet this criteria. For example, both Coleman et al. [56] and Li et al. [57] were able to produce nanosheets by exfoliating layered materials using ultrasonic cavitation. These particles could be used to create thin films, reinforce polymers, create catalysts, and carry out reactions in future chemical processes. Ultrasonic cavitation has also been used extensively to modify the morphology of suspended particles. For instance, Suslick et al. [45] utilized the inter particle collisions created by ultrasonic cavitation to agglomerate and smooth micro-scale copper and nickel particles. Doktycz and Suslick [58] were also able to show that other metals, such as
iron, tin, and zinc could also be agglomerated, provided their melting points were low enough that they could be reached by the cavitation induced collisions of the particles. Ultrasonic cavitation has also been used by Grinstaff et al. [43] to produced amorphous iron through the decomposition of Fe(CO)\textsubscript{5} inside the cavitation bubble and subsequent rapid cooling of the molten iron which forms. Afzalinia et al. [59] utilized cavitation to replace a costly solvothermal process that created a ceramic particle to be used as a catalyst for the desulfurization of fuel. They also reported that ultrasonic cavitation improved the activity of the catalyst by improved mixing of the fuel catalyst mixture. Akbas et al. [60] also used ultrasonic cavitation to create ceramics, specifically, BaTiO\textsubscript{3} ceramics with improved purity and dielectric properties.

In addition to the ultrasonic sonochemistry used in liquid-solid systems, it has been frequently used in liquid-liquid systems to carry out various chemical processes. In many cases it significantly shortened reaction times and reduced the harshness of the conditions required to carry out the reaction. For example Kowalska and Balczewski [61] were able to carry out a Bradsher reaction to create aromatic compounds known as polyacenes at room temperature and mild chemical conditions, which resulted in a faster, more energy efficient reaction. Ultrasonic cavitation was also able extended the range of compounds that could be used in the Bradsher reaction because the chemical precursors used in the process were less likely to undergo secondary reactions under the milder conditions. Naeimi and Didar [62] were also able to show that cavitation is able to produce so called ‘green’ reactions by reducing the harshness of the conditions required to initiate chemical reactions.

Ultrasonic sonochemistry has also been used extensively to create and modify polymer compounds. The polymer degradation phenomenon by ultrasonic cavitation was extensively studied by Mohod and Gogate [63], who concluded that the physical sheering created by the motions at the bubble wall were responsible for breaking the polymer chains. Thus degradation is assisted by using low frequency ultrasound, increasing cavitation intensity, and reducing attenuation in the liquid medium. Kruus and Patraboy [64] showed that ultrasonic induced cavitation could be used to build polymers rather than break them up by making use of the formation of radical species to initiate the polymerization of dissolved monomers. Rokita et
al. [65] used ultrasonic cavitation to initiate cross linking in dissolved polymer solutions to create 3D macroscopic polymer gels.

Finally the physical effects of ultrasonic induced cavitation have also been used to disrupt microbes and improve the physical properties of liquid systems. For example, Gaikwad and Pandit [47] tested the effects of ultrasonic cavitation on water/oil emulsifications and found that the cavitation phenomenon could break up large droplets into smaller droplets. They also found that increased intensities and irradiation time lead to an increase in the volume fraction of oil emulsified in the water and a decreased droplet size. This would help stabilize the emulsification and reduce the need for surfactants. The shockwaves produced by cavitation have also been found to disrupt and destroy microbes in food and drink by Piyasena et al. [51]. They noted that ultrasonic cavitation could be used in combination with elevated temperatures and pressures to pasteurize and sanitize products without the thermal degradation to the desirable compounds that is associated with traditional methods of sanitation.

2.3.3 Hydrodynamic Sonochemistry

Hydrodynamic cavitation is an alternative means for producing the cavitation events used in sonochemistry. Instead of baths and probes, it utilizes traditional pumps and either orifice (Figure 8a) or Venturi type (Figure 8b) restrictions to cause the liquid to cavitate. Both restrictions create cavitation by utilizing the Venturi effect, which states that when an incompressible fluid flow’s velocity increases due to a decrease in the cross-sectional area of the flow, the pressure in the fluid flow drops. Because both devices reduce the cross-sectional area of the flow they force its velocity to increase resulting in a pressure drop to below the cavitation limit creating bubbles in the flow. After flowing through the restriction, the cross-sectional area of the flow is increased, which reduces its velocity and increases its pressure, causing the newly created bubbles to collapse. The collapse of these bubble releases energy in much the same way as ultrasonic cavitation, except that the events take place on larger time scales [66]. This can lead to some important differences in the two types of cavitation.
According to Arrojo and Benito, the bubbles generated in hydrodynamic cavitation tend to spend a longer time with low surrounding pressures than those generated by ultrasonic cavitation. This leads to greater expansion of the bubbles with less extreme low pressures, which decreases the amount of energy required to cause cavitation and leads to a large number of cavitation events per unit volume. Arrojo and Benito point out that this is both good and bad, as the high amount of cavitation bubbles in the fluid creates more reactions in the fluid, but also causes bubble interaction which can reduce the cavitation intensity. The larger time scales associated with hydrodynamic cavitation also include increased pressure recovery times, which result in energy being lost through the bubble wall and a less intense collapse. This can be rectified, at least partially, through the use of downstream restrictions, like stagnation plates, which generate a quicker pressure recovery [66].

Hydrodynamic cavitation has many of the same advantages over traditional chemical processes as ultrasonic cavitation, including increased reaction times, improved energy efficiency, and the creation of radical species. However, hydrodynamic cavitation is easier to scale up, as the equipment is far more common and the efficiency of pumps generally increases as their size increases [67]. Additionally, the number of cavitation events in a particular volume of fluid per unit time is higher in a hydrodynamic cavitation device than in an ultrasonic cavitation reactor, though they are generally less intense [66, 67].

Despite these advantages there has been much less research done with hydrodynamic cavitation reactors than ultrasonic reactors. Most of the studies that have been done focus on
the creation of radical species and advanced oxidation processes to break down contaminants in wastewater. Though most studies have been focused on wastewater treatment [68, 69], there has been some research focused on the synthesis of biodiesel [70] and the creation of nanoparticles [71]. Hydrodynamic cavitation has also been investigated for its potential to disrupt microbes in the liquid medium. Save et al. [50, 52], for example, discovered that it was much more efficient to use hydrodynamic cavitation to disrupt (break open) yeast cells than it was to use traditional methods, or even ultrasonic cavitation. It seems likely that most of the processes that can be done with ultrasonic cavitation could be done with hydrodynamic cavitation, except in the case where the pump would damage the process or be damaged by the process.

2.4 Conclusions

The traditional method for creating liquid lubricants requires the lubricant formulators to add components that do not strictly assist in the forming process to their products in order to ensure that they have sufficient shelf life to be transported from the place of their creation to the metal former. Additionally, the potentially long wait from creation to utilization prevents the lubricant formulators from making use of short lived, but highly effective chemical compounds. Cavitation in a fluid flow has numerous physical effects on the fluid, including, biocidal tendencies and mixing and agitation of the flow that may allow the number of nonlubricating additives to be reduced. Additionally, cavitation provides an opportunity to carry out chemical reactions to formulate a lubricant directly at the point of use that is not afforded by the traditional methods of chemical processing, thus allowing short lived chemical species to be used in metal forming lubricants without reducing the life of the lubricants. Cavitation also provides the opportunity to modify solid boundaries in contact with the lubricant flow, like the surface of the workpiece or suspended particles, that could further improve the quality of the lubrication in a metal forming process.
CHAPTER 3
OPPORTUNITIES TO IMPROVE LUBRICATION THROUGH CAVITATION

3.1 Introduction

Based on the information gathered in Chapter 2, cavitation has been identified as a phenomenon that is of particular interest to the realization of real time, point of use lubrication formulation. However, before it can be applied it is necessary to identify the specific ways in which cavitation benefits the tribological conditions in a metal forming process. This includes the chemical and physical modifications that can be made to both the lubricant and the workpiece to improve the tribological performance of the system. Additionally, it is necessary to determine how sonochemistry can be applied to metal forming processes so that real time processing of the lubricant can be realized. The ultimate goal of compiling this information is to identify operations that can be performed by combining sonochemical processes with metal forming operations so that analytical models and experiments can be designed and so that future researchers will have a good place to start their research into this field.

3.2 Real Time Lubricant Formulation

Lubricant formulation takes place in two spheres, chemical processing to create specific molecules and physical processing to create and manipulate the solid structures that may be present in the lubricant.

3.2.1 Chemical Processing

Formulation of a lubricant in real time requires the development of ways to rapidly influence the chemical properties of the lubricant precursors. The exploitation of cavitation in sonochemical reactions has been shown to be able to achieve this goal. The most obvious use of cavitation is the rapid synthesis of chemical species, but there are many other uses that can also be achieved. Among them are the use of cavitation to reduce the molecular weight of polymer chains, remove surface oxides from solid surfaces to improve their reactivity, and activate boundary layer additives before contact.
Reducing the weight of polymer chains has several important benefits to lubricant quality. First, sludge produced by polymer chains created as the lubricant is used becomes less soluble in the base lubricant as the length of the chain increases. This means that sludge tends to build up over time as a greater and greater number of the chains grow too large to be held in solution. By breaking these large chains into smaller chains, the life of the lubricant can be improved by reducing the buildup of sludge in the system. This point is illustrated in Figure 9, which shows how the shock waves from a collapsing cavitation bubble might affect a mass of entangled polymer chains.

Figure 9: Cavitation Bubble Dispersing and Degrading Sludge Forming Polymer Chains

Another use for reducing the weight of polymer chains comes in the form of utilizing functionalized polymer chains of different molecular weights to produce certain physical properties. For example, a functionalized group on the end of a chain may be especially attracted to the workpiece, allowing it to bond tightly to the surface of the part. Because of this these chains will crowd into the surface of the part, tightly packing at the surface, creating a solid-like layer on the surface. This is beneficial in that it makes the lubricant more resistant to being removed from surface, but also prevents the polymer from gaining the benefits associated with being more loosely packed and free to move. By utilizing cavitation to reduce the weight of polymer chains, the long chains are divided into short chains, though this does not happen all at once. This leaves both long and short chains in the lubricant at the same time, both with functionalized groups for bonding to the metal surface. Near to the surface both the long and short chains will form a tightly grouped formation similar to the formation of polymer chains of equal length, but farther from the surface the longer chains become more free to move as the short chains are no longer present to interfere with their motion [72, 73]. This point is
illustrated in Figure 10, which shows a mixture of short and long chains bonded to the metal surface with functional groups. Thus the benefits of both crowded polymer chains and uncrowded polymer chains can be obtained by reducing the molecular weight of long chains to create a mixture of long and short chains.

![Figure 10: Lubricant Formed with Both Closely Packed Short Chain and Loosely Packed Long Chain Polymers](image1)

The removal of surface oxides from solid surfaces by the intense bursts of energy created by the collapsing bubbles in a cavitating fluid creates a great opportunity to improve the properties of metal forming lubricants. The clean metal surfaces created as a result of this action are much more reactive than the surface of the workpiece when it is delivered to the forming company. This means that the cleaned surface can react with the lubricant to form strong chemical bonds that anchor the lubricant to the surface of the workpiece, preventing it from being squeezed out of the contact zone and increasing the share of the contact load that it can support.

![Figure 11: Micro-jets Removing Surface Oxides to Expose Reactive Metal Surfaces](image2)
Some of the chemical additives in the lubricant are meant to activate when exposed to the intense heat and pressure of colliding surface asperities in sliding contact. One example of this type of additive is zinc dialkyl-dithiophosphate (ZDDP), which is an anti-wear additive that forms a protective surface layer when subjected to the intense heat created by sliding surfaces in boundary layer lubrication regimes. The diffusion of heat and radical species into the lubricant, as shown in Figure 12, may provide a useful avenue for activating these types of useful molecules. They could be used to create the surface protection afforded by the compound before the workpiece and die come into contact, rather than waiting for the collision of the unprotected surfaces to cause the additive to activate.

![Inactivated Chemical Species](image)

**Figure 12**: Cavitation Creating Heat (q) and Radicals to Activate Useful Chemical Compounds

### 3.2.2 Physical Processing

In addition to the chemical benefits afforded to the lubricant by the cavitation phenomenon, physical changes to the lubricant are also achievable. The main physical effects caused by cavitation are improved mixing, particle breakup and aggregation, surface texturing, and biocidal tendencies. By employing these beneficial properties to improve the tribological conditions at the die-workpiece interface, it may be possible to reduce the amount of additives that add cost to the lubricant and reduce its potential effectiveness.

The improved mixing caused by the shockwaves and turbulence created by the cavitation phenomenon also offered several benefits to lubricant quality. As it was described in Chapter 2, lubricants often consist of a base to which a myriad of additives are combined. In many cases the additives are not soluble in the base lubricant, so other additives called emulsifiers
are added to ensure that the contents of the lubricant do not separate while not in use. These emulsifiers do not directly contribute to the desirable qualities of the lubricant and are at best dead weight. Cavitation may help reduce, or even eliminate, the need for these chemicals due to its ability to break up aggregating droplets with the turbulence and shockwaves created by the collapsing bubbles. The domination of drag forces on the resultant smaller particles help to prevent the droplets from separating out of the emulsion, as shown in Figure 13.

![Figure 13: Breakup of Suspended Droplets to Reduce Their Tendency to Come Out of Emulsion](image)

Cavitation also has a large effect on particles suspended in the fluid and solid surfaces in contact with the fluid. The breakup of brittle particles and welding of ductile particles caused by high speed collisions in the fluid can be harnessed to improve the bulk properties of the lubricant. For example, nano-sheets of lubricating particles may be created from the breakup of the layered materials that interface with the liquid. The process takes place due to the micro-jets created by the asymmetric collapse of a bubble at a solid surface. As shown in Figure 14 the impingement of the micro-jet on the surface of the layered structure causes very small particles to be broken off of the substrate. This provides the opportunity to make use of nano-scale particles without the need for the complex manufacturing techniques which are currently required to create them.
In addition to the chemical benefits afforded by micro-jets and particles colliding with solid surfaces discussed in section 3.2.1, there are also beneficial effects associated with structurally modifying the surface. Namely, the impinging micro-jets and particles create small divots in the surface of the workpiece that help to transport the lubricant into the deformation zone, trap wear particles, and create closed lubrication pockets. The process that leads to the creation of this texturing is illustrated in Figure 15. The degree of effectiveness of this micro-surface texturing is determined by the particular shape of the dimples and their spacing, so it is important to be able to control both the number of cavitation events on the workpiece surface and the intensity of the events.

The shock waves and micro-jets that appear to be useful in modifying solid particles have the additional benefit of creating an environment that is inhospitable for micro-organisms, as shown in Figure 16. These micro-organisms live in the lubricant and feed on the oils and additives that make it up, leaving behind degraded chemicals, slimes, and sludge. These organisms are normally dealt with by adding biocidal compounds into the lubricant mix, which adds cost to the system without improving the system’s performance. By utilizing cavitation
to help control these microbes, lubricants could be formulated with less biocidal additives, reducing their cost and improving their performance.

Figure 16: Disruption of Microbes Caused by Cavitation Shockwaves and Shearing Forces

3.3 Integrating Cavitation into a Metal Forming Process

The numerous opportunities to improve the performance of metal forming lubricants through the use of cavitation are attractive, but the challenge of integrating the two processes must be overcome first. Principally, there are two ways that this integration could be done.

The first is to create a cavitation reactor that processes the lubricant before it is delivered to the metal forming process. The second method is to fully integrate the two processes by creating cavitation using the metal forming equipment itself. The first solution is relatively simple to carry out because it allows the two systems to be designed and operated independently of each other, while the second approach has the advantage of taking place extremely close to the actual deformation process, but is more difficult to implement.

A vast majority of the benefits discussed in this chapter can be attained with a separate cavitation reactor, especially those benefits which do not require interaction with the workpiece. The reactor itself can be of either ultrasonic or hydrodynamic design, though the low yields and low efficiency of ultrasonic sonochemical reactors would likely push the design of the reactor towards a hydrodynamic construction. This is also the easier of the two types of sonochemical reactors to implement because, in order to supply liquid lubricant to the workpiece, the metal former is already in possession of the pumps which would drive the
lubricant flow. In the worst case, they would be required to purchase stronger pumps to overcome the additional resistance created by the cavitating in the flow.

The set up might look something like the configuration proposed in Figure 17. The configuration shown in Figure 17 basically consists of a pump taking lubricant from a reservoir and forcing it through a cavitation chamber to process it. The processed lubricant is then supplied to the particular metal forming application. A pressure relief valve allows the pressure upstream of the cavitation chamber to be controlled and the intensity of the cavitation in the device can be adjusted in real time via an intensity adjusting knob. This allows the process to be highly controllable and enables cavitation to be started and stopped at will to improve process efficiency and prevent over processing of the lubricant. After the lubricant is used in the metal forming process, it can either be collected in the main sump in the case that it is reusable or it can be diverted to a waste sump in the case that it is expended upon use. This setup can benefit any metal forming process that takes advantage of liquid lubricants because the processing of the lubricant take place outside of confines of the actual forming process. The downside to this setup is it only allows one to take advantage of some of the numerous potential benefits of cavitation because the cavitation events do not occur at the surface of the workpiece.

Figure 17: Real Time Lubrication Processing with a Separate Cavitation Reactor System
If the lubrication designer wanted to utilize cavitation to achieve the benefits associated with collapsing bubbles at the workpiece surface, such as cleaning, texturing, and chemically modifying, the source of the cavitation must be very close to the surface of the workpiece. This can be achieved by allowing the workpiece itself to become part of a hydrodynamic cavitation reactor. In this setup the lubricant would be forced to cavitate by squeezing it between the workpiece and a rigid wall, allowing the lubricant to cavitate directly at the surface of the part. This can be done by either using lubricant pumps to force the lubricant through a tightly controlled clearance between the part and a ‘die’ or by allowing the motion of the metal and viscosity of the lubricant to force the lubricant between the die and the workpiece in a hydrodynamic lubrication film. Figure 18 illustrates how these two concepts might be applied to a drawing process, where Figure 18a shows the first method and Figure 18b shows the second method.

The first method is actually very similar to the separated sonochemical reactor discussed previously in this section, except for it is more difficult to control the cavitation because the gap is dependent on the workpiece surface which is neither stationary nor uniform. In order for this method of cavitation to perform properly, it is likely that the size and shape of the workpiece will need to be tightly controlled in steps prior to the cavitation processing. In cases
where the lubricant cannot be confined to the area between the die and the workpiece a variation on this technique, in which a probe that directs a cavitating flow of lubricant at the workpiece surface, may be used. The probe can be moved over the surface of the workpiece to achieve the benefits of cavitation at the workpiece surface before the forming process. A conceptual sketch of one such design is given in Figure 19. In this case, the probe could be set up in front of a stamping or rolling operation. As the sheet is pulled underneath the probe, the cavitation created by the lubricant accelerating through the probe will both texture the surface and apply processed lubricant to the workpiece before it reaches the rollers or stamping press. This type of equipment could be beneficial for a number of metal forming processes that utilize continuous strips of flat metal, such as stamping, rolling, deep drawing, and drawing of workpieces with flat faces.

Figure 19: Probe Used to Create Cavitation Over the Surface of a Flat Workpiece

The second method of producing cavitation at the workpiece surface is highly related to the hydrodynamic and plastic properties at the tool-workpiece interface and, though these properties have been studied in numerous metal forming operations, their effect on cavitation has yet to be examined. This type of cavitation can also be induced in the hydrostatic extrusion process because the process conditions and geometry are similar to those that occur in the hydrostatic drawing process. A depiction of a hydrostatic extrusion process resulting in the creation of cavitation at the workpiece surface is given in Figure 20. In this process two dies
are used. The first is a light reduction capable of achieving hydrodynamic lubrication and the second is the major reduction die in which the majority of the deformation takes place. As the plunger increases the pressure inside the die case, an imbalance in forces acting on the billet causes it to be pushed through the dies. During the extrusion, the lubricant is squeezed from the entrance to the exit of the first reduction creating a sudden drop in pressure at the end of the reduction, resulting in the formation of cavitation bubbles in the flow. These bubbles collapse both within the bulk fluid and at the workpiece surface. Those that collapse in the bulk fluid have the effect of processing the lubricant only, while those that collapse at the workpiece surface can process the lubricant and chemically and physically alter the surface of the workpiece. These changes in the lubrication and surface topology of the workpiece may improve the conditions in the second reduction where a majority of the deformation takes place.

![Figure 20: Depiction of the Creation of Cavitation in a Double Reduction Hydrostatic Extrusion Process](image)

Another process that could be adapted to take advantage of cavitation technology is the backwards extrusion process. Lubricant can be supplied to the workpiece deformation zone through a hole in the center of the punch (assuming that the hole does not negatively affect the strength of the punch). When the lubricant is pressurized to the level required to create
hydrodynamic lubrication, the lubricant will leave the inside of the punch and begin to escape between the cup wall and the punch nose. As it is squeezed between the two bodies, cavitation is created and cavitation events occur at the workpiece surface and in the bulk fluid. This process is depicted in Figure 21 and may provide a tribological advantage to future operations on the inside of the cup, like further shaping of the interior or finishing operations.

Figure 21: Cavitation Created by Lubricant Flow in the Backwards Cup Extrusion Process

Though the list of metal forming processes presented in this section of the report is not exhaustive, it should provide some useful examples of how to create useful cavitation in metal forming processes. Through a thorough understanding of the behavior of lubricants in various metal forming operations, ideas similar to the ones proposed in this paper may be applied to an even more extensive range of operations.

3.4 Conclusions

Cavitation and sonochemistry offer numerous potential benefits to the tribological conditions at the workpiece tool interface. Chemically, cavitation is capable of activating chemical additives, preventing long polymer chains from forming sludge, cleaning solid surfaces to make them more attractive to the lubricant, and creating short lived, but effective lubricating compounds. Physically, cavitation offers the benefits of improved mixing of the
lubricant and its additives, breakup of suspended solid particles, surface texturing, and disruption of the microorganisms that can infest lubricant systems. There are two distinct methods for achieving these potential boons: i) a cavitation reactor which is a part of the lubricant pumping system (i.e. separate from the workpiece) and ii) a cavitation reactor which incorporates the workpiece and/or is integrated with the deformation process itself. The first method is relatively simple to implement, as it simply requires that traditional hydrodynamic cavitation reactors be added to the existing metal forming lubricant supply systems. However, it does not benefit from the interactions between the cavitation phenomenon and the workpiece surface because it is removed from the workpiece surface. The second method on the other hand is capable of realizing these benefits. It can be achieved by squeezing the lubricant between the workpiece and rigid die which can either be done by tightly controlling the gap between a die and the workpiece as the lubricant is pumped between them or by utilizing hydrodynamic cavitation to pull the lubricant between the two surfaces. The former method is achievable with current understanding of cavitation and metal forming, while the latter requires further research.
CHAPTER 4
MATHEMATICAL MODEL OF THE HYDRODYNAMIC DRAWING PROCESS

4.1 Analytical Modeling Goals

As discussed in previous chapters, cavitation may present numerous opportunities for metal formers to improve the tribological performance of their processes. One of the methods to produce cavitation that takes advantage of chemical and physical modifications of the workpiece’s surface is to squeeze the lubricant between the die and the workpiece to create cavitation using the hydrodynamic lubrication regime. However, this method of producing cavitation has not been studied and, before equipment can be made that utilizes it in this fashion, it is necessary to more fully understand how cavitation can be created in a metal forming process. In order to provide a theoretical background for this new method of producing cavitation, it is necessary to explore the equations that govern the lubricant in a metal forming operation with an analytical model.

For the purposes of this research, the drawing process is used as the sample process because its continuous and steady state nature make it easy to study without detracting from the applicability of the analysis. The following derivation shines light on how hydrodynamic cavitation might be achieved in a metal forming process by clever manipulation of the process variables and die geometry in the drawing process.

4.2 Nomenclature

\( A_3 \): Area of 3\textsuperscript{rd} control surface
\( A_{c.v.} \): Area of control volume projected onto x-y plane
\( B \): update constant
\( D, D_0, D_r \): instantaneous workpiece diameter, original workpiece diameter, final workpiece diameter
\( c_{pw} \): specific heat of the workpiece
\( \dot{E}_p, \dot{E}_k, \dot{E}_w, \dot{E}_{tot} \): rate of energy brought into/out of control volume by pressure, kinetic energy of fluid, work on the control surfaces, net rate of mechanical energy entering/leaving C.V.
\( h, h_i, h_1, h_2 \): instantaneous fluid film thickness, fluid film thickness at the inlet to the reduction zone, thickness at control surface 1, at C.S. 2
\( K \): material strength coefficient
\( k \): conductivity of lubricant
\( m \): shear friction factor
\( \vec{N} \): unit normal to the control surface
\( n \): strain hardening exponent
**P, Po:** instantaneous fluid pressure, static fluid pressure at the inlet of the draw

**Q:** volumetric flow rate of the fluid

**q:** dummy variable for inlet zone analysis

**q_{gen}:** heat generated in control volume per unit volume

**q_{die}, q_{workpiece}:** heat flux per unit area to the die, to the workpiece

**R_e, R_o, R_p:** radius at the exit of the die land, radius of the die land, radius of the product

**r:** radial direction

**r_{1}, r_{ce}** (in thermal analysis) radius of the die at the start of the solution step, radius to the centroid of the control volume

**S:** step size (x-direction)

**SA/Vol:** instantaneous surface area to volume ratio

**T, T_w, T_d, T_{old}, T_{new}, T_{FD}:** temperature, temperature of workpiece surface, die surface, workpiece temp. at beginning of solution step, end of step, die surface temp. predicted by finite difference analysis

**t:** time required for a portion of the workpiece to move from one step in the solution to the next

**U:** instantaneous velocity of the workpiece

**u, u_1, u_2:** velocity of the fluid, velocity of fluid at control surface 1, at C.S. 2

**V:** velocity of the product

**V_C.V.:** volume inside control volume

**v:** velocity of undeformed billet

**v_s:** (in thermal analysis) velocity of workpiece surface

**W_P:** Heat released by plastic work

**x, x_o, x_r:** distance along the die wall, distance to start of reduction zone, distance to end of reduction zone

**x_c:** (in thermal analysis) horizontal distance to centroid

**Y:** initial yield stress of workpiece

**y:** distance perpendicular to the die wall

**y_c:** (in thermal analysis) vertical distance to centroid

**Z_i:** distance from the intersection of the die and workpiece to the start of the conical die section

**z:** distance measured along the drawing axis

**a, a_c, a_d:** half angle of the die, half angle of the convergent area of the exit zone, half angle of the divergent area of the exit zone

**β:** pressure viscosity exponent

**δ:** temperature viscosity exponent

**ε:** effective strain in the workpiece

**θ:** circumferential direction

**η, η_i:** fluid viscosity, fluid viscosity under no pressure and ambient temperature condition

**ρ_w, ρ_r:** density of the workpiece, density of the lubricant

**σ_y, σ_z:** flow stress, axial stress

**τ, τ_w, τ_s:** shear stress in the fluid film, shear stress on workpiece surface, shear stress on control surface

### 4.3 Background Information

Drawing is a metal forming operation in which a rod, wire, or tube is pulled through one or more dies with convergent geometry. As the workpiece travels from the large side of the die to the small side, its outer dimensions are reduced as its length increases. The process is carried out on numerous length scales, but generally the feed stock is long enough that at least some of the process is considered to occur in steady state conditions. Additionally, drawing is generally carried out at temperatures that fall into the cold working range for most metals. This results in a low cost product that has tightly controlled dimensions and surface quality, as well
as improved mechanical properties. Drawing is commonly used to create seamless tubing, metal wire, and bar stock with numerous cross-sections out of a variety of metals.

As with other metal forming operations, lubrication in the drawing process falls into one of several categories, i) boundary layer, ii) hydrodynamic, and iii) mixed lubrication. From the standpoint of creating hydrodynamic cavitation in the drawing process, hydrodynamic lubrication is the most interesting lubrication regime. Hydrodynamic cavitation is the only lubrication regime in which the lubricant flows from one side of the die to the other in an uninterrupted flow. As it does, it is squeezed between the die and the workpiece until it is suddenly released at the exit of the die. This rapid release of pressure causes the lubricant to rush through the exit geometry of the die, possibly causing the pressure in the lubricant to drop below the pressure at outlet of the die. This action is ideal for creating cavitation if it can be optimized and controlled.

The basic geometry which will be used in the derivation of the equations which define the hydrodynamic drawing process is given in Figure 22. The workpiece starts with a diameter of $D_o$ on the inlet side of the die and is reduced to a diameter of $D_f$ at the product side of the die. The inlet zone starts at the beginning of the conical part of the die and ends when the workpiece begins to plastically deform. The reduction zone in the die begins where the workpiece starts to plastically deform and ends where the plastic deformation of the workpiece stops. The exit zone then extends from the point at which plastic deformation stopped to the outlet of the die. The thickness of the lubricant film, $h$, is defined by the normal distance between the die and the workpiece and the drawing speed of the process, $V$, is defined as the speed at which the product is pulled through the die.
4.4 Inlet Zone Derivation

The inlet zone is defined as extending from the start of the taper on the die to the onset of plastic deformation in the workpiece. In this zone, the workpiece is assumed to behave as a rigid-plastic material. Thus, in the inlet zone the workpiece will behave as a rigid material of known diameter ($D_o$). The change in the temperature in the fluid film in the inlet zone will be ignored because the film thickness is large enough in the majority of the inlet zone that the temperature rise in the fluid film due to viscous shearing is expected to be very small. Due to the complicated nature of the equations governing a fluid film defined in cylindrical coordinates and because the thickness of the film is expected to be small with respect to the diameter of the rod, the forces on the fluid element will be evaluated in rectilinear coordinates. It will also be assumed that the fluid only flows in one direction (parallel to the drawing direction) and that the fluid flow is assumed to be laminar. Because the fluid film is axisymmetric, the system can be reduced to a two dimensional system, as shown in Figure 23a. The analysis of the inlet zone follows closely with the techniques presented by Bloor et al. [36], except for the Reynolds equation, which must be re-derived due to the circular nature of the part. The horizontal axis will be the $Z$-axis and $Z=0$ will be at the line where the billet would touch the die if there were no fluid film. The vertical axis will be the $r$-axis and $r=0$ will be at the center of the part. The horizontal distance from the origin to the start of the taper on the die is $Z_i$ and it is assumed that the pressure in the fluid will remain at a constant inlet
pressure \( P_o \) until it reaches this point. After the fluid reaches the taper in the die, its pressure will begin to rise as a result of a steady decrease in the fluid film thickness \( h \) creating a wedge effect. The thickness of the film in the inlet zone can be easily described with Equation 2 because both the die and workpiece behave as rigid bodies.

\[ h = Z \tan(\alpha) \]  

Equation 2.

![Figure 23: a) Geometry in the Inlet Zone; b) Stresses Acting on a Differential Fluid Element in the Inlet Zone](image)

In order to determine when the inlet zone ends one must be able to determine what fluid pressure would cause the workpiece to yield. If friction on the surface of the workpiece is ignored and the workpiece is assumed to obey von Mises’ yield criteria this can be easily calculated as shown in Equation 3, where \( \sigma_z \) is the axial stress in the workpiece and \( Y \) is the material’s initial yield stress.

\[ P = Y - \sigma_z \]  

Equation 3.

In order to determine when the pressure rises high enough to yield the workpiece, the equations which govern the fluid film in the inlet zone must be derived. First, the forces on the fluid element must be determined and summed. In this case we are concerned with the forces which act in the direction of the fluid flow. These forces are 1) the normal force on the element due to pressure and 2) the shearing force on the element that results from the non-uniform velocity filed in the flow, as seen in Figure 23b. Summing these forces yields Equation 4.
\[ 0 = dP \ast dr - d\tau \ast dz \quad \text{Equation 4.} \]

This equation can be rearranged into the differential equation shown in Equation 5 by relating the shear stress to the rate of change in the fluid velocity \((u)\) and the fluid viscosity \((\eta)\).

\[ \frac{dP}{dz} = \frac{d\tau}{dr} = \eta \frac{d^2 u}{dr^2} \quad \text{Equation 5.} \]

This differential equation can be solved to yield Equation 6 by applying the following stiction boundary conditions: 1) the speed of the fluid at the die wall \((r = \frac{D_o}{2} + h)\) will be zero, 2) the speed of the fluid at the surface of the workpiece \((r = \frac{D_o}{2})\) will be equal to the speed of the workpiece. The speed of the workpiece can be given by Equation 7, where \(V\) is the drawing speed of the product and \(D_f\) is the final diameter of the workpiece.

\[ u(r) = \frac{dP}{dz} \frac{r^2}{2\eta} - \frac{1}{2} \left( \frac{dP}{dz} D_o h + \frac{dP}{dz} h^2 + 2\eta \right) \ast \frac{r}{\eta h} \]

\[ + \frac{1}{8} \left( 8\eta h + \frac{dP}{dz} D_o^2 h + 2D_o \frac{dP}{dz} h^2 + 4D_o \eta \right) \]

\[ \eta \quad \text{Equation 6.} \]

\[ v = V \left( \frac{D_f}{D_o} \right)^2 \quad \text{Equation 7.} \]

Now that the expression for the speed of the fluid has been derived, it can be integrated over the annulus that is perpendicular to the flow direction to obtain an expression for the flow rate as shown in Equation 8 (this equation is also referred to as the integrated form of the Reynold’s equation). It should be noted that the flow rate of fluid is a function of fluid viscosity, fluid pressure, and the film thickness.

\[ Q = \int_{\frac{D_o}{2}}^{\frac{D_o}{2} + h} 2\pi r u dr = -\frac{1}{12} \pi h (D_o h^2 + h^3) \frac{dP}{dz} \frac{1}{\eta} - \frac{1}{12} \pi h (-6D_o v - 4vh) \quad \text{Equation 8.} \]
The expression for the flow rate should be rearranged to give an expression of the pressure in the film as a function of the fluid viscosity, flow rate, and the film thickness, as shown in Equation 9.

\[
\frac{dP}{dz} = 2\eta \frac{(3\pi h v D_o + 2\pi h^2 v - 6Q)}{\pi h^3 (D_o + h)}
\]  

Equation 9.

Due to the high pressures observed in the fluid film, the viscosity of the fluid cannot be considered constant throughout the inlet zone. The viscosity of the fluid will be assumed to be defined as shown in Equation 10, where \( \eta_i \) is the viscosity (N-s/m\(^2\)) of the fluid at atmospheric pressure and room temperature, \( P \) is the pressure (Pa) in the fluid film, and \( \beta \) is the pressure viscosity exponent (1/Pa). Thus the pressure gradient in the film can be given by Equation 11.

\[
\eta = \eta_i e^{\beta P}
\]  

Equation 10.

\[
\frac{dP}{dz} = 2\eta_i e^{\beta P} \frac{(3\pi h v D_o + 2\pi h^2 v - 6Q)}{\pi h^3 (D_o + h)}
\]  

Equation 11.

It is desirable to remove the exponential term from the above expressions so that pressure boundary conditions can be applied without significantly complicating the equations. To do this the expression for the pressure should be multiplied by \( e^{-\beta P} \), as was done by Bloor et al. [36]. This results in Equation 12.

\[
e^{-\beta P} \frac{dP}{dz} = 2\eta_i \frac{(3\pi h v D_o + 2\pi h^2 v - 6Q)}{\pi h^3 (D_o + h)}
\]  

Equation 12.

In order to finish removing the exponential term, a dummy variable is used. The dummy variable, \( q \), is defined according to Equation 13 and Equation 14.

\[
q = \frac{1}{\beta} (1 - e^{-\beta P})
\]  

Equation 13.
\[
\frac{dq}{dz} = e^{-\beta P} \frac{dP}{dz}
\]

Equation 14.

Equation 14 can then be substituted into Equation 12 to arrive at Equation 15. In order to solve this differential equation, it is necessary to rewrite this equation using Equation 2 so that the \(h\) terms are replaced with \(z\) terms, as shown in Equation 16.

\[
\frac{dq}{dz} = 2\eta_i \frac{(3\pi h v D_o + 2\pi h^2 v - 6Q)}{\pi h^3 (D_o + h)}
\]

Equation 15.

\[
\frac{dq}{dz} = \frac{2\eta_i (3\pi \tan(\alpha) z v D_o + 2\pi \tan(\alpha)^2 z^2 v - 6Q)}{\pi \tan(\alpha) z^3 (D_o + \tan(\alpha) z)}
\]

Equation 16.

Now the differential equation can be solved using the boundary condition (Equation 17).

\[
P(Z_i) = P_o \rightarrow q(Z_i) = \frac{1}{\beta} \left( 1 - e^{-\beta P_o} \right)
\]

Equation 17.

The solution to the differential equation gives \(q\) as a function of \(z\) and the flow rate and should be rearranged using Equation 2 to replace the \(z\) terms with \(h\) terms. The resulting solution is given in Equation A1 in the appendix. In order to determine the thickness of the film at the onset of plastic yielding one needs to convert the yielding pressure given in Equation 3 to \(q\) using Equation 13. This can be used to relate the film thickness at the end of the inlet zone to the flow rate of the fluid. Unfortunately, another equation is needed to determine the film thickness at the onset of plastic yielding. Bloor et al. obtain this equation by assuming that the velocity in the film varies linearly from the die wall to the workpiece [36], however, this assumption breaks down for large film thickness, very soft workpieces, and fluids with low viscosity. In order to improve the accuracy of the model, the required equation will instead come from the equations describing the fluid film in the deformation zone, as outlined in the following section.

4.5 Reduction Zone Derivations

To date, the deformation zone has been extensively studied in most metal forming operations. In the 1960’s Avitzur put a great deal of emphasis on the extrusion and drawing
processes and developed numerous analytical models to describe the processes [74, 75]. These models made use of techniques like upper and lower bound analysis to determine the optimal tool geometry, loads on the tools, and machine load requirements. Though a simpler technique is used to analyze the reduction zone, this knowledge serves as the building block for the analysis of the hydrodynamic lubrication film in the reduction zone.

4.5.1 Yield Conditions

In order for the fluid to establish a stable film over the workpiece during deformation, the film must produce sufficient pressure to yield the workpiece. Additionally, because of the small size of the fluid film, it is not expected to greatly affect the material’s strain at a particular position in the die. This leads to the assumption that the pressure in the fluid film can be determined through the material yield criteria. This is not done in most models which deal with hydrodynamic lubrication of drawn or extruded parts, but will be adopted here due to several advantages. Chiefly, this assumption allows the model to be easily modified to handle various workpiece materials and strain hardening functions. It has the added benefit of making the derivation of film thickness much simpler, by reducing the number of unknowns that need to be determined from three to two. To this end, slab analysis was used to find the pressure required to cause the material to yield at each point in the die [76]. The slab of material analyzed and the stresses acting on the slab are shown in Figure 24 and the differential equation derived from the summation of these forces is given in Equation 18. This can be further simplified by using Equation 19 and Equation 20 to arrive at Equation 21. It should be noted that this analysis ignores dynamic effects in the deformation process and redundant strain in the workpiece.
Figure 24: Stresses Acting on a Slab of the Workpiece in the Reduction Zone

\[ 0 = 2\sigma_z dx + d\sigma_z x + 2P dx + \frac{2\tau_w dx}{\tan(\alpha)} \]

Equation 18.

\[ P = \sigma_y - \sigma_z \]

Equation 19.

\[ \tau_w = mK = \frac{m}{\sqrt{3}}\sigma_y \]

Equation 20.

\[ \frac{d\sigma_z}{dx} = -\frac{2\sigma_y}{x} \left( 1 + \frac{m}{\sqrt{3} \tan(\alpha)} \right) \]

Equation 21.

The flow stress of the workpiece can be defined in many ways, but one must ensure that the flow stress at a strain of zero is equal to the yields stress used in the inlet zone analysis. This rules out the simple power law stress-strain relationship, but stress-strain relationships like the Swift law, Equation 22, would be appropriate. The effective strain, \( \varepsilon \), is given by Equation 23.

\[ \sigma_y = K \left( \varepsilon + \left( \frac{Y}{K} \right)^{\frac{1}{n}} \right)^n \]

Equation 22.

\[ \varepsilon = 2 \ln \left( \frac{D_o}{D} \right) \]

Equation 23.
An example of several pressure profiles generated for various friction factors in this fashion is shown in Figure 25. Note that the diameter for which the yielding pressure is zero represents the maximum achievable reduction for the given friction condition, as the drawing stress alone is enough to cause yielding in the product. Furthermore, it is important to recognize that the pressure required to continue plastic deformation is not the same as the flow stress of the material; it controls only one portion of the stress state. In general, the pressure decreases as the workpiece is drawn down due to the increasing axial stress in the material. The peaks in the curves in Figure 25 occur due to the material’s flow stress increasing faster than the axial stress builds.

![Figure 25: Lubricant Pressure Distribution Derived for an Aluminum Workpiece (K=200MPa n=0.2), for Various Shear Friction Factors](image)

### 4.5.2 Initial Lubricant Thickness

The geometry used in this zone is defined in Figure 26a. The coordinate system used in this zone is defined so that the x axis lies along the die wall and position of x=0 is at the apex of the cone which makes up the reduction zone of the die. The y axis is perpendicular to the x axis and points towards the center of the workpiece and a y value of 0 represents the die wall. Now that the pressure distribution in the film has been determined it is possible to determine the thickness of the film in the deformation zone as a function of the x-position along the die. To do this, it is once again assumed that the thickness of the film will be very small in comparison to the diameter of the workpiece, so the curvature of the differential fluid element
can be ignored. Additionally, surface of the workpiece is assumed to be essentially parallel to the surface of the die. Thus, the thickness of the fluid film is given by the y distance from the die wall to the surface of the workpiece. The flow is assumed to be axisymmetric and is assumed to be in the –x direction only, with no flow in the θ or y directions.

As was done in the inlet zone, the forces acting in the direction of flow on the differential fluid element, shown in Figure 26b, must be summed to arrive at Equation 24, which can be expanded into the differential equation shown in Equation 25.

\[
0 = dP \, dy - dτ \, dx
\]  

Equation 24.

\[
\frac{dP}{dx} = \frac{dτ}{dy} = \eta \frac{d^2 u}{dy^2}
\]  

Equation 25.

This differential equation can be solved by using the stiction boundary conditions shown in Equation 26 and Equation 27, \( U \) is the instantaneous speed of the workpiece given by Equation 28. The solution to Equation 25 gives an expression for the speed of the fluid, as shown in Equation 29.

\[
u(y = 0) = 0
\]  

Equation 26.
\[ u(y = h) = U \quad \text{Equation 27.} \]

\[ U = \left( \frac{D_p}{2x\sin(\alpha)} \right)^2 \frac{V}{\cos(\alpha)} \quad \text{Equation 28.} \]

\[ u = \frac{dP}{dx} \left( y^2 - hy \right) \frac{2\eta}{h} + Uy \quad \text{Equation 29.} \]

Now, the flow rate of the fluid through the deformation zone can be determined by integrating the speed of the flow over the area between the die and the workpiece, as shown in Equation 30. The \( \pi \) and \( x \) term appear in this equation because the curvature of the differential area was considered to account for the shrinking of the differential area segment with reduction in the die’s diameter. Carrying out the integration in Equation 30 leads to Equation 31.

\[ Q = \int_0^h 2\pi \sin(\alpha) x u dy \quad \text{Equation 30.} \]

\[ Q = \frac{\pi \sin(\alpha) x \left( \frac{dP}{dx} \right) h^3}{3\eta} + \pi \sin(\alpha) x \left( \frac{U}{h} - \left( \frac{dP}{dx} \right) \frac{h}{2\eta} \right) h^2 \quad \text{Equation 31.} \]

Now that the flow rate in the reduction zone has been determined as a function of the film thickness, the thickness of the film at the onset of yielding must be determined. To do this, an expression for the flow rate as a function of the film thickness at the start of the deformation zone must be determined. This is accomplished by replacing the variable \( x \) with the value of \( x \) at the beginning of the deformation zone \( \frac{D_0}{2\sin(\alpha)} \), which results in Equation 32. This expression can be equated with the flow rate in the inlet zone at the onset of plastic yielding to determine the initial thickness of the fluid film in the reduction zone. This will be an important boundary condition for determining the film thickness in the remainder of the deformation zone.
\[ Q = \frac{\pi \sin(\alpha) \left( \frac{D_0}{2 \sin(\alpha)} \left( \frac{dP}{dx} \right) h^3 \right)}{3\eta} + \pi \sin(\alpha) \left( \frac{D_0}{2 \sin(\alpha)} \left( \frac{U}{h} - \left( \frac{dP}{dx} \right) h \right) \right) h^2 \]  

Equation 32.

4.5.3 Lubricant Thickness in the Reduction Zone

Now that the thickness and flow rate at the transition between the inlet zone and the reduction zone are known, it is possible to determine the thickness of the fluid film anywhere in the reduction zone. This is because the mass and, by extension, the volume of the fluid must be conserved because the fluid is incompressible. This leads to the conclusion that the derivative of the flow rate with respect to the direction of flow (x) must be zero everywhere. So by taking the derivative of the flow rate, setting it equal to zero, and rearranging so that the \( \frac{dh}{dx} \) terms are consolidated one arrives at Equation A2, shown in the appendix. This differential equation describes the change in film thickness as a function of the x position, the derivatives of the fluid pressure, the viscosity and its derivative, and the current fluid film thickness. Recall that the pressure and its derivatives are taken from the pressure profile determined in the slab analysis of the workpiece in section 3.2.1.

In order to solve the differential equation presented in Equation A2, a numerical technique is used. Specifically, a forward Euler technique can be employed to approximate the thickness of the film at any point in the reduction zone. However, due to the temperature dependent changes in the fluid viscosity, solving for the lubricant film thickness is more involved than simply setting up the problem and marching the solution from one end of the die to the other. Obtaining an accurate solution necessitates the determination of the temperature in the fluid film at each point in the die.

4.5.4 Temperature Considerations

In order to determine the temperature of the lubricant at each step in the solution, Equation A2 must be coupled with an equation that describes the thermal state in the lubricant film. The one dimensional steady state heat conduction equation can be used to fill this role, assuming that the amount of heat that is transferred from one segment of the film to the segments adjacent to it is insignificant when compared to the amount of heat transferred between the workpiece and die. The one dimensional steady state heat conduction equation is given in Equation 33,
where $k$ is the heat conduction coefficient for the lubricant and $q_{gen}$ is the amount of heat generated in the fluid due to mechanical losses per unit volume.

$$k \frac{d^2 T}{dy^2} + q_{gen} = 0$$

Equation 33.

The solution to Equation 33 can then be written as Equation 34, where $T_w$ is the temperature of the workpiece, $T_d$ is the temperature of the die. The average temperature is found by integrating this equation over thickness of the lubricant, as shown in Equation 35. This average temperature will be used to calculate the viscosity of the fluid at the next step, which allows the stepwise solution of Equation A2 to account for changes in temperature dependent properties of the lubricant film. However, before this can be done the heat generated in the lubricant and the temperatures of both the workpiece and die surfaces must be determined.

$$T(y) = -\frac{q_{gen}y^2}{2k} - \frac{(-2T_wk - q_{gen}h^2 + 2T_dk)y}{2hk} + T_d$$

Equation 34.

$$T_{avg} = \frac{1}{h} \int_0^h T(y) dy = \frac{q_{gen}h^2 + 6T_wk + 6T_dk}{12k}$$

Equation 35.

$q_{gen}$ can be determined by finding the total amount of mechanical power dissipated in a segment, or control volume, of the lubricant and dividing it by the volume of the segment. The dissipated mechanical power can be determined by summing up the total amount of kinetic and potential energy entering and leaving the control volume in addition to the work done to the control volume by the workpiece through shear. To determine the heat generated between two solution states, the control volume is placed between the two steps, as depicted in Figure 27. Mechanical power is carried into and out of the control volume in three ways, i) the motion of the lubricant particles entering and leaving the control volume (kinetic energy), ii) the pressure of the fluid entering and exiting the control surface (potential energy), and iii) work done to the surface of the control volume through viscous shear.
The amount of power entering or leaving the control volume due to the pressure at the surface is given by Equation 36, where $\dot{E}_p$ is the power transferred to the control volume by the pressure ($P$) in the flow, $\vec{u}$ is the position dependent velocity of fluid, and $\vec{N}$ is the unit normal to the control surface. The power transfer across the control surface due to the motion of the fluid particles is given by Equation 37, where $\dot{E}_k$ is the power moved across the control surface by the motion of the lubricant particles and $\rho$ is the density of the lubricant. The power given to the control volume by the viscous shear done to its control surfaces is given by Equation 38, where $\dot{E}_w$ is the power delivered to control volume by shearing action, $\tau_s$ is the shear stress on the control surface, and $v_s$ is the component of velocity which is parallel to the control surface (in this case the workpiece velocity).

\[ \dot{E}_p = \oint P(\vec{u} \cdot \vec{N})dA \]  
Equation 36.

\[ \dot{E}_k = \oint \left(\frac{1}{2} \rho_f u^2\right) (\vec{u} \cdot \vec{N})dA \]  
Equation 37.

\[ \dot{E}_w = \oint \tau_s v_s dA \]  
Equation 38.

These equations can be easily simplified by breaking the control surface into four separate surfaces, two of which are perpendicular to the flow and two of which are parallel to the flow, as shown in Figure 28. It is clear that no power from the pressure in the fluid or the motion of its particles crosses the third or fourth control surface, because the direction of flow is parallel.
to the surface and thus \((\vec{u} \cdot \vec{n}) = 0\). Furthermore, the die cannot do work to the control volume through viscous shear, because the die does not move and thus \(v_z = 0\) at the fourth control surface. The sum of the power entering and exiting the control volume can be written as Equation 39 by assuming i) couette flow \(\frac{du}{dy} = \text{Const.}\), ii) constant workpiece velocity over the third control surface, iii) constant pressure across the first and second control surfaces, and iv) constant fluid properties \((\rho, \eta)\) over the control volume. Because convention dictates that the unit normal points outward from the control volume, negative signs must be added to the pressure and motion power terms so that power entering the control volume is positive and power leaving is negative. The area of the third control surface, \(A_3\), is given by Equation 40.

\[
\dot{E}_{tot} = \eta A_3 \left( \frac{U_1 + U_2}{2} \right)^2 - (P_2 - P_1)Q - \frac{\pi}{2} \rho_f \left[ D_2 h_2 (U_2)^3 - D_1 h_1 (U_1)^3 \right] \quad \text{Equation 39.}
\]

\[
A_3 = \pi \frac{D_1 + D_2}{2} \sqrt{\frac{(D_1 - D_2)^2}{2} + \frac{(D_1 - D_2)^2}{2 \tan(\alpha)}} \quad \text{Equation 40.}
\]

Figure 28: Control Surfaces of the Control Volume

Another way to think of Equation 39 is that \(\dot{E}_{tot}\) represents the total amount of mechanical power lost over the control volume. Conservation of energy dictates that this loss in mechanical power corresponds to a rise in the heat generated in the control volume. Thus the heat generated per unit volume in the control volume can be written by Equation 41, where
\( V_{C.V.} \) is the volume of the control volume. The volume of the control volume is given by Equation 42 - Equation 46.

\[
q_{gen} = \frac{\dot{E}_{tot}}{V_{C.V.}}
\]

Equation 41.

\[
V_{C.V.} = 2\pi r_c A_{C.V.}
\]

Equation 42.

\[
A_{C.V.} = \left[ \min(h_1, h_2) + \frac{1}{2}|h_1 - h_2| \right] S
\]

Equation 43.

\[
r_c = r_1 - x_c \sin(\alpha) - y_c \cos(\alpha)
\]

Equation 44.

\[
x_c = \left( \frac{\min(h_1, h_2) S}{A_{C.V.}} \right) \left( \frac{S}{2} \right) + \left( \frac{|h_1 - h_2| S}{A_{C.V.}} \right) \begin{cases} 
\frac{1}{3} S, & \text{if } h_1 > h_2 \\
\frac{2}{3} S, & \text{if } h_2 > h_1 \\
0, & \text{if } h_1 = h_2 
\end{cases}
\]

Equation 45.

\[
y_c = \left( \frac{\min(h_1, h_2) S}{A_{C.V.}} \right) \left( \frac{1}{2} \right) \min(h_1, h_2) + \left( \frac{|h_1 - h_2| S}{A_{C.V.}} \right) \left( \frac{1}{3} \right) |h_1 - h_2|
\]

Equation 46.

In addition to the heat generated per unit volume, one needs to know the temperature at both the workpiece and the die in order to determine the temperature of the lubricant at each step in the solution. The initial temperature of the workpiece must be given, but its temperature in subsequent steps can be calculated. The change in the workpiece temperature from the current step to the following step can be determined by taking an energy balance over the segment of the workpiece between the steps. For the purposes of this analysis heat transfer between adjacent segments of the workpiece has been ignored due to much larger temperature gradient that exists between the workpiece and die. Thus, the change in the workpiece temperature is given in Equation 47, where \( t \) is the amount of time it takes for the workpiece to move from one step to the next, \( \frac{SA}{Vol} \) is the surface area to volume ratio of the workpiece segment being examined, and \( W_p \) is the amount of plastic work per unit volume generated in the workpiece.
for the current step. The plastic work is determined by integrating the stress-strain curve from the strain in the current step to the strain in the next step, as shown in Equation 48. The amount of heat transferred to the workpiece from the lubricant \((q_{\text{workpiece}})\) can be written using Equation 49, where the negative sign ensures that a negative quantity is achieved if heat leaves the workpiece.

\[
\Delta T_w = \frac{q_{\text{workpiece}} \left( \frac{SA}{Vol} \right) t + W_p}{\rho_w c_{pw}} \quad \text{Equation 47.}
\]

\[
W_p = \int_{\varepsilon_i}^{\varepsilon_i+1} \sigma(\varepsilon)d\varepsilon \quad \text{Equation 48.}
\]

\[
q_{\text{workpiece}} = -k \frac{dT}{dy} \big|_{y=h} = q_{gen}h + \frac{-2T_w k - q_{gen} h^2 + 2T_d k}{2h} \quad \text{Equation 49.}
\]

The temperature on the surface of the die is more difficult to define since it remains in place as the workpiece moves through it. This means that it reaches some steady state temperature, because, unlike the workpiece, there is ample time for the heat to spread throughout the die. Thus the temperature on the surface of the die cannot be determined in a stepwise fashion. To surmount this problem, the die surface temperature will be determined in an iterative fashion. This is carried out by making an initial guess at the surface temperature of the die and using this guess to solve for the thickness of the lubricant film at each solution step, using Equation A2 and Equation 33. Along the way the heat transferred to the die at each step of the solution, given in Equation 50, is recorded. A good starting guess for the die temperature is the ambient temperature, as this is a logical lower bound.

\[
q_{\text{die}} = k \frac{dT}{dy} \big|_{y=0} = -\frac{-2T_w k - q_{gen} h^2 + 2T_d k}{2h} \quad \text{Equation 50.}
\]

Once the final step in the solution is reached, the recorded heat flux values are used, alongside suitable boundary conditions, to create a finite difference model to solve the steady state heat conduction equation in the die, as shown in Figure 29a. The output of the finite difference model is the temperature at various points in the die for the given boundary
conditions, as shown in Figure 29b. The die surface temperatures are then recorded and compared to the temperature distribution that was assumed for the die surface to check for convergence. If the temperature at any point on the die differs too much from the original guess, a new guess is made and the solution process is repeated. At any point on the surface of the die the new guess for the temperature should be dictated by Equation 51, where $T_{FD}$ is the temperature predicted by the finite difference model and $B$ is a constant between 1 and 0. In general, $B$ should be kept low, 0.01 to 0.05, because the solution is very sensitive to changes in the lubricant temperature and large changes in the temperature of the die can lead to instability of the solution.

$$T_{new} = T_{old} + B(T_{FD} - T_{old})$$

Equation 51.

Thus, through the use of a stepwise process to determine the thermal and physical state of the lubricant film and the workpiece, and an iterative process to determine the temperature distribution in the die, a complete thermal and physical picture of the hydrodynamic drawing process is obtained. This process is summarized in the flow chart in Figure 30. The analytical model presented in this paper is extremely flexible and is applicable to a wide variety of drawing processes, as it can be adjusted to account for a wide range of drawing speeds, die geometries, material and lubricant properties, flow stress definitions, and thermal conditions.
Figure 30: Flow Chart for the Solution Scheme Posed to Solve for the Lubricant Film Thickness in the Reduction Zone of a Drawing Die

4.6 Exit Zone Derivation

Analysis of the outlet zone in our model will start by using the assumptions and techniques used in the previous analyses of the outlet zone and be modified as needed to fit the current needs of the hydrodynamic drawing model. For the purposes of establishing the equations that govern the exit zone it will be assumed that i) the workpiece changes from a plastically deforming body in the reduction zone to a rigid body in the outlet zone and ii) the characteristics of the outlet zone do not affect either the inlet or reduction zones of the model.

In order to fully determine the properties and behavior of the lubricant film in the outlet zone, it is necessary to establish geometric relationships and completely define the geometry at the die exit. However, this creates some problems because the clearance between the workpiece and die greatly affects the pressure in the flow as it escapes the die and it is not known beforehand. In order to determine the clearance between the workpiece and the die exit, a guess of the workpiece’s final diameter must be made and used to determine the pressure profile in the fluid film as it escapes the die.

The determination of the pressure profile at the die exit is done using the same methodology that was used to determine the pressure profile in the inlet zone of the die. The major difference is that the definition of the film thickness in this zone is more complex (it could be any
continuous function and may be defined in a piecewise fashion) and the pressure boundary condition is defined at the end of the zone (exit of the die) rather than at the start of the zone. Additionally, the flow rate of the lubricant is also known, as it was defined in the determination of the initial height of the fluid film. For the purposes of the initial study of the exit zone, the die geometry will be defined as shown in Figure 31. Because the geometry is not smooth, it is necessary to define it in a piecewise manner, which requires the solution to be carried out for each section individually. For each section of the die exit, the differential equations describing the pressure in the fluid film will be re-derived using the methodology presented in the inlet zone section of the derivation. The analysis will start with the furthest zone from the reduction zone and proceed toward the reduction zone, ensuring that the pressure is continuous from one zone to the next.

Figure 31: Geometry of the Exit Zone

Figure 32 illustrates the geometry of just the zone furthest from the entry of the die (i.e. the divergent area of the exit zone). The thickness of the fluid film can clearly be defined using Equation 52. Following the derivation set out in the analysis of the entry zone of the die and solving for pressure in terms of the position in the examined zone and the flow rate of the lubricant, it is possible to derive Equation 53. The boundary condition for the next area in the exit zone analysis is defined by plugging in the axial position at the entry of the current zone into Equation 53 and solving for the pressure.
Figure 32: Geometry of the Divergent Area of the Exit Zone

\[ h_d = (R_e - R_p) - z \tan(\alpha_d) \]  

Equation 52.

\[ P_2 = \]

\[-\frac{1}{\beta} \ln \left( \frac{1}{\pi D_p^3 \tan(\alpha_d) h_3^2 (h_3^2 + 2h_3 \tan(\alpha_d) z + \tan(\alpha_d) z^2)} \right) (\pi D_p^3 \tan(\alpha_d) h_3^4 e^{-\beta P_3} - \right.\]

\[ 12\eta Q \beta D_p h_3^2 \tan(\alpha_d) z + 12Q \eta D_p^2 \beta h_3 \tan(\alpha_d) z - \]

\[ 12\eta Q D_p h_3 \beta \tan(\alpha_d)^2 z^2 - 6\eta \beta \pi D_p^3 h_3^2 \tan(\alpha_d) z - \]

\[ 6\eta \pi D_p^3 h_3 \beta \tan(\alpha_d)^2 z^2 + \pi D_p^3 \tan(\alpha_d)^3 h_3^2 e^{-\beta P_3} z^2 + \]

\[ 6\eta Q D_p^2 \beta \tan(\alpha_d)^2 z^2 + 2\pi D_p^3 \tan(\alpha_d)^2 h_3^3 e^{-\beta P_3} z - 12\ln(\Gamma_2) \eta Q h_3^4 \beta - \]

\[ 2\ln(\Gamma_2) \eta V \pi D_p^3 h_3^4 \beta - 24\ln(\Gamma_2) \eta Q h_3^4 \beta \tan(\alpha_d) z - \]

\[ 12\ln(\Gamma_2) \eta Q h_3^4 \beta \tan(\alpha_d)^2 z^2 - 4\ln(\Gamma_2) \eta V \pi D_p^3 h_3^4 \beta \tan(\alpha_d) z - \]

\[ 2\ln(\Gamma_2) \eta V \pi D_p^3 h_3^4 \beta \tan(\alpha_d)^2 z^2 ) \]

where \( \Gamma_2 = \frac{h_3 (D_p + h_3 + \tan(\alpha_d) z)}{(D_p h_3 + h_3 + \tan(\alpha_d) z)} \)  

Equation 53.

Figure 33 illustrates the next area in the exit zone analysis (i.e. the land area of the exit zone). The thickness of the fluid film in this area is constant and is given by Equation 54. Once again, this is used to derive an equation for the pressure as a function of the axial position and the flow rate, as shown in Equation 55. The boundary condition for the next zone is derived by determining the pressure at the inlet side of this area.
Figure 33: Geometry of the Land Area of the Exit Zone

\[ h_L = R_L - R_P \]  \hspace{1cm} \text{Equation 54.}  

\[ p_3 = -\frac{1}{\beta^*} \ln \left( \frac{-6\eta\beta \pi h_3 V D_p - 4\eta\beta \pi h_3^2 V + 12\eta\beta Q + h_3^3 \pi e^{-\beta p_4} D_p + h_3^2 \pi e^{-\beta p_4}}{\pi h_3^3 (D_p + h_3)} \right) \]  \hspace{1cm} \text{Equation 55.}  

Figure 34 illustrates the final area in the exit zone (i.e. the convergent area of the exit zone). The thickness of the lubricant in this area is defined by Equation 56. This thickness function is used to derive Equation 57, which defines the pressure in the zone as a function of the axial position and the flow rate. In a similar fashion to the other zones, the pressure at the start of this zone must be determined to ensure continuity with the reduction zone.

Figure 34: Geometry of the Convergent Area of the Exit Zone
\[ h_c = R_L - R_p + z \tan(\alpha_c) \]  

Equation 56.

\[ P_4 = \]

\[ -\frac{1}{\beta} \ln \left( \frac{1}{\tan(\alpha_c)h_5^2\pi D_p^3(h_5^2 - 2h_5 \tan(\alpha_c)z + \tan(\alpha_c)^2 z^2)} \tan(\alpha_c)h_5^4\pi D_p^3 e^{-\beta P_5} + \right. \]

\[ 12Q\eta h_5 D_p \beta \tan(\alpha_c)^2 z^2 + 12Q\eta D_p^2 \beta h_5 \tan(\alpha_c)z - \]

\[ 12Q\eta \beta D_p h_5^2 \tan(\alpha_c)z - 6Q\eta D_p^2 \beta \tan(\alpha_c)^2 z^2 - \]

\[ 2\tan(\alpha_c)^2 h_5^3 \pi D_p^3 e^{-\beta P_5} z + \tan(\alpha_c)^3 h_5^2 \pi D_p^3 e^{-\beta P_5} z^2 - \]

\[ 6V\eta \beta D_p^3 h_5^2 \tan(\alpha_c)z + 6V\eta h_5 \pi D_p^3 \beta \tan(\alpha_c)^2 z^2 - \]

\[ 4\ln(\Gamma_4)\eta V h_5^3 \pi D_p^2 \beta \tan(\alpha_c)z + 2\ln(\Gamma_4)\eta V h_5^2 \pi D_p^2 \beta \tan(\alpha_c)^2 z^2 + \]

\[ 12\ln(\Gamma_4)\eta Q h_5^2 \beta + 2\ln(\Gamma_4)\eta V h_5^2 \pi D_p^2 \beta - 24\ln(\Gamma_4)\eta Q h_5^2 \beta \tan(\alpha_c)z + \]

\[ 12\ln(\Gamma_4)\eta Q h_5^2 \beta \tan(\alpha_c)^2 z^2 \right) ; \]

where: \[ \Gamma_4 = \frac{h_5(D_p + h_5 - \tan(\alpha_c)z)}{(D_p + h_5)(h_5 - \tan(\alpha_c)z)} \]  

Equation 57.

For each guess of the final workpiece diameter, this analysis must be carried out and the pressure at the start of the exit zone must be determined using the exit zone analysis laid out previously. Inevitably, the guess will be wrong and the pressure determined from the exit zone analysis will not match the pressure determined in the reduction zone analysis. If the guess causes the predicted pressure to exceed the pressure at the end of the reduction zone, the product diameter must be decreased. If the predicted pressure is less than the reduction zone pressure, the workpiece diameter must be increased. This process is repeated until the results converge to an acceptable degree, leaving the modeler with a complete picture of the pressure and thickness profiles in the inlet, reduction, and exit zones. It is important to note that the pressure gradient in the exit zone of the die is much greater than the pressure gradient in the reduction zone and that the final workpiece diameter is likely only a few microns different from the diameter of the die land. This means that there is no need to recalculate the pressure at the exit of the reduction zone for each guess of the final workpiece diameter, simply using the pressure of the film at the die land diameter will suffice.
In some cases, the pressure required to push the lubricant though the exit zone at the prescribed flow rate will be so high that thickness of the lubricant film is required to be greater than the thickness of the film predicted for the end of the reduction zone. In order for this to occur, the deformation must continue into the land zone of the die. Of course, this means that the last of the three zones examined in the exit zone analysis is ignored and the pressure at the end of the die land must be made to match the pressure at the end of the reduction zone.

In order to demonstrate the results of such an analysis, two case studies are presented. Both case studies examine output results from the mathematical model which describes the inlet and outlet zones, but for the purposes of examining the behavior of the lubricant in the outlet zone, it will be sufficient to simply define the conditions at the end of the reduction zone. The properties of the lubricant and the geometry of the outlet are also needed. The same fluid properties are used for both case studies, but the outlet geometry is different due to the final diameter of the draws not being equal. The fluid properties are defined as follows: i) the nominal viscosity is 0.093 Pa – s and ii) the pressure viscosity exponent is $2.9 \times 10^{-8}$ $\frac{1}{Pa}$. Both processes will be assumed to have a product velocity of 1 m/s and an outlet pressure of 0 Pa.

The outlet geometry of the first case study is as follows: i) the diameter of the die exit is 35mm, ii) the diameter of the die land is 30 mm, iii) the length of the die land is 0.2 mm, and iv) the die half angle and the relief half angle are both 10°. The thickness of the film at the end of the reduction zone is 1.16 µm and the flow rate is $80.6 \times 10^{-9} \frac{m^2}{s}$. Using the iterative process laid out above, it is determined that there is too much resistance in the land for the lubricant to escape if the clearance between the product and die land is less than the lubricant thickness at the end of the reduction zone. Therefore, the workpiece continues to deform into the die land until the final product diameter is 29.9971 mm, which corresponds to a clearance of 1.91 µm. The pressure profiles for the land and the divergent areas of the exit zone are given in Figure 35, where the exit of the die is at position $z = 0$. It can be seen that the pressure drops rapidly from its initial value at the end of the reduction zone into negative numbers as it passes through the die land. As the lubricant travels through the divergent area of the exit zone, the pressure then rises back to the ambient pressure of 0 MPa. This drop into negative pressures might cause the fluid to cavitate as the tension placed on the fluid will cause any gaseous imperfections in the lubricant to grow and become unstable.

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The outlet geometry of the second case study is as follows: i) the diameter of the die exit is 45 mm, ii) the diameter of the die land is 40 mm, iii) the length of the die land is 0.2 mm, and iv) the die half angle and the relief half angle are both 10°. The thickness of the film at the end of the reduction zone is 3.11 µm and the flow rate is 199.8*10^{-9} m^3/s. Using the iterative process laid out above, it is determined that the fluid at the outlet pressure and flow rate could escape the exit zone with a lower clearance than the thickness of the lubricant at the end of the reduction zone. Therefore, the workpiece will turn rigid before it reaches the die land. In this case study the final product diameter is 39.9962 mm, which corresponds to a clearance of 1.91 µm. The pressure profiles for the convergent, land, and the divergent areas of the exit zone are given in Figure 36. In this figure the pressure in the convergent, land, and divergent areas of the die exit zone are marked in blue, red, and green, respectively. It can be seen that the pressure drops by a small amount in the convergent area of the die, but the major drop happens in the die land. Just as the lubricant exits the die land, it briefly drops to a negative value; however, it only maintains a negative value for a relatively short distance compared to the first case study. As the lubricant travels through the divergent area of the exit zone, the pressure then rises back to the ambient pressure of 0 MPa. Due to the decreased length of the zone of negative pressure, it is much less likely for the flow in case two to cavitate when compared to the lubricant in the first case study.
4.7 Extension to Multiple Reduction Dies

Due to the shrinking of the fluid film thickness over the length of the die, the film thickness may not be sufficient to completely separate the die and workpiece surfaces over the entirety of the reduction zone. If this occurs, the assumption that there is a stable fluid film on the surface of the part does not hold and the lubrication regime will fall into the mixed lubrication region. In order to avoid this, the die can be split into multiple separate reduction zones, between which pressurized lubricant can be supplied to refresh and strengthen the fluid film. The number of reduction zones and the pressure of the lubricant supplied to each can be optimized to ensure proper lubrication of the workpiece in a variety of conditions. This strategy of producing hydrodynamic lubrication may also prove useful because cavitation created in the exit zone of one die may be used to formulate the lubricant or texture the surface of the workpiece before the next reduction. Figure 37 shows an example of a die set that is capable of providing pressurized lubricant to multiple individual die segments.
Figure 37: Multiple Reduction Drawing Die Capable of Supplying Pressurized Lubricant to the Die Segments [77]

The first die section will not be supplied with pressurized fluid because there is no way to obtain a high quality seal on the undeformed rod. Every section after the first section can be pressurized due to the plastic deformation of the workpiece creating a sealing effect. The major limit to the fluid pressure which can be supplied to the inlet zones of the die is that the pressure cannot be greater than the yielding pressure of the material in the inlet zone, as this would cause yielding at the exit of the previous die and prevent the rod from being pulled through. Additionally, the die designer must ensure that the temperature of the drawing dies is maintained as near to room temperature as possible in order to achieve the maximum possible film thickness for a given process. This ensures that the viscosity of the lubricant is as large as possible during the drawing of the rod.

By applying the analytical model presented in the previous sections to each of the individual sections, the model can be easily extended to account for the proposed multiple reduction die. Because there is no deformation between the die segments, the drawing stress from one section can be considered the back stress in the inlet zone of the next section and, thus, yielding pressure will not change from the end of one segment to the start of the next. Essentially, the stress state in each of the die segments is identical to the stress state in a corresponding section of a die which completes the entire reduction in one step. Therefore, the pressure in the fluid film is not dependent on the number of dies in the process, but on the current reduction of the
workpiece. Because the film pressure on the workpiece is easy to find for all the die segments, the only additional information the designer needs to provide to extend the model to multiple consecutive reductions is the diameter of the workpiece at the start and end of each reduction and the applied fluid pressure in the inlet of each section.

4.8 Case Studies

To demonstrate the solution scheme, a case study will be examined. The fluid film will be simulated for the drawing of an aluminum rod (K=200 MPa, n=0.2, \(\sigma_y=70\) MPa, \(c_p=1800\frac{kJ}{kgK}\), \(\rho=857\frac{kg}{m^3}\)) from 50mm to 30mm. The velocity of the product will be set to 1m/s, the die half angle will be 10°, and the inlet length will be set to 10mm. No augmenting pressure will be supplied to the lubricant in the inlet zone. The lubricant will be considered a fully formulated, naphthenic industrial oil whose viscosity is given by Equation 58 where T is difference between the temperature in the fluid and the reference temperature, \(\eta_l = 93 \times 10^{-3}\frac{Ns}{m^2}\), \(\beta = 2.9 \times 10^{-8}\frac{m^2}{N}\), and \(\delta = 0.0625 \frac{1}{k}\). The conductivity of the lubricant and die were considered to be 0.12 and 60.5 \(\frac{W}{mK}\), respectively. Equation 21 was used to determine the pressure in the fluid film assuming a shear friction factor, \(m\), of 0.035. The differential equation was solved numerically and a polynomial function, Equation 59, was fit to the solution to allow it to be easily digested by the model. The coefficients \(a_0\) through \(a_6\) are given in Table 1. For the finite difference analysis of the die, the outer diameter of the die was considered to be 0.2 m and the die was considered to have a land with a length equal to 5% of the length of the reduction zone. A convective heat transfer coefficient of 1000 \(\frac{W}{m^2K}\) was applied to the outside surface of the die. The finite difference analysis discretized the die into 64 equal radial steps and 64 equal axial segments.

\[
\eta = \eta_l e^{\beta P - \delta T}
\]  
Equation 58.

\[
P = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^5 + a_5 x^5 + a_6 x^6
\]  
Equation 59.
<table>
<thead>
<tr>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
<th>$a_5$</th>
<th>$a_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.616e11</td>
<td>8.872e12</td>
<td>-2.023e14</td>
<td>2.450e15</td>
<td>-1.661e16</td>
<td>5.981e16</td>
<td>-8.932e16</td>
</tr>
</tbody>
</table>

The thickness and temperature rise in the fluid film predicted by the model over the reduction zone are given in Figure 38. The thickness of the film is small, below 200 nm, over the entire length of the reduction zone due to the low speed of the drawing process. The overall rise in the temperature of the lubricant was $70^\circ C$, which is quite large and would have a definite impact on the properties of the fluid. The reduction in the thickness of the lubricant film is a product of the reduced viscosity of the oil due to the temperature rise in the fluid and the increasing surface velocity of the workpiece as the draw continues. The predicted fluid film thickness is likely below the surface roughness of the workpiece, so the lubrication regime for this example would likely fall into the mixed lubrication category. In order to achieve hydrodynamic lubrication, a method of augmenting the thickness of the fluid film is required.

![Figure 38: Thickness and Temperature in the Fluid Film Predicted by the Analytical Model of the Hydrodynamic Drawing Process with No Inlet Pressure](image)

The pressure profile predicted by the analytical model for this case is illustrated in Figure 39. There is a rapid rise in the pressure as the lubricant is squeezed into the entry of the die, followed by a more gradual increase in pressure as the workpiece begins to deform and work harden. The gradual increase in the pressure is followed by a gradual decline in the pressure as the axial stress starts increasing faster than the flow stress of the material. This trend
accelerates until the fluid is near enough to the end of the die to escape and the pressure drops below the pressure required to deform the material plastically. In the exit zone of the die, the lubricant is forced to accelerate between the workpiece and the die land causing the pressure in the fluid to drop considerably before it recovers in the divergent area of the die.

The model predicts a drop to -2.5 MPa, which is about 25 atmospheres below ambient. This pressure is not realistic due to the model not accounting for the development of cavitation bubbles, which would begin to form in the fluid as its pressure drops below the vapor pressure of the lubricant and mitigate the pressure drop. However, the minimum pressure predicted by the model does give an idea for the potential to create cavitation.

The most obvious method of increasing the fluid film thickness is to increase the drawing speed. This has the effect of increasing the initial film thickness, which increases the thickness of the lubricant film further into the reduction zone. By increasing the drawing speed from 1 to $10^2$ m/s, the model predicts that the film thickness can be increased by an order of magnitude (as shown in Figure 40a). However, this increased film thickness requires that 10 times more power be supplied to the process, which may be problematic for processes which are already power intensive due to their size.

It is well known that pressurizing the lubricant in the inlet zone can have an augmenting effect on hydrodynamic lubrication films. To investigate the effect of increasing the supply pressure of the lubricant, the first simulation was run through the mathematical model again,
but this time an augmenting pressure of 60 MPa was added to the inlet zone. The results of
this simulation are shown in Figure 40b. Clearly, the thickness of the fluid film has been
greatly increased, with the film thickness in this simulation being about 10 times thicker than
the film thickness in the unpressurized simulation. The addition of an inlet pressure seems to
be a promising way of ensuring that a hydrodynamic film can be established, but the rapid drop
in the thickness of the film still needs to be addressed to ensure that a hydrodynamic film can
be established over the entirety of the reduction zone. Another problem that must be worked
out is how to maintain a highly pressurized fluid in the inlet zone of the die.

Figure 40: Thickness and Temperature in the Fluid Film for a) No Inlet Pressure and
Increased Velocity and b) Elevated Inlet Pressure

The pressure profiles for the lubricant traveling through the dies in each of these two cases
is shown in Figure 41. The pressure profiles for each of these case studies are very similar to
the pressure profile predicted in the first case study, except that the time scale has been
condensed by an order of magnitude for the increased velocity study and the pressure at the
entry zone of the die has been increased for the high pressure simulation. The minimum
pressures achieved for the high velocity and high pressure studies are about -2.5 MPa and -0.1 MPa, respectively. Therefore, it appears that using an augmented pressure in the inlet zone of the die reduces the tendency to cavitate greatly. However, in the case of the high velocity drawing, the tendency to cavitate is identical to the first case study, suggesting that achieving both cavitation and full hydrodynamic lubrication is best achieved by increasing the velocity of the draw rather than increasing the pressure at the inlet zone.

Figure 41: Pressure Profile of the Lubricant from the Single Die; a) 10 m/s 0 MPa Case Study; b) 1 m/s 60 MPa Case Study; left) Full Profile; right) Zoomed into the Pressure at the Exit Zone of the Die

As a demonstration of the model’s applicability to a die set with multiple consecutive reductions, the following case study is presented. The workpiece properties, fluid properties, and other model parameters were kept the same in this example as in the first case study, except that the die was segmented into 3 separate reductions. The first die reduces the workpiece from 50mm to 47.5mm, the second reduces the workpiece to 40mm, and the third to 30mm. The static pressure applied to each of the die segments is 0 MPa for the first section and 60
MPa for the second and third sections. The workpiece temperature is carried over from die to die and the temperature of the lubricant in the inlet zone of each die is taken to be the current temperature of the workpiece. The simulation of the lubricant film using this information produced the results summarized in Figure 42a.

The segmentation of the die into three dies and the application of pressurized lubricant to the last two segments has served to increase the thickness of the fluid film greatly, but there is a significant drop in the thickness of the lubricant over the third die. This drop would likely cause the lubrication regime to fall out of the hydrodynamic regime into the mixed regime, and must be corrected to ensure that a stable lubricant film is maintained. It is also worth noting that the temperature rise in the fluid film is significantly less for the multiple reduction die than it was for the single die. This is due to the splitting of the dies providing additional surfaces for the dies to be cooled and serves to increase the thickness of the fluid film by better maintaining the viscosity of the lubricant.

By optimizing the pressure supplied to the lubricant in the inlet zone of each die, the hydrodynamic lubrication process may be induced in all of the non-sealing die sections. For example, by increasing the inlet pressure in the third die segment from 60 MPa to 90 MPa in the previous case study, the lubricant film thickness can be bolstered significantly over the last die, as shown in Figure 42b. In this case, adding the highly pressurized third reduction die prevents the film thickness from dropping below the 2 μm mark, but the technique could be adjusted to produce larger films if necessary.
Figure 42: Thickness and Temperature in the Fluid Film Predicted for a Drawing Process with 3 Reductions 60MPa Pressurized Lubricant Supplied to the Second Die and a) 60MPa Inlet Pressure for the Third Die b) 90MPa Inlet Pressure for the Third Die

The pressure profiles for these two case studies are given in Figure 43. The main difference between these profiles and the single reduction profiles is that the general shape of the pressure curve is broken up over the three dies. In between each die, the pressure drops to below the ambient pressure just as the lubricant leaves the die land, just as was the case for the single die case studies. However, because of the augmenting pressure at the beginning of the 2nd and 3rd dies, the pressure in the lubricant never drops low enough for rarefaction to occur, so cavitation cannot occur at the exits of the 1st and 2nd dies. At the end of the third die, the potential to cavitate is also very low, because the exit zone conditions are very similar to those encountered in the single die with augmented inlet pressure case study. The minimum pressures for the 0 MPa, 60 MPa, 60 MPa and the 0 MPa, 60 MPa, 90MPa studies are -0.35 and 0.034 MPa, respectively. In this case, it appears that the increased film height produced by the greater inlet pressure in the third die has reduced the potential to create cavitation in the flow.
This suggests that through proper optimization of the die geometry and supplied pressure, lubricant films of sufficient thickness to establish hydrodynamic lubrication may be established in low speed drawing processes. Additionally, these case studies suggests that it may be possible to achieve hydrodynamic cavitation as a result of creating a hydrodynamic lubrication film if the circumstances are correct. The chance to develop cavitation appears to increase when the thickness of the film is small and the velocity of the draw is big.

4.9 Extension to Predict Cavitation Conditions

In order to gain information about the intensity of the cavitation created as the lubricant is released through the exit zone, it will be necessary to use the Rayleigh-Plasset equation to predict the time dependent behavior of a bubble as it travels through the hydrostatic die. This will require an understanding of the vapor pressure of the lubricant, the dissolved gas content in the lubricant, and some guess of the initial size of the gaseous imperfection. Some of this can be guessed to get qualitative results, but it will be difficult to gain any real accuracy without...
exact numbers. An additional confounding factor in this kind of analysis is that the thickness of the lubricant film is very small, so it is very likely that any bubbles created will be affected by the die and the workpiece walls, disrupting its spherical shape. There may also be problems associated with the laminar flow analysis that has been carried out thus far, as turbulence is very likely to develop in the presence of cavitation.

Still, analysis of the behavior of a bubble using the Rayleigh-Plasset Equation is a useful tool in understanding cavitation in a hydrostatic drawing die. The simplest form of the Rayleigh-Plasset Equation is written in Equation 60, where \( \rho_L \) is the density of the liquid, \( P_{Go} \) is the initial pressure of the gas in the bubble, \( R \) is the radius of the bubble, \( k \) is the polytrophic constant, and \( S \) is the surface energy per unit area. It assumes that the bubble begins as a spherical impurity containing contaminant gases and vapor from the liquid medium. The contaminant gas is considered to behave in a polytrophic manner, as defined in Equation 61, and its partial pressure inside the bubble can be determined using Equation 62. Furthermore, it is assumed that there is no heat or mass transfer between the liquid and the bubble.

\[
\frac{P_v(T_\infty) - P(t)}{\rho_L} + \frac{P_{Go}(R_0)}{\rho_L} \left(\frac{R_0}{R}\right)^{3k} = R \frac{d^2R}{dt^2} + \frac{3}{2} \left(\frac{dR}{dt}\right)^2 + \frac{4\nu_L \left(\frac{dR}{dt}\right)}{\rho_L R} + \frac{2S}{\rho_L R}
\]

Equation 60.

\[
P_G = P_{Go} \left(\frac{R_0}{R}\right)^{3k}
\]

Equation 61.

\[
P_{Go} = P(0) - P_v(T_\infty) + \frac{2S}{R_0}
\]

Equation 62.

An expression for the pressure in the fluid as a function of time is needed to determine the size of the bubble as it travels in the lubricant from the inlet of the die to the exit. This can be determined by using the equations laid out in the sections covering the inlet, reduction, and outlet zones. Once a function or tabulated time history of the pressure in the die is determined, initial conditions must be set. In this case, it is helpful to consider the bubble in an equilibrium condition before it enters the die. Thus, the initial conditions presented in Equation 63 can be used to solve Equation 60. However, solving Equation 60 must be done numerically, as the problem is highly nonlinear and complicated.
\[ R(0) = R_0; \quad \frac{dR}{dt}(0) = 0 \]  

Equation 63.

4.10 Conclusions

In order to determine the feasibility of creating hydrodynamic cavitation in a hydrodynamic drawing process, an analytical model describing the pressure, temperature, and thickness of the lubricant as it travels through the die was derived. The model was derived considering strain hardening of the material and heat transfer between the workpiece, lubricant, and die, as well as heat transfer between the die and the environment. Additionally, it can be used to analyze multiple reduction hydrostatic drawing dies, which may be useful in creating cavitation to formulate the lubricant and to texture the workpiece surface in real time. The model was applied in several different case studies, including: i. conventional drawing, ii. drawing at high speed, iii. drawing with a pressurized inlet zone, and iv. drawing using a multiple reduction die and pressurized inlet zones. The following conclusions were drawn from the study.

i. The conditions to create hydrodynamic cavitation in the drawing process are present and can be manipulated by adjusting factors like the outlet geometry, inlet pressure, and drawing speed.

ii. Through the application of a multiple reduction die and pressurized lubricant in the inlet zone, the thickness of the lubricant film can be greatly increased, even at low speeds.

iii. Splitting the die into multiple reductions allows the designer to reestablish a large film thickness and counteract the tendency for the film thickness to collapse as the reduction of the workpiece increases.

iv. The analytical model derived in this study is extremely flexible and can rapidly determine the lubricant film thickness, as well as the temperatures in the die, workpiece, and fluid film, at any point in the reduction zone for a wide range of drawing conditions.
CHAPTER 5
DEVELOPMENT OF A CAVITATION DEVICE

5.1 Overview
Testing the concepts laid out in the previous chapters requires an experimental setup to be developed so that rigorous tests can be carried out. The first experiments that need to be performed must determine if cavitation is capable of processing the lubricant in real time. This requires the creation of an experimental apparatus capable of introducing cavitation into the lubricant. The development and initial tests of such a device are detailed in the following sections.

5.2 Development of Experimental Device

5.2.1 Requirements
The experimental device for testing the effects of cavitation on the lubricant must be at least somewhat relative to the types of lubrication systems that are employed by metal formers. Currently, liquid lubricants are supplied to the tool workpiece interface by either submerging the workpiece or dies into the lubricant sump or by delivering the lubricant via a pumping system. Delivering the lubricant with a pumping system offers the opportunity to force the lubricant through a restriction that can lead to hydrodynamic cavitation. A system such as this allows for the testing of many of the potential benefits of creating cavitation in the lubricant that are laid out in Chapter 3 and is relatively simple to create. This makes it an ideal target for initial experiments into the effects of cavitation on metal forming lubricants.

The proposed system will consist of three parts, i) a pumping system, ii) a lubricant reservoir and iii) a cavitation device. The first two parts of this system are relatively easy to implement because they are basic parts of any fluid transporting system. The pumping system should consist of a pump and motor that are capable of moving the desired fluid at the desired flow rate through the system. The lubricant reservoir is simply a plastic tank in which the supply and return lines can be submerged.

The last part of the system which must be developed is the cavitation device. This device must be able to create hydrodynamic cavitation in the lubricant, as well as create a controlled
expansion of the cavitated liquid so that the intensity of the cavitation can be controlled. Furthermore, the parameters of the device should be able to be easily varied so that minimal effort is expended in testing the device under a variety of conditions. Finally, the resulting flow, post cavitation inception, must be viewable so that the properties of the flow can be visually observed and recorded.

These major system components are to be combined into a single apparatus that is mobile, places the cavitation device at a convenient working height, and prevents vibrations from the pumping system from causing the apparatus to shake uncontrollably. To do this, a frame with a very heavy base should be fabricated. The frame should have several shelves for the various system components to be housed and should provide easy access to system components so that maintenance and modification can be carried out easily. In order to protect the pump from cavitation, the lubricant sump should be placed above the pump so that there is sufficient net positive suction head to prevent cavitation at the pump inlet. The device will be referred to as the external cavitation device due to the fact that the cavitation is created outside of the metal forming dies that it would potentially supply lubricant to. A mockup of the proposed apparatus is given in Figure 44.
5.2.2 Design of the Cavitation Device

The design of the cavitation device follows the basic concepts of hydrodynamic cavitation laid out in chapter 2. Namely, cavitation is created by forcing the lubricant to flow through a low cross-section throat so that the pressure in the lubricant is reduced below the cavitation threshold as it speeds up to maintain a constant mass flow rate through the throttle. The lubricant is then exposed to a pressure recovery zone in which the velocity is suddenly reduced to cause the newly create bubbles to collapse. This is accomplished by creating a device that
consists of two zones connected by a needle valve. The lubricant moves from the high pressure zone past the needle valve, which causes cavitation bubble to form and expand. The lubricant then flows into the low pressure zone, which acts as the pressure recovery zone of the device. The needle valve in the device consists of a tapered plug that can be pushed towards or away from a tapered wall to adjust the size of the gap through which the fluid must flow. This concept is illustrated in Figure 45, which illustrates the high pressure cavity and needle valve of the device, and Figure 46, which illustrates the adjustable low pressure side of the device. Also pictured are some of the important components of the cavitation device.

Figure 45: High Pressure Side and Needle Valve of the Cavitation Device
5.2.3 System Configurations

Over the course of testing, two different experimental setups were tested. The first configuration of the system makes use of a gear pump to provide high pressure hydraulic oil to the cavitation device. The gear pump has a displacement of 4.10 ml/rev and a rotation speed of 2000 RPM, which creates a flow rate of 8.2 L/min (2.2 gal/min). The gear pump is compatible with hydraulic oil and fluids that have viscosities greater than hydraulic oil. This is because there is a small clearance between the pump gears and the wall of the pump through which the fluid can escape if its viscosity is too low. Additionally, the pump cannot be used with liquids that can cause corrosion of the tool steel gears that drive the flow. The lubricant sump employed in this configuration was a thin clear plastic container, which allowed changes in the bulk lubricant to be observed during an experiment. A picture of the experimental apparatus in the first configuration is provided in Figure 47.

Figure 46: Low Pressure Side of the Hydrodynamic Cavitation Device
The second configuration of the experimental apparatus makes use of a plunger pump instead of a gear pump. The plunger pump has three plungers and operates at a speed of 1750 RPM with a displacement of 8.6 mL/rev to produce a flow rate of 15.1 L/min (4 gal/min). The increased flow rate of the plunger pump has the downside of requiring more power than the motor can deliver to reach pressures of 3000 psi, so tests carried out with this pump were limited to 1000 psi. The plunger pump has several advantages over the gear pump used in the first configuration. First, because the pressurization is created through a combination of check valves and reciprocating plungers rather than the clearance between the pump walls and rotating gears, back flow is not as much of an issue. This means that the flow rate of the plunger pump will be more consistent than the gear pump, even if the working fluid is changed to one with a different viscosity. The wetted components of the plunger pump are made from stainless steel and ceramic components which are resistant to corrosion. The combination of the corrosion resistant materials and the lack of clearances in the pumping system make the pump compatible with a large number of fluids. The major downside of this pump is that it
creates more distinctive pressure pulses due to operating with only three plungers rather than a multitude of teeth.

A cooling system was also added to this configuration of the setup to prevent a significant rise in the temperature of the base fluid that could lead to confounding temperature related changes in the lubricant being tested. Heat was removed from the system by using an aluminum container as the reservoir. This container was placed in a water bath, which was chilled with a small refrigeration system. However, even with these modifications, temperature rise was still a problem. To compensate for this, experiments were carried out by running the system until the fluid reached a predetermined temperature, at which point the pump was turned off and the system was allowed to cool down. This process of intermittently turning the system on and off was repeated until the desired total processing time was reached. As a note, this process could be eliminated if a powerful enough cooling system were introduced to the reservoir, but the amount of energy released by the system is large and large cooling systems are expensive.

A picture of the modified experimental apparatus in this configuration is shown in Figure 48.

Figure 48: Experimental Setup in the Second Configuration
5.2.4 Preliminary CFD Investigations of the Cavitation Device

In order to gain a full understanding of the cavitation device and obtain some information that may be useful for later analysis of the cavitating flow through the equipment, some preliminary computational fluid dynamics (CFD) simulations are performed on the device geometry. The code that is used in this research is the Fluent module of the commercial finite element package ANSYS Workbench 17. For the purposes of this initial investigation, only a relatively simple analysis of the fluid flow through the cavitation device is carried out. The simulations are carried out under the steady state assumption using the pressure based solver with the absolute velocity formulation. The simulations consider only viscous laminar flow and ignore the effects of temperature, chemical species, and phase change. This does greatly reduce the accuracy of the simulation, but qualitative information about the flow is gained. This information, along with experimental observations will serve as the basis for making first level predictions about how a lubricant flow will behave when it is exposed to cavitating conditions.

The process variables that are examined in the current CFD analysis are i) the flow rate of the lubricant, ii) the position of the plug in the needle valve, and iii) the pressure of the lubricant at the outlet of the cavitation device. The output variables that are investigated are the pressure and velocity fields of the flow. This information can be used to determine the conditions that a cavitation nucleation site travels through on its path from the inlet of the device to the outlet. This ignores some important effects, like the interaction between bubbles and the changes in the pressure and velocity fields created by the change in density that goes along with the formation of cavitation bubbles, but may provide some important insight into the conditions that are beneficial for producing intense cavitation.

The simulations of the lubricant flow through the cavitation device used a quarter model of the fluid filled region in the center of the device to simulate the fluid domain. The fluid used in the simulations was ISO 32 light hydraulic oil, which has a density of 857 kg/m³ and a dynamic viscosity of 0.02742 kg/m/s. Three different models were simulated to capture the effect of changing the position of the needle valve. The three positions analyzed were 1mm from the fully closed position, 0.5mm from closed, and 0.25mm from closed. Each model was meshed with tetrahedral elements so that there are several elements between the outer walls of the
device and plug. The meshes for the three different position cases are shown in Figure 49 (note that the two planes of symmetry in the device were used to reduce the geometry to a quarter model, reducing the computation costs of the simulation). Boundary conditions were placed on the mesh to represent the walls, symmetry conditions, inlet, and outlet of the chamber. The inlet condition was set with a velocity boundary condition, which corresponded with one of the three flow rates examined. The flow rates and corresponding velocities are given in Table 2. The outlet of the device was simulated with a pressure boundary condition. In most cases, the pressure was set to zero, but pressures of 100 and 500 kPa were also examined for the most open and most closed positions with the medium flow rate. In total, 13 simulations of the lubricant flow through the cavitation device were carried out.

![Figure 49: Mesh Used to Simulate the Lubricant Flow through the Cavitation Device](image)

**Table 2: Inlet Velocities to Represent Each Simulated Flow Rate**

<table>
<thead>
<tr>
<th>Flow Rate [m$^3$/s] *10$^{-4}$</th>
<th>0.91324</th>
<th>1.3666</th>
<th>2.0533</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Velocity [m/s]</td>
<td>0.08543</td>
<td>0.12786</td>
<td>0.19210</td>
</tr>
</tbody>
</table>

The algorithms used to describe the relationships between pressure and velocity and to discretize the space were as follows. The pressure velocity coupling was modeled with the SIMPLE scheme. The spatial discretization was modeled using the Least Squares Cell based approach for the gradient, the second order method for the pressure, and the second order upwind method for the momentum. The under relaxation factors were set to 0.3 for the
pressure, 1 for the density, 0.7 for the body forces, and 0.15 for the momentum. The hybrid approach was used to initialize the solution and a minimum of 5000 steps was used to simulate the flow to ensure that the solution was no longer changing.

The results of the simulations were, unsurprisingly, very similar due to the nearly identical geometry in the simulations. An example of the pressure distribution in the lubricant flow is given in Figure 50. In all of the simulations, the maximum pressure occurs at the inlet and the minimum pressure occurs at the tip of the needle valve. This behavior occurs due to the incompressible nature of the lubricant. As the area through which the fluid can flow decreases, the velocity of the flow must increase in order for mass to be conserved. The energy required to increase the velocity of the lubricant comes from the energy stored as pressure in the flow, resulting in a pressure drop as the lubricant passes through the partially closed needle valve.

Figure 50: Typical Pressure Distribution for the Lubricant in the Cavitation Device (Results from Valve Position: 0.5mm from Closed, Inlet Velocity: 0.12786 m/s)

There are, however, some key differences between the simulated cases that should be noted. First, the magnitudes of the pressures are vastly different depending on both the flow rate and
the position of the needle valve. In general, the magnitudes of both the minimum and maximum pressures increase as the valve is closed and the flow rate is increased, as shown in Figure 51. Based on the charts given in Figure 51, the maximum pressure is proportional to the flow rate. However, the relationship between the position of the valve and the maximum pressure is decidedly nonlinear. This nonlinear relationship is likely proportional to \( \frac{1}{x} \) because at a position of 0mm, or fully closed, it should take an infinite amount of pressure to create a flow. Unlike the maximum pressure in the device, the minimum pressure and the flow rate are not related by a linear relationship. This is likely due to a combination of the effects from viscous losses and velocity dependent pressure losses, but may also be related to the downstream conditions created by altering the flow rate.

![Figure 51: left) Maximum; right) Minimum Pressure vs Inlet Velocity for Lubricant Flow through the Cavitation Device](image)

The investigation of the effects of increasing the outlet pressure were just as expected. An increase in the pressure at the outlet creates a corresponding rise in pressure everywhere else in the flow (i.e. the pressure gradients remain constant from one outlet pressure to the next and the magnitudes vary by a scaler equal to the difference in the outlet pressure between two simulations), assuming all other conditions are held constant. This trend is shown in Figure 52, which shows a 1:1 correlation between the outlet pressure and the maximum and minimum pressures.
The velocity fields for the four simulations that make up the extreme values of flow rate and valve position are shown in Figure 53. These velocity profiles are in line with the information gained from the pressure distribution, in that the minimum pressures occur in the areas where the velocity of the fluid is highest (i.e. at the tip of the needle valve). Another interesting trend to note is the tendency for the bulk of the lubricant flow to concentrate at the center of the low-pressure cavity when released from a more closed valve. In contrast, flows released from valves that are more open have less momentum to carry them through the center of the low-pressure cavity and tend to spread the flow more evenly across the chamber. This actually has an effect on the pressure in the recovery zone, as seen in Figure 54. The increased velocity of the lubricant in the recovery zone results in a decreased pressure in the initial recovery zone and then increased oscillations in the lubricant pressure after it passes the hook on the die.
Figure 53: Velocity Profiles from Selected Simulations
Figure 54: Pressure Profiles in the Recovery Zone for Two Different Valve Positions
In order to convert the information gained from the CFD simulations of the cavitation device into useful information about the actual experiment and its implications to the greater research project, the results need to be put into context with the literature that represents the current understanding of the hydrodynamic cavitation process. The two most in-depth discussions of hydrodynamic cavitation technology and its implementation are given by Gogate and Pandit [67], who discussed the promising aspects of hydrodynamic cavitation technology for future improvement of sonochemical processes, and Arrojo and Benito [66], who discussed the factors limiting the adoption of hydrodynamic cavitation as a mainstream chemical process. Both papers give a detailed discussion of the parameters that are important to the cavitation process and especially emphasize the importance of the chemical and physical properties of the fluid and the pressure field to which the cavitation nucleation sights are exposed.

Specifically, fluids with low vapor pressure and high surface tension will yield the most intense cavitation. Additionally, the residence time of bubbles at low pressure and the speed at which they are returned to high pressure are very important for obtaining the desired effect of the cavitation assisted process. Another recommendation from Arrojo and Benito is to increase the output pressure of the device. They theorize that this increases the violence of the bubble collapse by suppressing excessive bubble growth. Many of the recommendations made by these two groups of researchers can be examined, at least to some degree, by the low-level analysis carried out in this report.

On the first point, lubricants meet the chemical and physical properties of a good cavitation medium quite well. This is because a side effect of their high viscosities is a low vapor pressure and high surface tension. However, in practice it can be difficult to achieve cavitation in these liquids because the vapor pressure is so low that it is very difficult to create the initial rarefication of the nucleation site to create a bubble. Their high viscosity also plays a negative role because it suppresses the change in the bubble’s size and dampens the bubble collapse, reducing the intensity of the cavitation. Additionally, it takes a greater driving pressure to force the fluid to flow through the restrictions that create the cavitation, which increases energy costs. It also means that high throughput pumps like centrifugal pumps must be replaced with positive displacement pumps, which have a lower flow rate and are more expensive to operate.
The residence time of bubbles in particular pressure fields can be studied by employing point tracking from a variety of initial positions to determine how bubbles might behave in the flow. While this was not specifically done in this analysis, some information can be gained from the examination of the pressure and velocity fields observed in the simulations. First, because the rarefaction event that cause the initial growth of the bubble corresponds to the area where the velocity of the fluid is at a maximum, the time spent at low pressure is expected to be short. Furthermore, the large pressure gradient created by the increased viscosity of lubricants (when compared to traditional solvents) further reduces the time that the bubble spends in the low-pressure zone by reducing the size of the zone. Despite these encouraging results, the simulations indicate that careful attention must be given to the outlet geometry of the device because the low pressure recovery zone created in this setup when the valve is nearly closed will prevent the collapse of the bubble. This is easily rectified by modifications to the geometry of the outlet die, but may be difficult to discover without the use CFD analysis.

The assertion that the increased outlet pressure created by the presence of downstream restrictions is beneficial is difficult to understand given the 1:1 relationship between the pressure in the device and the outlet pressure. Essentially, because the outlet pressure does not affect the pressure gradient, the value of the outlet pressure should have very little effect on the cavitation conditions observed in the flow. That being said, manipulating the downstream pressure does give the opportunity to manipulate the pressure field created by non-optimal geometries back into a workable region. Therefore, it may be used as a process control measure to prevent excessive time in the rarefaction zone and thus prevent excessive growth, ensuring that the collapse is as energetic as possible. The manipulation of output pressure may also be a way to increase the process window for hydrodynamic cavitation processes by allowing the process designer to take advantage of geometries that produce large gradients in the pressure field, but produce undesirable bubble growth due to excessively low pressures.

Another interesting note to make about the cavitation device explored in this work is that it does not follow the traditional methods for creating hydrodynamic cavitation. While both Gogate’s and Arrojo’s discussions mention the use of Venturi and orifice type restrictions, this research makes use of a cavitating valve. This may have important implications for the effectiveness of the cavitation produced by the device that can only be revealed by comparing
the flow through Venturi devices and orifice plates to the CFD analysis carried out in this report. Clearly, extensive CFD analysis of both the current research device and the alternative methods of producing hydrodynamic cavitation are necessary in order to fully understand the factors affecting cavitating flows.

5.2.5 Visual Observations of the Cavitation Device

The first visual observations of the device were carried out with the first system configuration discussed in section 5.2.3. The pressure in the system is monitored through pressure gauges attached to the supply and return lines of the device, and the cavitating flow can be observed in the low pressure zone through the viewing port in the top of the device. Experiments were carried out using ISO 32 light hydraulic oil as the working fluid, which was circulated continuously between the sump and the cavitation device using a gear pump. The flow rate through the cavitation device was held constant due to the nature of the gear pump employed, but the pressure in the high pressure zone was adjusted by rotating the adjusting screw to open and close the needle valve at the heart of the device. The temperature in the hydraulic oil was monitored periodically to ensure that it did not become excessive due to cavitation heating, as the sump was not cooled. The flow though the low pressure side of the device was recorded using a high speed camera for later analysis.

The operation of the device was examined by subjecting the lubricant in the high pressure side of the device to pressures from 0 to 2000 psi. The three different types of geometry pictured in Figure 46 were tested in the low pressure side of the device. Dimensioned drawings of the expansion dies used in these tests can be found in the appendix (Figure A1 - Figure A3). Stills from the high speed videos taken of the flow through the low pressure zone of the device are shown in Figure 55. It can be seen that the higher the pressure in the device, the larger the bubble cloud produced at the exit of the needle valve. The geometry of the inserts in the device also plays a large role in the evolution of the bubble cloud as it passes though the low pressure side of the device.

Also of note is the observation that the hooked die and toothed die tended to concentrate the bubble cloud in the area between the needle valve and the restriction created by the dies (i.e. the left side of the pictures shown in Figure 55). There are a number of reasons why this may be the case, but two probable explanations are that i) the number of bubbles created is
increased as the needle valve is closed and the bubbles are simply trapped by recirculating flow created by the particular geometric restrictions of the dies and ii) the increased speed of the fluid through the center of the device created as the valve is closed creates a low pressure zone that allows the life of the bubbles and the size of the individual bubbles to increase. CFD analysis of the lubricant flow through the device in section 5.2.3 gives some credence to both of these theories. Specifically, the number of bubbles created should increase as the valve is closed because the magnitude of the low pressure at the tip of the valve is greatest for more closed valve positions, which should lead to a more dense bubble cloud. Additionally, it is shown that, at least in the case of hooked dies, the closing of the needle valve concentrates the flow in the center of the device and increases the velocity at which the fluid can leave the initial zone created by the hooks. This has the effect of reducing the recovery pressure and may hinder the destruction of the bubbles.

![Figure 55: Stills from High Speed Recordings of the Cavitation Device in Operation](image)

The next set of visual observations was taken with the equipment in the second device configuration. The expansion dies used in these tests had thin fins that extended perpendicularly to the flow. Dimensioned drawings of this expansion die are given in the appendix (Figure A4 and Figure A5). High speed video stills taken using these dies, the plunger pump, and water as the working fluid are given in Figure 56. There are several
interesting observations that can be made from this figure. The first is that there are alternating pulses in which cavitation increases followed by the cavitation dying down. During the intensification term of the cycle, cavitation bubbles form in the space between the fins which are fourth from the left and in the space between the 5th and 6th sets of fins. The amount of bubbles created around the fins and the distance they travel appear to be independent of the operating pressure, suggesting that they are created by the increase in the flow rate created by the pulsing of the plunger pump. The second phenomenon of note is that cavitation bubbles do not form around the needle valve in the lower pressure experiments. This can be attributed to the fact that the fins are close together and relatively stiff so they may create a significant back pressure at the valve outlet that prevents the rarefaction event from taking place. At 1000 psi a small ring of short lived bubbles is created around the end of the plug, but these bubbles are short lived and do not develop into a cloud. Therefore, the intensity of their collapse should be higher than the bubbles in the clouds observed in the experiments involving the other three expansion die sets.

![Figure 56: Stills from High Speed Recordings of the Cavitation Device Fitted with Thin Finned Dies](image)

5.3 Particle Breakup Experiments

After the development of the external cavitation device was completed, an experiment to test the usefulness of the device by using it to demonstrate one of the beneficial concepts laid out in the previous chapters was conducted. Specifically, the ability of the device to create
hydrodynamic cavitation that is capable of breaking solid particles suspended in the fluid is tested. Presumably, breaking apart particles in a lubricant could lead to the creation of very small particles in the fluid, which may be better able to lubricate than their large counterparts due to their ability to become trapped between surface asperities. These tests were carried out using 10µm diameter spherical graphite (obtained from US Research Nanomaterials, Inc.) as the particles to be broken apart and water as the base fluid. Water was used as the working fluid because the particles can be imaged while still suspended in water using cryogenic SEM techniques.

Cryogenic SEM’s, like the one shown in Figure 57, make use of liquid nitrogen to rapidly cool a sample so that the samples is instantly frozen in place. This prevents the need for the samples to be dried before being placed in the SEM chamber, which must be safeguarded from the production of vapors while in use. Additionally, under vacuum conditions, the outer surface of the water can be removed by sublimation to reveal the structure of the particles underneath.

Figure 57: JEOL 7600F SEM Equipped with a Gatan Alto Cryo Preparation Chamber Used to Visualize Particle Suspensions
The concentration of spherical graphite particles in the suspension was 0.5% by weight. The plunger pump was used to drive the fluid, and the thin finned expansion dies shown in Figure 56 were placed in the pressure recovery zone. The particles were cavitated by adjusting the valve position to produce a 1000 psi pressure drop from the high pressure side of the device to the low pressure side. The suspension was processed for 8.5 minutes. The graphite suspension was then collected and taken to the Cryo SEM at North Carolina State University’s Analytical Instrumentation Facility (AIF). An SEM picture of the spherical graphite particles from the supplier is shown on the left side of Figure 58, and an SEM photograph of the particles after being processed with the external cavitation device is given on the right. It can be seen that the shape of the particles has been greatly modified by the hydrodynamic cavitation in the device. While the particles originally had a very smooth semi-spherical shape, after being exposed to hydrodynamic cavitation they took on a much more irregular shape. The size of the particles has also been reduced, with particles as small as 6 µm being present after cavitation. Additionally, there are many particles that have developed flat surfaces after being processed. These changes in shape are likely due to the particles breaking apart as the shockwaves and microjets created by the collapsing bubbles caused high speed collisions between the suspended particles. Based on these results, it seems likely that the external cavitation device is capable of creating cavitation conditions that are suitable for testing a number of the concepts laid out in Chapter Three.

Figure 58: a) Spherical Graphite Particles Suspended in Water: left) As Received; right) After Being Processed with the Rigid Body Cavitation Device
5.4 Conclusions

A device referred to as the external cavitation device has been developed to serve as a proving ground for various hydrodynamic cavitation induced lubricant formulation concepts, discussed in earlier chapters of the dissertation. The device consists of a needle valve that can be adjusted to create cavitation and a low pressure zone with an observation window that can be fitted with a number of dies to control the behavior of the fluid after it passes the needle valve. Additionally, it can be easily fitted with various pumps so that the working fluid and flow rate of the device can be adjusted to meet the requirements of any experiments designed for the device. The simplicity and flexibility of the external cavitation device will allow a variety of experiments to be carried out, including tests of the effects of hydrodynamic cavitation on fluids containing polymers and solid particles, attempts to create chemical reactions using hydrodynamic cavitation, investigations into controlling microbial growth with hydrodynamic cavitation, and many more.

CFD simulations of the device show how cavitation can be induced in the device as well as what steps might be taken to control the development of cavitation bubbles after they are created. It was determined that moving the valve to a more closed position increased the tendency for the fluid to cavitate, but, for the particular expansion die studied, also tended to decrease the recovery pressure leading to a reduced intensity of the bubble collapse. Proper optimization of the geometry in the recovery zone is required to achieve optimal cavitation conditions. The CFD simulations of the device are followed up with observations from high speed video of the low pressure zone. Several different expansion die geometries are tested, and it is determined that the choice of recovery zone geometry plays a large role in the development of the bubble cloud. It was also determined that the bubble cloud density increased as the valve was closed, confirming the observation from the CFD analysis that closing the valve would increase the tendency for the fluid to cavitate.

After these initial tests of the external cavitation device, the equipment was modified so that it could be cooled more easily and a greater number of experiments could be carried out. This was accomplished by fitting a plunger pump to the device and cooling the fluid reservoir with a water bath system. After these modification were made to the system, the device was used to break apart spherical graphite particles suspended in water. Cryo SEM analysis of the
particles after being exposed to hydrodynamic cavitation showed that significant fracture events occurred causing the shape of the particles to be altered and their size reduced (in some cases to as small as 6 µm in diameter). In addition to demonstrating that hydrodynamic cavitation could be used to break apart particles suspended in a lubricant, the results from this test also indicate that the external cavitation device will be useful in testing the real time lubrication formulation concepts laid out in Chapter Three.
CHAPTER 6
EFFECTIVENESS OF NANO-LUBRICANTS CREATED WITH HYDRODYNAMIC CAVITATION

6.1 Experimental Overview

In addition to ensuring that hydrodynamic cavitation can perform the same operations as acoustic cavitation, an understanding of the effectiveness of hydrodynamic cavitation when compared to traditional acoustic cavitation based methods must be determined. To accomplish this, the external cavitation device was used to create nano-lubricants whose performance is compared to nano-lubricants created using an ultrasonic bath. Two metal forming tribo-tests were used to evaluate the performance of the lubricants. The first was the ring compression test, which is designed to determine the shear friction factor for a workpiece-lubricant pair. The second test was the ball penetration test, which is designed to test the material pickup resistance provided by a lubricant.

6.2 Nano-Particle Dispersion

To test the effectiveness of hydrodynamic cavitation in dispersing nano-particles into a lubricant, several canola oil based nano-lubricant suspensions were created. Canola oil was chosen because it is both compatible with the pumping system and biodegradable. Unfortunately, the distribution of particles in the lubricant could not be determined using the Cryo SEM because the surface of the oil cannot be sublimed away to reveal the structure underneath.

As mentioned in the overview of this chapter, lubricants were formulated using both the external cavitation device and the ultrasonic bath, which represents the traditional method of creating these nano-lubricants. The ultrasonic bath was used to create lubricants with two types of suspended particles. The first was 20-30nm SiO$_2$ particles and the second was 40nm CuO particles, both of which were procured from US Research Nanomaterials, Inc. The lubricants with SiO$_2$ particles were tested in concentration of 0.5, 1, and 2% by weight, while the CuO lubricants was tested in concentrations of 0.5% and 1% by weight, as shown in Table 3. The lubricants were first weighed out and then sealed in glass jars. The glass jars were then
placed in an ultrasonic bath and sonicated for two hours to initially mix the lubricants. Due to settling of the particles, the lubricants were sonicated for another hour before being used in ring and ball penetration tests to ensure adequate dispersion of the particles at the testing time.

Table 3: Nano-Lubricants Formulated with the Ultrasonic Bath

<table>
<thead>
<tr>
<th>Concentration</th>
<th>SiO₂</th>
<th>CuO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1%</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2%</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

After evaluating the nano-lubricants created with the ultrasonic bath, the lubricant with the best performance in the ring compression tests, discussed in the next section, was chosen to be recreated with the external cavitation device. This lubricant turned out to be the 2% SiO₂ lubricant. The lubricant was formulated with ten thirty second pulses, which corresponds to cycling the fluid through the device about forty times. Once the last pulse was completed, the lubricant was used immediately after cooling back to room temperature.

6.3 Ring Compression Test

The ring compression test is performed using a short ring-shaped specimen, forged axially between two flat, parallel, rigid tools. Whether the inside diameter of the ring increases, decreases, or remains constant depends on the magnitude of frictional stress. When the friction force is small, the inside diameter increases. As friction force increases, rate of outward flow decreases. After the frictional force exceeds a critical value, only part of the ring flows outward, while the remainder flows inwards towards the center. As a result, the inside diameter is reduced. To put a numerical value to the observed friction, the dimensions of the compressed rings are compared to calibration curves generated using finite element analysis. These calibration curves are generated by simulating the ring compression process with different levels of shear friction factor (m) and plotting the relationship between the reduction in height and diameter for each simulation, as show in Figure 59. These curves were generated for an
AL6061 sample with the following initial dimension: outer diameter of 31.75 mm (1.25 in), internal diameter 15.88 mm (0.625 in), and height of 10.59 mm (0.417 in).

![Graph showing calibration curves for ring compression test](image)

Figure 59: Calibration Curves for the Ring Compression Test Generated by DEFORM 2D

In the ring compression tests carried out in this experiment, material of the ring sample is Aluminum 6061 T6. Its dimensions are: outer diameter of 31.75 mm (1.25 in), internal diameter 15.88 mm (0.625 in), and height of 10.59 mm (0.417 in), which are consistent with the widely used ratio 6:3:2. The surface roughness of the samples is about 0.25 – 0.38 μm (10-15 μin). The rings were compressed to a reduction in height of about 48%. An example of the samples before and after they were compressed is provided in Figure 60. The 150 ton press and the ring compression test setup are shown in Figure 61.
Each compression test was carried out by first cleaning the surface of the sample in acetone, followed by dropping the sample into the lubricant, letting the lubricant drip off the sample for thirty seconds, and positioning the sample directly in the middle of the upper platen using a 3D printed jig. The stroke of the machine was controlled manually by using a string potentiometer to keep track of the position of the ram relative to the base of the press. After each test, the platens were cleaned with acetone, polished using polishing paper to remove any
material pickup on the dies, and finally, cleaned with acetone again to remove any remaining debris.

The first set of experiments conducted used the nano-lubricants formulated with the ultrasonic bath. The reductions of the inner and outer diameter of each ring sample after being compressed are shown in Figure 62, which also contains the calibration curves obtained from FEA simulations of the process. The shear friction factors for each data point were interpolated using this chart and used to make the histogram shown in Figure 63, which gives the average shear friction factor for each lubricant and the standard deviation of each lubricant test. Based on the test results, the plain canola oil and the 0.5% CuO suspension were the least effective of the lubricants tested, having nearly identical shear friction factors. The 1% CuO suspension reduced the shear friction factor observed in the tests by about 0.014 when compared to the base oil and the lower concentration suspension, but was not as effective as any of the SiO\textsubscript{2} suspensions. The SiO\textsubscript{2} suspensions were able to reduce the shear friction factor by between 0.028 and 0.040 depending on the concentration of particles, with a general downward trend as the concentration of particles increased. This represents a decrease of between 9 and 13%.
Figure 62: Results of the Initial Ring Compression Tests Plotted with Friction Calibration Curves Obtained from FEM Analysis

Figure 63: Shear Friction Factors from Initial Nano-Lubricant Tests Using the Ultrasonic Bath to Disperse the Particles
In a separate set of ring compression experiments, a lubricant created by the external cavitation device was compared to a lubricant created by the ultrasonic cavitation device. Because the 2% SiO$_2$ performed best in the previous set of ring compression tests, it was chosen to be the test lubricant in this set of experiments. The nano-lubricants used in this set of ring compression tests are given in Table 4. Note that ring compression tests were also conducted on the base canola oil to act as a control group for the experiment. These tests were carried out under the same conditions as the last set, but, because a different bar of Al6061 was used to create the rings, the magnitude of the results are different. The results of these tests are depicted in Figure 64, which shows the average shear friction factors for the lubricant formulated by the ultrasonic bath and the external cavitation device are nearly identical. Additionally, both nano-lubricants have shear friction factors which are significantly lower than that of the base oil. Based on these results, it can be concluded that hydrodynamic cavitation is just as capable of producing nano-formulated lubricants as ultrasonic cavitation, but with the advantage that it is significantly less time intensive and can be scaled up easily. Finally, it should be noted that the shear friction factors are significantly lower than those that were determined in the previous ring compression study, but the percentage of the decrease between the unprocessed oil and the nano-lubricants is still about 10%. The differences between the two tests are likely caused by a change in the chemical makeup of the bar stock or a difference in the age of the stock which can affect the properties of precipitation hardening alloys like AL6061.

Table 4: Lubricants Produced to Compare the Effectiveness of Nano-Lubricants Formulated by the External Cavitation Device and Ultrasonic Bath

<table>
<thead>
<tr>
<th>Lube Designation</th>
<th>Control No Particles</th>
<th>2% SiO$_2$ ECD</th>
<th>2% SiO$_2$ US Bath</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td></td>
</tr>
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</table>
6.4 Ball Penetration Tests

Another method to test the effectiveness of the lubricants created in the ultrasonic bath and the external cavitation device is the ball penetration test, which tests the lubricant’s ability to prevent material pickup and galling. This test is performed by using a punch to force a hardened steel ball through a tubular workpiece that is surrounded by dies that prevent it from expanding radially and moving away from the punch. A before and after picture of the workpiece and ball are shown in Figure 65. As the ball slides through the workpiece, the tribological conditions become more severe due to the lubricant becoming starved as the sliding distance increases and the surfaces expand. When the severity reaches a certain level, the lubricant will no longer be able to prevent the material from cold welding from the workpiece to the ball and galling will occur. The pickup resistance of the lubricant can be tested by observing how far the ball slides before this point is reached. Additionally, the load required to push the ball though the device can be used to evaluate the results of the test because the onset of galling is associated with a spike in the load required to push the ball through the sample.
Figure 65: Ball Penetration Samples left) Before; right) After

For the purposes of these tests, the same 150 ton press, see Figure 61, that was used to carry out the ring compression tests was used to force the ball through the sample. The tooling used to perform the experiments is given in Figure 66. The tests were performed on tubular steel (AISI 1018) samples with a height of 44.45mm (1.75in), an outer diameter of 31.75mm (1.25in), and an inner diameter of 18.25mm (0.719in). The balls used in the test were made from a chrome steel with a diameter of 20.95mm (0.825in), which resulted in a forming reduction of about 13.7%. The samples were prepared by submerging the workpiece into the lubricant to coat all surfaces before placing it into the die and pushing it to the bottom. The balls were then submerged in the lubricant and positioned on the workpiece. The test was carried out by pushing the ball through the workpiece while the load and stroke were recorded using a load cell and a string potentiometer. After the tests, the samples were ejected and sectioned, as shown in Figure 65. Photographs of the inner surface were then taken with a stereo microscope so that the onset of galling for each sample could be determined.
The lubricants tested in this experiment were the 2% SiO$_2$ lubricants formulated with the external cavitation device and an ultrasonic bath. A control test consisting of just the base canola oil was also carried out. Figure 67 shows the inside surfaces of the samples after being sectioned post experiment. The top red line on the figure represents the topmost surface that was touched by the ball, the second red line represents the topmost level that galling can be observed, and the blue line represents the point at which the entire sample can be said to be galling. It is clear that the SiO$_2$ lubricant prepared in the ultrasonic bath produced less galling than the base oil. Similarly, the 2% SiO$_2$ suspension created by the external cavitation device also resulted in reduced galling when compared to the control test, but did not produced results that were as good as the lubricants formed in the ultrasonic bath. The benefits of the two SiO$_2$ lubricants can also be observed in the load stroke curves, Figure 68, collected by the load cell on the press. The maximum load observed in the control test was 92,000 lbf or 46 tons, while the maximum loads observed in the two ultrasonic bath formulated lubricants were 86,000 and 56,000 lbf or 43 and 28 tons, both lower than the maximum load observed in the control test. The maximum load observed in the test using the lubricant produced by the external cavitation device was 73,000 lbf, or 36.5 tons, and is in-between the loads from the two results obtained from the ultrasonic bath lubricants.
Figure 67: Inside Surfaces of Ball Penetration Samples for Unprocessed Canola Oil and 2% by Weight SiO$_2$ Nano-Lubricant Produced in the External Cavitation Device and the Ultrasonic Bath

Figure 68: Load Stroke Curves from the Ball Penetration Test Experiments
6.5 Conclusions

In order to compare the effectiveness of the hydrodynamic cavitation and acoustic cavitation at dispersing nano-particles into a lubricant, several nano-lubricants were formulated using both techniques. To determine the best lubricant to use in comparisons of the two processes, the traditional method of creating these nano-particle dispersions was employed to create several test candidates. The effectiveness of the nano-lubricants formulated with several concentrations of SiO$_2$ and CuO nano-particles were tested with the ring compression test. Of the lubricants tested, it was discovered that the lubricant with a 2% concentration of SiO$_2$ by weight was the most effective at reducing the shear friction factor.

The ring compression and ball penetration tests were used to compare the effectiveness of a nano-lubricant formulated with hydrodynamic cavitation to one formulated with acoustic cavitation in the form of an ultrasonic bath. The results of the ring compression tests showed that both the nano-lubricants formulated with hydrodynamic cavitation and acoustic cavitation were able to reduce the shear friction factor by about 10% when compared to the base oil alone. Additionally, the results of the ball penetration tests indicated that both methods of dispersing the lubricant were able to reduce the amount of material pickup and galling when compared to the control group. Based on the results of these tests, hydrodynamic cavitation can be used as a substitute for acoustic cavitation for these types of operations. Using hydrodynamic cavitation to formulate nano-lubricants will greatly increase the speed in which these nano-lubricants can be created as well as increasing the quantity that can be produced to industrially relevant levels.
CHAPTER 7
CONCLUDING REMARKS

The separation between metal formers and lubricant formulators leads to several inefficiencies that prevent the optimal performance of metal forming operations. Formulating the lubricant in real time, at the point of use, would allow metal formers to potentially take advantage of short lived chemical compounds and reduce the number of additives required to ensure the proper function of the lubricant. One way this new manufacturing paradigm can be realized is to combine lubrication technology with sonochemistry. Metal forming lubrication is a well-developed field in which the topology of the surfaces, chemistry of the lubricant, and nature of the forming process must be matched to achieve proper material flow, reduce energy costs, and protect the surfaces of the dies and workpiece. Sonochemistry is becoming an increasingly common technology that involves the use of the high temperatures and pressures that occur in and around a collapsing cavitation bubble to create chemical and physical changes to a cavitating fluid. Sonochemistry is primarily carried out using acoustic cavitation with an ultrasonic bath or probe, but these techniques are limited to small, lab scale applications because they become less efficient at large scales and cannot be cost effectively applied at industrial levels. Hydrodynamic cavitation is an attractive alternative for creating sonochemical changes to fluids because it is driven by pumps, which tend to increase in efficiency as their size increases. Thus, it can be scaled up at low cost.

After carrying out a review of the relevant lubrication and sonochemistry technologies, several potential applications for sonochemistry in the metal forming lubrication field have been identified. Sonochemistry may be employed to create chemical species that either could not be created previously or are too short lived to be of any practical application in the current manufacturing environment. Additionally, its ability to modify polymers by inducing copolymerization and cutting long polymer chains has several potential applications for improving the tribological conditions in the metal forming process. The interactions between collapsing cavitation bubbles and solid particles and surfaces offers a cost effective way to create useful suspension based lubricants and beneficial surface textures. There are, of course,
numerous other applications such as improved mixing, controlling microbial activity, and creating more stable water-oil emulsions.

There are two ways that these potential benefits can be applied to metal forming processes. The first is creating the lubricant close by but independently of the process that it is supporting. An external cavitation device that makes use of hydrodynamic cavitation has been proposed for this purpose. The second method for utilizing cavitation to augment metal forming lubrication is to create hydrodynamic cavitation directly at the workpiece surface. This can be done by employing special die geometry to create a Venturi effect at the workpiece surface or by using hydrodynamic lubrication to create the squeeze and release action that leads to hydrodynamic cavitation. The first method is obviously easier to implement because it does not require the total integration of the two processes, but the second method offers the opportunity to create cavitation directly at the workpiece surface, which is the only way to access potential benefits like real time surface texturing of the workpiece.

While it is very attractive to use hydrodynamic lubrication to create cavitation at the workpiece surface, to the best of the author’s knowledge, there is no prior research in this area. Therefore, an analytical model of the drawing process was derived in which the pressure profile of the lubricant in a hydrodynamic drawing process could be determined to verify the potential to create cavitation using hydrodynamic lubrication. This model was derived by breaking the die into three sections, the entry, reduction, and exit zones, and solving for the fluid properties in each section. It considers complex workpiece and lubricant properties, thermal effects, die geometry and can be extended to account for augmented inlet pressure and multiple consecutive die reductions. Several case studies were examined and, based on the pressure profiles obtained, the conditions to create cavitation are present as the fluid escapes the exit zone at the die land. The tendency to cavitate was increased as the thickness of the fluid film decreased and the velocity of the product increased.

Equipment that creates hydrodynamic cavitation was developed so that the concepts identified as being potential targets for real time lubrication formulation via cavitation could be examined. The device works by forcing fluid through a needle valve to create cavitation. After the inception of cavitation, the fluid travels through a pressure recovery zone that can be fitted with several inserts that control the pressure recovery in the fluid. The device was
analyzed with CFD and the flow though the recovery zone was observed with a high-speed video camera to determine the effects of various device settings on the cavitation created by the system. It was determined that the closer to the closed position the valve was, the greater the tendency to create cavitation. Furthermore, the geometry in the pressure recovery zone plays an extremely important role in the development of the cavitation bubbles and must be properly optimized to effectively realize the benefits of hydrodynamic cavitation.

The usefulness of the external cavitation device was then expanded by fitting it with a plunger pump so that a greater variety of fluids could be tested and a cooling bath to help control the temperature rise in the working fluid. The device was then used to examine the effects of hydrodynamic cavitation on graphite particles suspended in water. It was determined that the hydrodynamic cavitation produced by the equipment could break apart the particles to disperse smaller graphite particles into the fluid. This indicates that the conditions produced by the external cavitation device are sufficient for testing the real time lubrication formulation concepts laid out previously in the dissertation.

Just because the external cavitation device can be used to create useful cavitation phenomenon does not mean that it is as effective as acoustic cavitation at accomplishing the task. A comparison between the effectiveness of nano-lubricants created via the traditional, acoustic cavitation and the hydrodynamic cavitation produced by the external cavitation device was conducted using the ring compression and ball penetration tests. SiO$_2$ nano-particles were dispersed into canola oil using both cavitation techniques and the resulting lubricants were used in the abovementioned tribo-tests. In both tests, the lubricants formulated with hydrodynamic cavitation performed similarly to those formulated in the ultrasonic bath. Therefore, it was determined that hydrodynamic cavitation could be used as a cost effective and easy to scale-up alternative to traditional acoustic cavitation for dispersing nano-particles into a lubricant.

Based on the research carried out in this dissertation, hydrodynamic cavitation is an attractive method of achieving real time lubricant formulation due to its high scalability and wide range of applications to the metal forming process. Employing this technology could lead to a new manufacturing paradigm in which lubrication is improved, tool life is extended, the use of toxic substances is reduced, and part quality is improved.
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\[ q = \frac{6 \eta Q}{\pi \tan(\alpha) D_o h^2} + \frac{2 \eta \ln(D_o + h) v}{\tan(\alpha) D_o} + \frac{12 \eta \ln(D_o + h) Q}{\pi \tan(\alpha) D_o^3} \]

\[
- \frac{2 \eta \ln(z) v}{\tan(\alpha) D_o} - \frac{12 \eta \ln(z) Q}{\pi \tan(\alpha) D_o^3} - \frac{6 \eta v}{h \tan(\alpha)} - \frac{12 \eta Q}{\pi h \tan(\alpha) D_o^2} \\
- \left( \frac{1}{\pi \tan(\alpha)^3 D_o^3 z_o^2 \beta} \right) \left[ 6 Q \eta D_o^2 \beta \right] + 2 \eta \ln(D_o + z_o \tan(\alpha)) v \pi \tan(\alpha)^2 D_o^2 z_o^2 \beta \]

\[
+ 12 \eta \ln(D_o + z_o \tan(\alpha)) Q \pi \tan(\alpha)^2 z_o^2 \beta \\
- 2 \eta \ln(z_o) v \pi \tan(\alpha)^2 D_o^2 z_o^2 \beta \\
- 12 \eta \ln(z_o) \pi \tan(\alpha)^2 z_o^2 \beta - 6 v \eta \pi \tan(\alpha) D_o^3 z_o \beta \]

\[ + 12 Q \eta \tan(\alpha) D_o z_o \beta - \pi \tan(\alpha)^3 D_o^3 z_o^2 \]

\[ + \pi \tan(\alpha)^3 D_o^3 z_o^2 e^{-\beta P_o} \]  

Equation A1.

\[ \frac{dh}{dx} = \left[ -\pi \sin(\alpha) \left( \frac{dP}{dx} \right) \frac{h^3}{3 \eta} - \pi \sin(\alpha) x \left( \frac{d^2P}{dx^2} \right) \frac{h^3}{3 \eta} \right] 
\]

\[ + \pi \sin(\alpha) x \left( \frac{dP}{dx} \right) h^3 \left( \frac{dn}{dx} \right) \]

\[ - \pi \sin(\alpha) \left( - \left( \frac{dP}{dx} \right) \frac{h}{2 \eta} + \frac{U}{h} \right) h^2 \]

\[ - \pi \sin(\alpha) x \left( - \left( \frac{d^2P}{dx^2} \right) \frac{h}{2 \eta} + \frac{dP}{dx} \frac{dn}{dx} \frac{h}{2 \eta^2} - \frac{2 U}{x h} \right) h^2 \]

\[ + \pi \sin(\alpha) \frac{x}{\eta} \left( \frac{dP}{dx} \right) h^2 + \pi \sin(\alpha) x \left( - \left( \frac{dP}{dx} \right) \frac{h}{2 \eta} - \frac{U}{h^2} \right) h^2 \]

\[ + 2 \pi \sin(\alpha) x \left( - \left( \frac{dP}{dx} \right) \frac{h}{2 \eta} + \frac{U}{h} \right) h \]  

Equation A2.
Figure A1: Straight Expansion Die Dimensions
Figure A3: Toothed Expansion Die Dimensions
Figure A4: Thin Finned Die Dimensions Page 1
Figure A5: Thin Finned Die Dimensions Page 2