STUDY OF INTERFACE FRICTION REDUCTION USING LASER MICRO-TEXTURED DIE SURFACES IN METAL FORMING

DISSERTATION

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By

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ABSTRACT

The metal forming process, such as forging, is one of the manufacturing processes where metal is pressed, pounded or squeezed under great pressure into high strength parts. Before the process, lubricant is applied to dies to promote the flow of metal, to reduce friction and wear, and to aid in the release of the finished part. The most commonly used lubricant is liquid based lubricant, such as water-based graphite, synthetic oils, liquid soap, and etc. Under high pressures and reductions the lubricant film often breaks down and causing poor metal flow and wears.

This study explores the possibility of using Laser texturing on the tool and its relevance to micro-lubrication in bulk forming. High interface friction is a primary cause for adhesive pickup in cold forging and extrusion of alloys. This study investigates reduction of interface friction through laser texturing of die surfaces, with the hypothesis that textures entrap lubricants hence improving boundary lubrication. Coarse and fine microgrooves were created using pulsed laser on hardened H-13 dies, and tests with axis symmetric aluminum alloy rings and plane strain rectangle coupons carried out with different lubricants. Both ring test and plain stain stamping test have several limitations including low interface pressures and low surface expansions. However, they have many advantages including ease of experimentation, ease of texturing (flat surfaces), ease of measurement (flat surfaces) and reasonable sensitivity to frictional changes. Cold upsetting was selected as the evaluative
technique as it avoids the close coupling presented between friction and heat transfer in hot or warm upsetting. Aluminum alloy 5150 rings and AISI 1040 steel rectangle coupons were used as the workpiece materials. Besides their high tendency for surface adhesion, both materials have proper yield stresses which can be handled by lab equipment. The workpieces were upset to different height reductions using oil lubricants with varying viscosities to explore both advantages and limits of texture/lubricant combination. These tests show textures indeed decrease interface friction with coarse ones being more robust and fine ones being lower friction.

In addition to experimental evaluation, theoretical analysis was done based on the Reynolds’s equation, slab method of deformation analysis and the link between the design of grooves and friction factors investigated. The theoretical analysis is included in Appendix and the results of this analysis are needed to interpret the results of experimental investigation.
Dedicated to my family
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CHAPTER 1

INTRODUCTION

1.1 Problem statement

Two surfaces in sliding contact produce friction, which is normally characterized by a coefficient of friction $\mu$ defined as the ratio of the resisting force to the normal force or load. Under dry conditions $\mu$ is usually a constant independent of sliding speed and load known as Amonton’s Law of dry friction. In metal forming processes however the situation is quite different. Here the normal die pressure is very high and the coefficient of friction decrease with an increase in the die face pressure due to plastic deformation of the contact points or asperities within the contact zone between the die and workpiece. Also due to plastic deformation there is an increase in new surface area that could strongly affect interface friction. Furthermore the friction is also affected by the sliding speed, the rate of deformation of the workpiece and, the temperatures in the contact zone. The magnitude of the coefficient of friction depends on lubrication regime and tribological conditions within the contact zone.

Solution of the lubrication problem in metal forming is complicated on account of different physical mechanisms present in coupled phenomena – solid mechanics, fluid mechanics and, heat transfer, and our varied understanding of these mechanisms. However the problem may be clarified by observing the different lubrication regimes that may exist between two sliding surfaces.
In dry friction virgin and highly reactive surfaces are generated on the workpiece during plastic deformation with no lubrication. The oxide layers, which would otherwise help prevent seizure, are broken – this regime is commonly referred to as sticking friction with a shear factor value of unity.

When the two surfaces are separated by a lubricant film thickness $h$ that is much larger (10 times of more) than the RMS value of the surface roughness of either of the two surfaces, the asperities of the two surfaces will not interact and the regime is said to be Hydrodynamic or Full-Film lubrication. For this regime, pressure distribution, lubricant rheology, temperature field and friction characteristics are described by the hydrodynamic lubrication theory. Friction conditions are decided by the viscosity of the lubricant and the relative velocity between the die and workpiece. This regime is expected but not common in metal forming, especially in hot forging.

In thin film lubrication the thickness of the film is typically between 3 and 10 times the RMS value of the workpiece roughness. Hence the asperities may touch but have a negligible effect on the friction characteristics which are still developed by forces in the liquid film. However there is local elastic deformation of the surfaces asperities. Thus thin film lubrication is also called Elastohydrodynamic (EHD) lubrication.

Mixed-film lubrication applies to situations where the film thickness is less than 3 times the RMS of the workpiece surface. For most metal forming processes the lubrication conditions are know to be either thin film or mixed film.
Fig 1.1: Striebeck curve and Lubrication regions [15]
Finally, another lubrication condition that prevails in forging is boundary lubrication. The load then is essentially carried by extremely thin reaction films on the asperity tips. This is controlled by the chemistry of surfaces, the active ingredients in the lubricant and the local deformation of the asperities. The lubricant may be a liquid or a substance coated on the surface. Boundary lubrication does not lend itself to reliable analysis and hence most of the knowledge is empirical with little analytical information. Boundary lubricants are typically substances composed of polar molecules such as with natural oils, fats, fatty acids and soaps.

Theoretically, one can identify lubrication regimes by the values of viscosity, sliding velocity and normal pressure. As shown in Fig 1.1 [15], the x coordinate is the ratio between the product of viscosity and sliding velocity and normal pressure, while y coordinates are its friction coefficient and film thickness accordingly.

The surface appearances which are heavily depended on how severe the asperities scratch on the matching surface are different for different lubrication regime. Fig 1.2 [23] show the SEM images of the surfaces after various lubrication states.
Fig 1.2: Appearances of deformed surfaces. (a) Boundary lubrication. (b) Smearing due to lubricant breakdown. (c) Hydrodynamic lubrication. [23]
From the forging tool life point of view, hydrodynamic lubrication condition is desired. At present, in industry practices, liquid based lubricant is flood sprayed to tools before forging. However, as we know, steel forging process introduces high pressure and high temperature. That causes most of lubricant to be squeezed out, resulting in boundary lubrications to be present at critical locations, even where a thick layer of lubricant is sprayed initially. Moreover, from environment point view, the less lubricant one uses the better. Fig 1.3 shows the schematic of squeezing of lubricant film in hot forging. There exist several contact patches during forging and each of them, the film is squeezed out; the heat is transferred directly from the billet to the die. While in the non-contact region, the lubricant squeezed out from contact regions may accumulate, which may block metal from filling the die corners.
Fig 1.3: A schematic of forging process illustrating the squeezing out of lubricant film due to high pressure.
This dilemma can be solved by engraving indentation textures at selected locations on tool surface. The textures act as micro lubricant reservoirs which will be able to retain lubricant under high pressure squeeze, and, together with plastic metal sliding on tool surface, permeated into contact zone to form mixed film lubrication. This process will dramatically improve the lubrication of metal forming. Moreover, after modeling the lubrication mechanisms of micro-textures, one will be able to control the lubrication to achieve the flawless metal forming processes.

1.2 Research objective

The primitive objective of this research is to enable engineers to select lubrication strategies in metal forming to achieve the best friction and minimize the consumption of lubricant. This objective will be reached by a) understanding lubrication mechanisms in the metal forming process. Based on existing work, develop an analytic model to predict the friction factor between the die and workpiece using geometric parameters of the micro-texturing employed, the parameters of forming processes, and lubricant physical properties and b) design and create tooling and micro-texturing on actual tooling, and c) obtain experimental results to compare with analytic results. FEA will be used for calibrating the experimental measurements to friction factor.

1.3 Research approach

The core of our approach is to create analytical models for texture lubrication under metal forming conditions. This lubrication is dependent upon many parameters such as load, tool’s velocity, surface roughness, temperature etc.
Numerical modules can be used to determine relationships between process parameters and frictional performances.

On the other hand experiments are used to verify the developed models. Plane strain upsetting and ring upsetting tests are used to verify the revised analytical models and make the models reflect the real forming conditions more precisely and reliably. Because of the limitations of FEM modeling, which are common in most current commercial FEM software, it is hard to directly simulate a lubricant film between the tool and the workpiece. The combination of using both FEM and indirect measurement experiments may be used to obtain lubrication data at any time of forming processes. In more details, FEM will be used to create a map between experimental measurements and friction which is the final research objective variable. The experimental measurements, such as ID changes, titling angles will be converted into the friction through this map.

Finally, a computer program that can be used in industry in developed based on our models. This software is compatible with popular commercial FEM engines, and able to be easily expanded based on the industry needs.
Fig 1.4: Research approach
1.4 Research significance and system benefits

Energy consumptions and costs have immense impacted on our competitiveness in the global forging marketplace. Thus there is a perpetual need for process development and technological advances. Forging is a discrete part making process that consumes material and energy, and in addition to the desired part, produces scrap and effluents. In hot forging, energy is spent in direct heating of forge stock to required temperatures, operation of press and other equipment, subsequent normalizing and cleaning of forgings. Heating is the biggest source of energy consumption in forging industry. For every pound of steel forged, close to 2000 - 4000 BTU of energy is used (based on an average specific heat of about 1-3 BTU/lb/K). Because of inefficiencies in heating and energy consumed in other areas of a forge shop, it could consume over 6000-8000 BTU / lb of steel. Similar numbers can be expected in non-ferrous forging also. Typical scrap rate in forge shops which are for conventional tolerances, ranges from 5000-10000 ppm. For near net forgings the scrap rate is close to 50,000 ppm. Scrap is associated with lack of process control and degradation of tool that is not identified in time. Based on a 10,000 ppm scrap rate and a 20% improvement in scrap rate related to premature failure (which may be 20-30% of all scrap), it translates to about 35 BTU per lb of steel forged.

Steel processing is one of the highest energy users in US. The steel industry accounts for 2-3% of total U.S. energy consumption. In steel industry, the energy consumed is approximately 10,000 BTU/lb (6.5 kWh/Kg) for primary steel making and secondary processing like rolling and cogging. AISI reports that 12- 15% of the cost of steel made is energy cost. 10-15% of this energy used is in secondary processing of steel (hot and cold rolling, cogging etc). [60] Every pound of aluminum scrapped would result in energy loss of almost 23,500 BTU in the primary processing
of aluminum alone. Every pound of steel saved from being scrapped in the forging industry saves energy to the tune of 10,000 BTU for the steel industry.

Another important ingredients in cost and energy consume of forgings is those of tooling involved. Die costs range from 10 to 15% of the cost of a forging [1]. This includes cost of die material, machining the dies and subsequent heat treatment, if necessary. The indirect cost of dies is however, far more significant. If tooling wears out or become unusable, the production has to be stopped to change dies. Setup times can range anywhere from under 10 minutes to over 3 hours, depending on the complexity of the setup, skill and practices used by the setup crew. This results in additional direct wages in material handling, tool rework and other overhead costs. Also, this may result in additional overtime premiums in the die shop and the forge shop, low resource utilization and in an extreme case; result in missed delivery to customers. If quality and inspection systems breakdown, if dies are not changed at the appropriate time, additional loss occurs due to scrap. Though tooling cost is only 10-15% of a forging cost, the indirect cost of tooling could be as high as 70%. Life of a forge tooling, hence, has great ramifications on the economic competitiveness of a forging company. Identifying different modes of die failure and understanding dominant mechanisms are essential first steps in the path to increasing die life. Without doubt proper lubrications will extend die lives pretty much.

In conclusion, the reduction of scrap, and longer die life are the most effective ways of the reduction of energy utilization which is the goals of every forging plant engineer or plant manager. This is essential to the survival of forging plants in the long run as well as viability of the new generation of precision forged parts.
1.5 Dissertation outlines

Chapter 1 outlines the motivation behind this work, objectives and research approach.

Chapter 2 presents an overview of current work on die lubrication and micro- and macro- textures for lubrication.

Chapter 3 presents results of aluminum alloy ring upsetting experiment, and the lubrication effects of the textured dies.

Chapter 4 presents results of plane strain upsetting tests using steel samples. These tests show relationships between texture pattern, lubricant properties and interface friction.

Chapter 5 summarizes the conclusions of this work and discusses the scope of future work.

Appendix Includes models for lubrication under forging conditions. These models describe how the lubrication film has been protected under tough forging conditions by means of concave textures on die surfaces.
CHAPTER 2
METAL FORMING LUBRICATION: A FUNDAMENTAL OVERVIEW

2.1 Lubricity mechanism in metal forming

Metal forming processes includes forging, extrusion, drawing, sheet stamping etc. The lubrication conditions vary a lot during these processes. For instance in the forging of steel, the temperature ranges from room temperature 67°F in cold forging to 2200°F in hot forging. The forging pressure is much higher than 45 ksi, which is flow stress of hot steel. Therefore one has to consider the working conditions in order to select the proper lubricants.

In metal working, the lubricant should: 1. control the friction: most of the time, low friction reduces the power requirement of the press. 2. separate the surface between the tool and workpiece, 3. reduce the wear, 4. have cooling function, 5. adapt to the varied working conditions, 6. be able to keep the lubrication durably, and 7. have many other requirements pin point to the specific processes[60].

The most popular lubricant used in metal forming is mineral oil. Generally, the mineral oil composes of many kinds of hydrocarbons. The structures of the molecules of those hydrocarbons are shown in Fig 2.1. They are alkane including paraffin and olefin, arene and a mix of them. The number of carbon atoms in the molecule is 10 to 70. As the number of the carbon atoms increases, the viscosity, flash
point, and boiling point also increase under room temperature and atmospheric pressure. During the metal forming process, with the increase in pressure, they will also increase. However, they decrease with the increase of the temperature. Therefore there is a change in lubrication during the process. This is shown in Fig 2.2 and Fig 2.3, respectively [60].

From Fig 2.3[58], one can find that viscosity of mineral oil shows good linearity (Newtonian) with respect to both temperature and pressure. However, under super high pressure or temperature higher than 400°C, the chain of the carbon atom in the molecule may break, and generate the short chain hydrocarbon molecules. These may result in the non-Newtonian property of the lubricant. Solidification under high pressure is another issue for the application of these kinds of lubricants.

The second lubricant used in metal forming is the nature oil, fats and their derivatives. These lubricants are refined from the nature resource, such as animal fat, vegetable oil, and ester produced from them. Therefore they have good environment proprieties.

The molecules of the component of the lubricants are usually fatty acid including both saturated and unsaturated acids, alcohol and amine etc. as shown in Fig 2.4[60].
Fig 2.1: The molecule of mineral oils [60]
<table>
<thead>
<tr>
<th>Molecular weight</th>
<th>Viscosity at 1 atm, cP (a)</th>
<th>Viscosity index</th>
<th>Average value of $a \times 10^4$ at a temperature of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37.8 C</td>
<td>98.9 C</td>
<td>0 C</td>
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<td><strong>Paraffinic Oils</strong></td>
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<tr>
<td>400</td>
<td>485</td>
<td>15.5</td>
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</tbody>
</table>

(a) 1 cP = 1 mPa·s

Fig 2.2: Viscosity-pressure coefficients for selected petroleum oils [60]
Fig 2.3: Viscosity changes with pressure and temperature [60]
Fig 2.4: The molecules in the natural oils [60]
Fig 2.5: Polar molecules grip on the iron surface [15]
We know that molecules of non-polar fluid, such as the mineral oil, attach themselves to metal surface by van der Walls force, which is relatively weak. The lubrication film generated by this mechanism is called physical adsorption film. The durability of this kind of film is not good. However, from Fig 2.4, one can find that the atom O in the molecule of the acid and alcohol results in the polar property of those molecules. As shown in Fig 2.5[15, 60], on the surface of the iron or steel, there is a thin layer of the iron oxide (FeO). The atom O in lubricant is likely to attract the Fe atom in the thin layer in order to reduce the surface energy. Therefore the lubricant molecule is planted on the metal surface, and the shear occurs at the tip of the molecule, as shown in Fig 2.5. This film is a good boundary lubrication film since it is firm and can withstand high pressure and asperity’s penetration. However the thermal stability of this kind of lubricant is an issue that we have to consider in deciding whether it can be used in high temperature metal forming.

2.2 Lubrication in hot forging

In hot forging, the lubricant is usually sprayed onto the tool surface whose temperature varies from 200°C to 700°C. Besides, the pressure applied on the lubrication film is very high. These require the lubricant used in the hot forging to have good thermal stability, oxidation stability and high temperature lubricity. Therefore the selection of the lubricants is very limited. The most popular lubricants are some solid lubricants, including some lamellar solids (graphite, molybdenum disulfide etc), soft metals, polymers, glass, and metal oxides, and some synthetic hot forging oils.

Fig 2.6 [31] shows the configuration of the solid lubricant films and lubrication mechanisms. A stepwise reduction in shear strength should exist, as the
path normal to the shear plane and from the substrate towards the sliding counterface (tool surface). The solid lubricant layer must adhere to the substrate and/or sliding counterface, but must not stick to itself.

2.3 Lamellar solids

2.3.1 Graphite

Graphite has a low friction coefficient and very high thermal stability (2000 °C and above), however the forging application is limited to a range of 500 to 600 °C in order to avoid oxidation. Fig 2.7 [18] shows the lubricity of the graphite with respect to the temperature in the air and vacuum.
Fig 2.6: Schematic of the solid lubrication film [31]
Fig 2.7: The lubricity of the graphite with respect to the temperature [18]

Effects of temperature on friction of graphite in air and vacuum. (a) Rubbed layer of graphite in air. (b) Outgassed graphite in vacuum; Hollow circle represents spectrographically standardized graphite; Solid circle represents Acheson AGR graphite.
At temperatures below 538°C, the friction coefficient (0.35-0.45) lubrication of the graphite in the air (0.1-0.2) is much better than that in the vacuum. This is because graphite absorbs the moisture or vapor in the air which can weaken the bonding force between layer structure of the carbon atoms and lower shear strength within the lubricant film. If the temperature is higher than 538°C, graphite is oxidized in air and this results in a rapid increase of the friction coefficient. However in vacuum, when the temperature is higher than 800°C, the bond force between the layer structure weakens providing lower shear strength. Then, in the vacuum, the graphite exhibits a good lubricity at higher temperatures.

2.3.1.1 The lubrication mechanism

Fig 2.8 [18] shows the crystal structure of graphite particle. As we know that the carbon atom has 6 electrons: each orbital, 1s, 2s or 2p, has 2 electrons. Generally the shape of the electron cloud in 1s and 2s is sphere while dumbbell shape in 2p orbitals.

Usually in 2p orbitals, there are 2 electrons whose electron clouds are dumbbell-shaped and perpendicular to each other. The energy of the electron in 2p orbital is slightly higher than that in 2s orbital. Therefore, one of the electrons in 2s orbital is easily prompted to 2p orbital yielding 4 valence electrons, one is in 2s orbital, three are in 2p orbit. This process is called electron hybridizing. The shape of the hybridized electron cloud is shown in Fig 2.9.a [15]. It looks like an asymmetric dumbbell. Here in carbon atom, one remaining 2s electron and three 2p electrons (2px, 2py, 2pz respectively) form a hybridized group of four electrons with four sp3 hybrid orbital directed along four evenly spaced axes as shown in Fig 2.9.b.
Fig 2.8: Layer structure of the graphite [18]
Fig 2.9: Hybridized electron clouds of the carbon atom [15]
In graphite, the electrons hybridize in a slight different way than above. After promotion of one 2s electron to the 2p orbital, a group of three electrons (one remaining 2s and two 2px and 2py) hybridizes and one 2pz electron remains unhybridized. The shape of an sp2 orbital is similar to that of an sp3 hybrid orbital, but the spatial orientation is quite different. The three sp2 hybrids orbits lie in a plane, are trigonally directed and have angles of 120° between them, which form strong bonds to each carbon. The remaining unhybridized 2pz electron is said to be delocalized; that is, it is not covalently bonded to any particular carbon atom and is capable of moving readily through the two-dimensional structure. The 2pz orbital retains its shape and is perpendicular to the plane defined by the three sp2 hybrid orbits.

Carbon atoms in graphite arrange in hexagonal structure (benzene ring). Three hybridized valence electrons of carbon atoms create “σ” bonds, in which carbon atom bond (C-C distance = 0.1415nm) to three other carbon atoms, arrange at the apexes of an equilateral triangle (Fig 2.10.a). The remaining unhybridized fourth electron, i.e. 2pz orbital forms a “π” bond by overlapping side to side with a pz orbital of an adjacent atom to which the carbon is attached by σ bond. The π bond and σ bond together constitute a double bond. Graphite, a planar molecule, thus has a hexagonal layered structure. Within each layer (plane), atoms are attracted to each other only by the weak van der Waals forces (London forces)[15].

As the necessary condition with which the lubricant with lamellar molecule structure can be a solid lubricant is that the firm intra-layer bond while loose inter-layer. The basal plane (Fig 2.8) of the graphite is connected by both σ and π bonds. Between layers, the attractive force is van der Waals force, which is weak. Although van der Waals force is weak, the shear force applied to break the van der
Waals force is still too high to take the graphite as a lubricant. According to Fig 2.7, in vacuum, the lubrication of the graphite is not good. In order to take the graphite as lubricant, one must weaken the van der Waals force to an acceptable level.

The intensity of the van der Waals force do relate to the π bonds. The overlap of the π orbital can result in the attractive interactions ranging from 0.39 eV (37 kJ/mol) to 0.8 eV (66 kJ/mol). In the air, the oxygen in H₂O molecule acts as a weak donor to the high electron density of π cloud. As a result, the electron-hole attraction between basal planes is reduced. This can explain why the good lubricity of the graphite in air (Fig 2.7.a). If the temperature is too low for graphite to absorb the water in the air, the lubricity is like that in vacuum, i.e. poor lubricity [18].
Fig 2.10: $\sigma$ and $\pi$ bonds in graphite’s crystal structure
2.3.1.2 The intercalation technology

Intercalation technology uses intercalant to react with the graphite to get the relatively weak interlayer bonding between graphite and intercalant, instead of the graphite-graphite bonding.

Both alkali metal, such as Na, K and Li, and halogen can be intercalants. In the intercalation, alkali metal is a donor while halogen is acceptor based on the charge transferring. In the donor case, the intercatant layer provides the electrons to the graphite sheet. This renders the intercalant layer positive charge while graphite layer is negative charge. Thus the $\pi$ bond is stronger than before. In acceptor intercalation, the intercalant is usually halogens or certain metal halides, the intercalant layer becomes negatively charged by attracting the electron from the graphite layer resulting in a small overlap between the $\pi$ orbital and halogen molecule orbital. Thus, from the tribology point view, this can achieve the low shear stress between the intercalant layer and graphite sheet. [18]

There always exists a tradeoff during intercalation, i.e. one cannot reach both low shear stress between the layers, high electrical and high thermal conductivity transverse to the layers. Donor intercalation, usually by alkali metal, tends to increase the electrical and thermal conductivity, because of the extensive change transfer between the metal and graphite layers. This increased bonding between intercalant layer and its neighboring graphite sheet translates into higher shear stress. In contrast, acceptor intercalation, usually by FeCl3, CuCl2, NiCl2, CdCl2 etc., tends to decrease the electrical and thermal conductivity in transverses layers. Because the Cl atom attracts the electron from graphite $\pi$ orbital, and this diminishes flow of the electrons and results in a high electrical impendence across the intercant layer and small overlap between $\pi$ orbital and molecule orbital of the chlorides. Acceptor
intercalation increase the anisotropy between intra-plane and inter-plane, the anisotropy ratio can be as large as $10^6$.

### 2.3.2 Molybdenum disulfide

#### 2.3.2.1 Lubricity mechanism

At atom level, MX$_2$, where M is transition a metal like Mo, W Nb and X is a chalcogen like S, Se, Te, has similar lamellar structure. But only MoS$_2$ is used as a lubricant. This is because the shear stress between the layers is the smallest in MoS$_2$ compared with other components. The crystal structure of MoS$_2$ consists essentially of plane of M atoms alternating with plane of X atoms in the sequence X:M:X:M:X…, as shown in Fig 2.11[21]. The atomic arrangement in each layer is hexagonal, and each M atom is surrounded by a trigonal prism of X atoms. Thus the force holding the atoms together in each group of X:M:X layers is relatively strong covalent bonds, whereas the force between adjacent X atoms is relatively weak van der Waals force.

Even the van der Waals force between layers is large enough to cause the high shear stress, which is not desired by tribologists. Fortunately in MoS$_2$, there exists another action that can weaken the van der Waals force, and enable it to perform as a lubricant. Fig 2.11 shows the lamellar structures for MoS$_2$ and NbSe$_2$. To the transition metal, the lowest unoccupied molecule orbital is the d-band, which is either empty or partially filled. The sub-band of “dz” is associated with the force between layers.
Fig 2.11: Crystal structure of MoS$_2$ and NbSe$_2$ [18]

- doubly-occupied (filled) $d_z^2$ orbital
- no long-range bonding
- staggered metal atoms
- low shear strength

- singly-occupied (half-filled) $d_z^2$ orbital
- long-range bonding
- aligned metal atoms
- increased shear strength
The highest occupied molecule orbital of the MX₂ layer structures is full with 16 electrons (ZrS₂). Subsequent electron additions for NbS₂, MoS₂ and TeS₂ go into the non-bonding, d-based dz² sub-band. This gradually narrows the band gap, progressively increasing the electrical conductivity while decreasing the shear stress between the layers. In lowest layer of MoS₂, all the accessible Mo and S orbitals are involved in strong intralayer bonding, leaving only high energy anti-bonding orbitals available for interlayer bonding. The dz² is completely filled with both electrons in MoS₂, but only half-filled (with an unpaired electron) in NbSe₂. The long range attraction between these singly-occupied orbitals (dangling bonds) is high enough to align the Nb atoms over each other between the Se-Nb-Se layers, as depicted in Fig. 2.11. Therefore this attraction enforces the van der Waals bonds between the layers and thus results in a stronger layer shear stress. In contrast, the Mo atoms are staggered between the S-Mo-S layers, because there is repulsion between the completely filled orbitals (because of the full filled electrons). This repulsion cancels part of the van der Waals force, thus dramatically reducing the interlayer shear stress. Fig 2.12 shows the lubricity of MX₂ comparing with that of the graphite in water obtained from the drawing of the steel sheet with 20% reduction.

The c/na ratio can be a measure to evaluate the interlayer shear stress. The larger c/na value means the larger van der Waals gap. In MoS₂, c/2a = 1.95 while c/2a = 1.82 in NbSe₂. This means wider band gap (van der Waals gap) and low interlayer stress in MoS₂ comparing those of NbSe₂.
Fig 2.12: lubricity of MX₂ comparing with that of the graphite in water [31]
2.3.2.2 Lubricity properties

Like graphite, MoS$_2$ has a low friction coefficient, but, unlike graphite, it does not rely on adsorbed vapors or moisture. In fact, adsorbed vapors may actually result in a slight, but insignificant, increase in friction (Fig 2.12[31]). MoS$_2$ also has greater load-carrying capacity and its manufacturing quality is better controlled (Fig 2.13[31]). Thermal stability in nonoxidizing environments is acceptable up to 1100°C, but in air it may be reduced to a range of 350 to 400°C.
Fig 2.13: Lubrication effect of Mo$_2$S-1 [31]

Effect of temperature and humidity on the friction of Mo$_2$S in air. Symbols: O, room atmosphere (40-50% relative humidity); □, <6% relative humidity. Test conditions: 2-in, diam ring of SAE 4620 steel with Rockwell C62 hardness rotated on edge against the flat surface of a disk of SAE 1020 steel; load, 40 lb. sliding velocity, 5.7 ft/min.
Variation of friction with load for surfaces lubricated with molybdenum disulfide paste (rubbing speed, 15.5 m/min); ×, plain mild steel; +, phosphated mild steel; ⊙, sulfided mild steel.

Fig 2.14: a) Lubrication effect of Mo$_2$S-2 [31]
Fig 2.14: b) Lubrication effect of Mo$_2$S-2 [31]

Variation of friction with load for surfaces lubricated with MoS$_2$ bonded with corn syrup (rubbing speed, 15.5 m/min); $\times$, plain mild steel; $+$, phosphated mild steel; $\bigcirc$, sulfided mild steel.
2.4 Methods of applying solid lubricants

2.4.1 Powdered solids

This is the oldest and simplest methods of applying solid lubricants are noted below.

(a) Burnishing. Burnishing is a rubbing process used to apply a thin film of dry powdered solid lubricant such as graphite, MoS$_2$, etc., to a metal surface. This process produces a highly polished surface that is effective where lubrication requirements and wear-life are not stringent, where clearance requirements must be maintained, and where wear debris from the lubricant must be minimized. Surface roughness of the metal substrate and particle size of the powder are critical to ensure good application.

(b) Hand rubbing. Hand rubbing is a procedure for loosely applying a thin coating of solid lubricant.

(c) Dusting. Powder is applied without any attempt to evenly spread the lubricant. This method results in a loose and uneven application that is generally unsatisfactory.

(d) Tumbling. Parts to be lubricated are tumbled in a powdered lubricant. Although adhesion is not very good, the method is satisfactory for noncritical parts such as small threaded fasteners and rivets.

(e) Dispersions are mixtures of solid lubricant in grease or fluid lubricants. The most common solids used are graphite, MoS$_2$, PTFE, and Teflon®. The grease or fluid provides normal lubrication while the solid lubricant increases lubricity and provides extreme pressure protection. Addition of MoS$_2$ to lubricating oils can increase load-carrying capacity, reduce wear, and increase life, and has also been
found to reduce wear and friction in automotive applications. However, caution must be exercised when using these solids with greases and lubricating fluids. Grease and oil may prevent good adhesion of the solid to the protected surface. Detergent additives in some oils can also inhibit the wear-reducing ability of MoS$_2$ and graphite, and some antiwear additives may actually increase wear. Solid lubricants can also affect the oxidation stability of oils and greases. Consequently, the concentration of oxidation inhibitors required must be carefully examined and controlled. Aerosol sprays are frequently used to apply solid lubricant in a volatile carrier or in an air-drying organic resin. However, this method should be limited to short-term uses or to light- or moderate-duty applications where thick films are not necessary.

2.4.2 Bonded coatings

Bonded coatings provide greater film thickness and increased wear life and are the most reliable and durable method for applying solid lubricants. Under carefully controlled conditions, coatings consisting of a solid lubricant and binding resin agent are applied to the material to be protected by spraying, dipping, or brushing. Air-cured coatings are generally limited to operating temperatures below 260 °C while heat-cured coatings are generally used to 370 °C. The most commonly used lubricants are graphite, MoS$_2$, and PTFE. Binders include organic resins, ceramics, and metal salts. Organic resins are usually stable below 300 °C. Inorganic binders such as metal salts or ceramics permit bonded films to be used in temperatures above 650 °C. The choice of binder is also influenced by mechanical properties, environmental compatibility, and facility of processing. Air-cured coatings applied by aerosol are used for moderate-duty applications; however, thermosetting resin binders requiring heat-cure generally provide longer wear-life. The most common method of
applying bonded coatings is from dispersions in a volatile solvent by spraying, brushing, or dipping. Spraying provides the most consistent cover, but dipping is frequently used because it is less expensive. Surface preparation is very important to remove contaminants and to provide good surface topography for lubricant adhesion. Other pretreatments used as alternatives or in conjunction with roughness include phosphating for steels and analogous chemical conversion treatments for other metals.

2.5 Metal oxides

Another kind of lubricant used in the hot forging or other hot metal forming is metal oxides. Only few oxides can be used in the hot metal forming temperature range. To act as a lubricant, an oxide film must fulfill a number of requirements, depending also on whether oxide is on the die or on the workpiece:

(a). The film must be continuous and thick enough to resist easy penetration by asperities and ensure reliable separation of the surfaces.

(b) If the film is attached to the workpiece, it must have sufficient ductility to follow surface extension. Otherwise the film will break. This condition is seldom fulfilled even when only the asperities are deformed.

(c) If the film is attached to the workpiece, its shear strength should be lower than flow stress k, and higher than k if attached to the die.

(d) If the film is damaged, it should reform rapidly. This depends on the temperature because the temperature decides the rate of oxidation, and also on oxygen access which is depended upon the process geometry. Therefore, it is possible to hot roll or hammer forge steel without a lubricant because reoxidation between passes or blows is permitted, during which scales act as lubricant. But failure would occur in extrusion where access of oxygen to the interface is denied for same reason.
(e) Some oxides are friable; they always break up into small particles. Loose particles are frequently incorporated into high-temperature lubricants. Especially when bonded to the surface by a suitable binder, they can provide a very useful separating, parting function, even though their shear strength may not be low. They cannot, however, follow the extension of a workpiece surface, and therefore they are seldom used in metalworking except as die (tool) coatings formed from the very hard and temperature-resistant oxides.

The oxides of only a few metals fulfill the requirements of the lubricant. Fortunately, iron is among them. For example, copper oxide softens above 500°C. Oxides of nickel, aluminum, titanium, lead and zinc are all harder than the substrate and are also brittle; however, magnesium oxide is friable and can act as a lubricant. No generalizations can be made regarding alloys.

An important metal oxide lubricant is PbO, which converts to the nonlubricating Pb3O4 at 370°C but reconverts to PbO at 480°C. Its effective temperature range is about from 300 to 700°C. Scale formed on iron at high temperature is of a layered structure.

In hot iron/steel forming the outermost oxygen-rich Fe2O3 layer and the intermediate layer of Fe3O4 are rather brittle, but the FeO layer immediately adjacent to the metal is capable of some limited deformation. At elevated temperatures some oxides soften quite rapidly and act as solid-film lubricants. Transformations in metals may contribute too. Thus, FeO becomes softer than iron above 900°C where Fe transforms from ferrite into the stronger austenite. Therefore in hot extrusion, the extrusion pressure decreased with temperature above 700°C, but it also increased with rate of deformation.

On steel, some alloying elements migrate to enter into the oxide (e.g., Si
forms SiO₂), and others form more complex spinels (e.g., NiFe₂O₄). The example of
the high temperature lubrication of the steels that have different alloy compositions is
shown in Fig 2.15[31].
Fig 2.15: Lubricity as a function of temperature for various steels [31]
On the surface brass the oxide is mostly ZnO, which is covered by the deformable and lubrications CuO in low-Zn brasses. When the CuO layer is penetrated, friction rises. The oxide of aluminum is very hard and brittle; of the alloying elements, copper has no effect, manganese increases resistance to damage when present as MnAl₆ and magnesium forms MgO at the oxide/air interface, resisting damage. Reactions with the atmosphere may further change the oxide film.

The lubricating properties of many oxides can be improved by mixing with graphite. Generally the oxide films are normally present on surfaces. Together with adsorbed films, they are important constituents of the contaminant film that permits limited deformation with dry surfaces. The oxidation of metals and alloys depends on the atmosphere and on the composition (and often minor elements) of the metal.

However a truly lubricating, low-shear-strength film, is obtained only when the oxide melts at the interface temperature, as for example the oxides of molybdenum and tungsten do; unfortunately, they also evaporate at relatively low temperatures, and the weight loss becomes intolerable. Molten lubricants should really be classified under hydrodynamic agents. Oxides chosen for their low shear strength or favorable melting range may be used as additives to other lubricants; some minerals also fall into the same category. In a sliding situation the key point is always the need for $\tau_s < k$ (k is shear yield strength); a harder oxide behaves as an abrasive. In machining, the task is to provide lubrication on the tool faces which contact the virgin surfaces generated by the cutting process. This can be most effectively done by incorporating the lubricant into the workpiece material. Some steels contain calcium-aluminum-silicate inclusions which affect now in the secondary shear zone.

Apart from providing some lubricating functions, oxides are of utmost important lubrication systems as they can aid the action of other lubricants, either by
simple mechanical entrapment of liquids into microscopic features of the oxide film or by reaction with lubricants that otherwise would be ineffective on pure metal surfaces.
CHAPTER 3

ALUMINUM RING UPSETTING TESTS USING LASER MICRO-TEXTURED DIES

3.1 Introduction

Micro textures on the function surfaces have been paid closed attention for improving tribology properties since later 1990s. The basic ideal is that micro-grooves on a function surface is a combination of several effects improving oil supply and reducing abrasion in the sliding contact [3]. Not only in plastic deformation of bulk metal, but also in the cases of sheet metal working or elastic contacts, surface texture can act as oil reservoirs, which retain the oil from being squeezed out and, moreover, transport lubricant to the severe situations. Usually, in metal forming condition, transported lubricant forms films to isolate direct asperity contacts, which, in turn, reduces real contact ratio of boundary lubrication and achieves mid-film lubrication. At some extreme conditions, such as higher surface sliding speed, if there is a sufficient supply of oil, film formed by transported lubricant may fully isolate direct contact of asperities to reach so-called hydrodynamic pressure pockets, which reduce friction dramatically. In addition concave structures on function surface are also good
places of entrapping wear particles tear from contacted counter surfaces and thus possible to avoid severe abrasive wear and ploughing friction. Presently zinc phosphate coating based lubricant is used in most cold forging processes, especially in cold steel forging, which always has a number of problems including: hazardous waste disposal, high equipment and energy costs associated with billet treatment, and human health risks. Recently researchers spent a lot of efforts to find out replacements for zinc phosphate coating. Some of them have similar or better lubrication effect comparing to zinc phosphate coating.

However, from tool surface engineering, micro-texture may be an alternative way to achieve economical lubrication at acceptable effect and environment friendly disposition. In this study, the classical ring test was selected for evaluating the effectiveness of laser textures in interface lubrication. The ring test has several limitations including low interface pressures and low surface expansions. However, it has many advantages including ease of experimentation, ease of texturing (flat surfaces), ease of measurement (flat surfaces) and reasonable sensitivity to frictional changes. Cold upsetting was selected as the evaluative technique as it avoids the close coupling present between friction and heat transfer in hot or warm upsetting. Pulsed laser texturing was used for the texture depths of 5-7 μm (these depths were found to be most effective in strip drawing [26]). Lubrication effects of the micro-texture on the die surfaces were compared with those without textures. Moreover, the sensitivities of the texture size for various lubricants were also studied. Numerical model was developed that replicated real experiment and its prediction compared with
experimental data. Lubricants used in this study are different SAE (Society of Automotive Engineers) oils and typical shop grease.

### 3.1.1 Typical frictions for cold aluminum forging

Without doubting, friction in metal forming depends on the lubricant in large extent. Buchner et al [17] tested four forging lubricants, A. Dispersion of graphite in water, B. Dispersion of graphite in water, C. Emulsion of a dispersion of graphite in water and mineral oil, and D. Dispersion of graphite in mineral oil, with respect to their lubricating effect and their applicability in the production of parts with long flow paths. Their experiments were performed on a rotational forging tribometer (RFT) that was originally designed for ring-on-disc test and specimens were made from Aluminum AA 2618. Their results showed that, in metal forming condition, typically friction coefficient ($\mu$) of 0.04 and 0.03 could be achieved by lubricant A and B, respectively. In addition, friction coefficient for lubricant C ranged from 0.03 to 0.55, while 0.04 to 0.09 for lubricant D. And their films were easily broken down if sliding speed was high. Kim et al [39] studied the forging process of aluminum 6061 wheel. Their typical friction factor ($m$) was 0.2.

Moreover, from the results of double cup backward extrusion test which is standard lubrication test in metal forming industry and characterized by high pressure and sliding speed, friction factor 0.065, 0.035, 0.04 and 0.075 can be achieved by lubricating zinc phosphate coating, MEC Homat, Daido AquaLub and MCI Z-Coat, respectively [25]. In addition, this kind of lubricants will not fail until the film or coating thickness is less than 0.3 times of RMS of surface roughness.
3.1.2 Application of micro-texture in friction reduction

In addition, there was a lot of research efforts spent on reducing friction by texturing workpieces in last two decades. Pettersson et al [53] gave the relationship between surface texture and tribological properties in dry and boundary lubricated sliding under light load. In their study, the textures were anisotropically etched on silicon surfaces and their influence was investigated on PVD coated TiN and DLC (diamond-like carbon) surfaces.
Fig 3.1: Two topologies of the textures used in Pettersson’s tests [53]
The substrate of the samples is silicon wafer on which two different texture patterns, groove and square, were anisotropically etched to a depth of 5 μm using potassium hydroxide (KOH) at 80 °C. Fig 3.1 shows the SEM images of two texture patterns. There are three different widths, 5, 20 and 50 μm, for each pattern. After etching, DLC and TiN coatings of 1μm thickness were deposited on the textured substrates through Balzers Sandvik PVD processes.

The sliding tests involved reciprocating sliding against a steel ball of 10 mm diameter. The testing samples include one flat, three grooved and three surfaces with square depression of each of the two coating types. The grooved surfaces were oriented with the grooves perpendicular to the sliding direction. The squares were oriented with two sides close to perpendicular to and two sides parallel to the sliding direction. One series of three parallel tests to 1000 cycles was run under dry conditions, and one series of three parallel tests run to 20,000 or 200,000 cycles under boundary lubricated conditions. A normal load of 5 N was applied with a spring and the normal and friction forces were measured by strain gauges. The sample was oscillating with a stroke of 2.5 mm at a frequency of 5 Hz and the tests were performed at room temperature.
Dry sliding between the steel ball and the TiN coated surfaces. (a) Two parallel tests on the flat surface. (b) All types of textured surfaces, including grooves (open circles) and square depressions (black squares) of three sizes each.

Fig 3.2: a) Test results [53]
Boundary lubricated steel ball against TiN coated surfaces, (a) flat and (b) 20 μm squares (open squares), 5 μm grooves (open triangles) and 20 μm grooves (open circles).

Fig 3.2: b) Test results [53]
Unlubricated sliding of the steel ball against DLC coated surfaces, (a) flat and (b) square depressions (black squares) and grooves (open circles) of the three sizes.

Fig 3.2: c) Test results [53]
Boundary lubricated DLC coated surfaces. (a) Flat (open circles) and texture with 20 \( \mu \text{m} \) square depressions (black squares). (b) The 5 and the 20 \( \mu \text{m} \) grooved textures (open circles) and the 5 \( \mu \text{m} \) square depression texture (black squares).

Fig 3.2: d) Test results [53]
From the results shown in Fig 3.2, for TiN coated samples, it is found that lubrication substantially decreases the coefficient of friction, against both textured and un-textured surfaces. When lubricated, the low friction conditions lasted shorter on textured surfaces than on the flat ones.

As to DLC coated samples, under the boundary lubricated conditions, a few of the textured DLC surfaces exhibited excellent performance. The flat surface, the 50 \( \mu \text{m} \) textures and the one interrupted by 20 \( \mu \text{m} \) square depressions could not keep the low friction and they suffered severe wear. The 5 and 20 \( \mu \text{m} \) grooved textures and the surface with 5 \( \mu \text{m} \) depressions exhibited a friction coefficient of around 0.05, which kept constant during all the 200,000 cycles. Therefore authors concluded that under certain conditions, it may be very beneficial to put a texture on a sliding surface. However the same texture may reduce the contact area. Much work must been done before one can design the surface texture for specific conditions.

Andriy et al [5] studied the lubrication effect of micro-dimple textures which were on steel disk surfaces and created by laser ablation process. Fig 3.3.a shows SEM image of the dimples. These dimples generate hydrodynamic pressure between oil-lubricated parallel sliding surfaces. Tribological experiments were conducted with a pin-on-disk apparatus at sliding speeds in the range of 0.015–0.75 m/s and nominal contact pressures that ranged from 0.16 to 1.6 MPa, as shown in Fig 3.3.b below. Two oils with different viscosities (54.8 and 124.7 cSt at 40°C) were used as lubricants.

Their test results indicated friction transitions on the Strubeck curve which means laser texturing expand the contact parameters in terms of load and speed for
hydrodynamic lubrication. Moreover this beneficial effect of the texturing are more pronounced at higher speeds and loads and with higher viscosity oil. Therefore, comparing with untextured surfaces of comparable surface roughness, laser surface texturing is able to reduce the friction coefficient substantially under similar operating conditions. In addition, they also found that a lower area dimple density is more beneficial for lubrication regime transitions; and laser surface texturing can be used to reduce friction in components that are operating under a boundary lubrication regime.

Wakuda et al [63] again verified the effect of micro-dimples on the frictional properties of a silicon nitride ceramic mated with hardened steel. The samples are hot-pressed silicon nitride ceramic material which was lapping finished to $R_a$ being less than 0.01 micron before surface texturing. Subsequent micro-dimpling was performed with either abrasive jet machining (AJM) or Excimer laser beam machining (LBM). The two micro-machining methods resulted in totally different dimple profiles, as illustrated in Fig 3.4.a.

The Pin-on-disk tests whose schematic is shown in Fig 3.4.b were used to study the lubrication and wear effects. The disks are of a variety of surface morphologies in which dimples were pattern machined with different size, density, and geometry.
Fig 3.3: a) SEM image of the micro-dimples and b) experiment schematic [5]
Fig 3.4: a) SEM images of the micro-dimples and b) experiment schematic [63]
The experimental results indicate the high potential of a micro-texturing technique for reductions in friction at line contact interfaces. Compared to a lapped smooth surface without texturing, some samples successfully realized reductions in friction coefficient from 0.12 to 0.10, which was verified that surface texturing is an effective key to friction reduction. Moreover an appropriate surface morphology can lead to dramatic reductions in friction over a wide range, covering boundary to mixed lubrication conditions at the line contact sliding interface. Therefore it retains the low friction under severe friction conditions without forming undesirable tribochemical films. The size and density of the micro-dimples are critical to the tribological characteristics, whilst the dimple shape did not significantly affect the friction coefficient regardless of rounded or angular profiles. The distribution of micro-dimples is also an important factor. A dimple size of approximately 100 μm at a density of 5–20% is recommended.

Wang et al [66] tried to optimize surface textures to maximal load carrying capacity. The textures of micro-pits which were ion etched and evenly distributed on SiC bearings working in water. From the experiments, they found that micro-pit texturing is an effective way to raise critical load for the transition from hydrodynamic to mixed lubrication of SiC thrust bearings in water lubrication. The load carrying capacity can be improved up to about 2.5 times comparing with that of untextured surface for proper geometry and distribution of the micro-pits. Moreover there exists an optimum range for the pit geometry factor, depth-diameter ratio, and the distribution factor, pit area ratio, where the load carrying capacity can be
improved maximally.

Two patterns of micro-cavities, characterized as textured area coverage of 8% and 30% of the surface area, were produced by laser ablation on an area of 8mm×10mm on polished steel discs. The laser-textured pattern of 8% converge consists of cavities with a large diameter/depth ratio, while the aspect ratio of the 30% cavities is low. The oscillating sliding tests which involve steel ball contacts on hardened and polished flat steel specimen surfaces were carried out. Three different metal working oils reflecting various viscosities were used as lubricants. The coefficient of frictions obtained from tests is about 0.15 which is typically from boundary lubrication regime [3]. Comparing to that without texture, both textures significantly reduced friction and wear under sliding conditions, among which the combination of high viscosity oil and a low density texture of micro-cavities with a large depth achieved the best lubrication effect. In addition its life of lubrication was between 3 and (at least) 100 times longer than that without texture.

Ryk et al. [59] also did the test of linearly oscillating sliding surfaces using samples made from piston rings and cylinder liners for internal combustion engines. Their results indicated that the kinetic coefficient of friction can be reduced by 30–40% and less lubricant consumption by the introduction of a laser-textured pattern of micro-cavities. The work of Golloch [29] shows friction reduction at higher velocities of piston ring tests. Texture on a sliding surface can act as micro pressure chambers to achieve localized hydrodynamic lubrication and thus coefficient of friction can be reduced by 35-50%.
Work done by Neudecker et al. [48], was focus on tools of metal forming and stamping and have shown that the kinetic coefficient of friction can be reduced by up to 14%, in comparison with a lapped surface (without texture).

Dumitru et al. [22] study the lubrication effects of micro-textures from the lubrication life point view. They found an eight times improvement of lubrication life for oil lubricated textured steel disc with micro-cavities with a smooth steel disc in pin-on-disc tests up to the dramatically friction rise (to $\mu = 0.5$) when comparing that of without textures.

The ring upsetting tests studied in Hu et al. [37] indicated the values of the coefficient of friction range from approximately 0.001 to 0.08 for polished, EDM’ed and turned surfaces of aluminum ring samples. The surface of their test setup was flat hardened surface (HRC 55) made from ANSI L6 steel and polished to a sub-micro surface finish.

In stainless steel sheet forming, the study of Wiklund et al [69] shows a positive linear relationship between surface roughness of blank and coefficient of friction which typically ranged from 0.04 to 0.12.

3.2 Texture Design and Fabrication

The effect of die/tool roughness on interface friction and lubrication has been studied for many years with large number of studies directed towards cold strip rolling and strip drawing [6, 61]. Among these, the investigations reported in literatures [6, 7, 12, 44, and 62] focused primarily on workpiece roughness and its
efficacy in entrapping and releasing liquid lubricants. Geiger, et al [26] was the first to consider Laser texturing on the tool and its relevance to micro-lubrication. They found in strip drawing that the texture shape and depth had a major influence on the friction factors. However, they did not explore the possibility of using micro-texturing in bulk forming. While texturing in general and laser texturing in particular have shown considerable promise in metal forming applications, several issues need to be resolved before their wider use in cold forging and sheet forming applications. These issues include: (1) What role does the geometry of the groove play in the entrapment of lubricant? (This was investigated for strip drawing applications according to [48].) (2) What roles do the proximity of the grooves and the surface coverage play in lubricant entrapment and its escape (boundary lubrication)? (3) What is the effect of interface pressure, velocity and surface expansion? and (4) What interface conditions will force the lubricant out and fill the grooves with the workpiece material?

In this study, the classical ring test was selected for evaluating the effectiveness of laser textures in interface lubrication. The ring test has several limitations including low interface pressures and low surface expansions. However, it has many advantages including ease of experimentation, ease of texturing (flat surfaces), ease of measurement (flat surfaces) and reasonable sensitivity to frictional changes. Cold upsetting was selected as the evaluative technique as it avoids the close coupling present between friction and heat transfer in hot or warm upsetting.

3.2.1 The texture design

3.2.1.1 The design of surface roughness of die surfaces
There are some literatures focused the substrate surface roughness before texturing. All of them show that one need serious consideration of the surface roughness of the substrate. Wiklund et al [69] studied Frictional mechanisms in mixed lubricated regime in steel sheet metal forming and concluded that frictional response showed a correlation to the surface topography, such as the amplitude parameter and texture aspect ratio parameter. When predicting the frictional response of surfaces with multi-component distributions, the standard deviation of the distribution above the mean line was more suitable. The frictional response in mixed lubricated regime is dominated by the original surface topography besides oil viscosity, sliding velocity, and pressure, which were held constant in their experiments. The correlation between coefficient of friction with respect to the surface roughness (Sq or Ra) is positive linear.

Geiger et al. [26], who studied nano-scale tribology property under minimum lubrication conditions with modest contact pressures and low sliding speeds on Cr-N ceramic plates with micro crater-like texture pattern in block-on-ring tests which were tested with a micro-tribometer. They found surface with roughness Sq=9.4 nm achieved comparatively low COF comparing to that of the reference which was without texture and Sq=5.5 nm. When Sq increased to 15.4 nm, friction is slightly increased. If surfaces consist of sharp peaks, formation of the thin boundary friction layer might be disturbed with respect to homogeneity, texture and thickness of the film. This could lead to higher friction. Based on these they concluded that a certain degree of surface roughness is required for supporting lubricating-promoting
mechanisms that reduce friction. However, if the roughness amplitude is too high, friction increases.

In addition Menezes et al [46] show, for the randomly polished steel forging die the coefficient of friction is lower than other machining marks. Hu and Dean [37] studied the relation between friction and surface topography using various lubricants and found that a random smoother surface could retain more lubricant and thus reduce friction.

Lakshmipathy and Sagar [43] studied the influence of die grinding marks orientation on friction in open die forging under lubricated conditions. They used H11 steel die to forge aluminum workpiece, which is very close to our situation. Two sets of dies, one with unidirectional grinding marks and other with criss-cross grinding marks were used. It was found that, for the same percentage of deformation, the dies with the criss-cross ground pattern required lesser forging loads when compared with the die having uni-directionally ground pattern. The friction factor was also lower during the forging process when the die with the criss-cross surface pattern was used. Then they concluded that the lubrication breakdown tendency is more when pressing is done with uni-directionally ground die than with criss-cross ground die.

Srivatsan [2003] studied the role of die surfaces finish in hot steel forging lubrications. Four flat dies were made from H-13 steel heat treated to 48-50 HRC in his study. The first die surfaces were ground to a surface roughness Ra value of 25 μin. The second one was stone polished to Ra value of 10 μin. Concentric grooves were machined onto two other dies, with Ra values of 50 and 100 μin respectively. The
lubricants in his tests are water based graphite with dilution ratios 1:10, 1:15 and 1:20 and synthetic oils. The tests were hot steel ring upsetting and samples were made from ANSI 8620 steel. His results show a clear dependence of the friction factor on the nature of the die surface. The coefficient of friction decreases with an increase in the surface roughness. The highest values of friction are obtained for the polished die (10 μ in.) and there is a drop in friction as the roughness increases. The friction factor was the least for the textured die (50 μin.) across all lubricants and dilution ratios. This can be explained by the fact that the circular grooves in the textured die act as a lubricant reservoir and the trapped lubricant is released to the interface as the deformation proceeds. Thus, there is a constant supply of lubricant to the deformation zone for a longer period of time in the textured die as compared to other surfaces. The polished die has a very smooth surface which increases the real area of contact between the work and the die, thereby causing an increase in friction. The ground surface (25 μin.) does provide better lubricant entrapment, but since the direction of grinding is not transverse to the direction of metal flow, the trapped lubricant is squeezed out prematurely. Between the two textured dies however, the smoother die (50 μin) exhibits better frictional property than the rougher one (100 μin). This clearly indicates that there is a threshold value up to which roughness actually aids metal flow. Beyond this, the deformation of the peaks in the rough surface requires greater force and since the friction is dependent on the normal force, increasing roughness above a certain range will be detrimental to metal flow.

Based on the pioneer’s research work, and also considering its less effect on
the final results, we intentionally hand polished die surface to the roughness of Ra is 2.0 µm to ensure the machining marks are randomly.

3.2.1.2 The design of texture pattern and size

The work of Nanbu et al [47] was focused on the lubrication effect of the various texture patterns. As shown in Fig 3.5 four group of texture patterns, U, R, T and W, were studied. They concluded that pattern T has most capability to create high pressure and hydrodynamic lubrication which are expected for forging applications.
Fig 3.5: Various texture patterns studied by Nanbu [47]
Their results further indicated that, for the three T shapes, the abilities to enhance the hydrodynamic action can be ranked in the sequence of T3, T1, and T2 if one consider interface sliding direction as indicated by the arrow in Fig 3.5. Both T1 and T2 experience pressure gradual reduction when they move into the EHL region due to the divergent wedge; however, the reduction by T2 is more severe because it has a longer divergent wedge. The pressure drop ratio in T1 is only one half of that in T2. Such a drop in T3 is even smaller.

For our situations, interface sliding speed has two directions, T3 pattern may not be applied if one needs good effects on both sliding direction. However pattern T1 is still good alternative for ring upsetting tests. Therefore, in our research, we adopted T1 as texture pattern.

Andersson [3] studied two patterns of micro-cavities, characterized as textured area coverage of 8% and 30% of the surface area, were produced by laser ablation on an area of 8mm×10mm on polished steel discs. The laser-textured pattern of 8% converge consists of cavities with a large diameter/depth ratio, while the aspect ratio of the 30% cavities is low. The oscillating sliding tests which involve steel ball contacts on hardened and polished flat steel specimen surfaces were carried out. Three different metal working oils reflecting various viscosities were used as lubricants. The coefficient of frictions obtained from tests is about 0.15 which is typically from boundary lubrication regime.

In the aluminum ring upsetting conditions, the pressure is more than Anderson’s and thus more lubricant may be squeezed out. Therefore two densities of
texture pattern, 5% and 10%, may be better for us. Moreover, in order to provide more lubricant, the cavity of each texture should be larger. Plus considering the axis-symmetry properties of the ring upsetting, the textures for our case are concentric circular grooves with the cross section of T1 as mentioned above.

3.2.1.3 The texture design in present aluminum ring upsetting test dies

As we mentioned in previous section, we selected H-13 steel as the die material which is also nitrided and heat treated to hardness about HRC 65. Before texturing, the surface of each die was hand polished to a roughness of Ra 2.0 µm to ensure the machining marks are randomly. The micro-texture selected for our study was concentric circular grooves whose cross section is T1 texture pattern (symmetry triangle), seeing section 3.2.1.2 or Nanbu et al [47]. The depth of the groove ranged from 10 to 40 thousandth of an inch (0.254-1.016 mm). Three sets of dies were made. One of them was not textured while the other two had coarse and fine textures, respectively. The distance between each groove is 1 mm for coarse texture while 0.5 mm for fine texture. The width of each groove is 100 micron for coarse texture and 50 micron for fine ones. Therefore the groove area converges are 10% and 5% for coarse and fine textured zones respectively, as we discussed above.

In addition based on the FEM simulations, one can find maximum surface expansion of ring sample after upsetting, based on which we designed texture zone which was a circular belt zone on the working surface of the die. The inner diameter and outer diameter of the circular belt zone are 0.25 and 1.5 inch, respectively. We only fabricated textures in that zone to save cost.
3.2.2 Texture fabrication

Initially the nano-machining was explored to fabricate textures but it could not provide satisfactory grooves. Theoretically nano-machining can achieve the machining precision up to 0.01 µm. However it is only success on soft material, such as aluminum, while, in our case, dies were heat treated to high hardness before fabrication to prevent distortion in fabricated textures. Laser ablation was a good alternative way to fabricate micro-textures on hard steel surface. This technique was successful in providing good textures.

3.2.2.1 Texture fabrication methods

Recently, people have developed some special texturing methods which can be used to texture hard tool or even hard-coated surfaces. For instance, shot blasting, electrical discharging, precision texturing, laser texturing, electro beam texturing are usually used to texture steel surfaces, while mill finishing, electrical discharging, laser texturing, electro beam texturing are applied to aluminum ones [32]. Among them, laser texturing or laser ablation is the first choice to fabricate micro-textures on the metal forming tools because of its good precision, easy control, and being able to texture any material. For example Etsion [24] and Yu et al. [75] used optimized laser-texturing to ablation textures on mechanical face seal rings made from silicon carbide has shown that the friction losses can be significantly reduced. Similarly, Wang et al. [66] have shown that the load-carrying capability of thrust bearings made from silicon carbide can be increased by laser-texturing [66].

The laser used in micro-texture fabrication is usually Excimer laser which
has been used in research only for a short time [23]. This kind of laser induces
nano-to-micro scale patterns on hard coatings such as TiN, TiCN, and DLC films [23
and 55] and is able to ablate all kinds of materials at very high rates without causing
much damage in and around the textured areas.

Excimer lasers are high pressure gas lasers emitting pulsed radiation in the
UV range. Only when laser beam energy density reaches a threshold, material then
can be ablated. Moreover the ablated surface topography depends on the energy
density. Thus different surface finishing, such as roughening, flattening, micro
texturing, can be achieved by varying the energy density of the laser beam, as shown
in Fig 3.6.b. When the energy is in the range of the ablation threshold, the surface gets
rougher due to non-uniform ablation because of local different absorption; while the
material is ablated homogeneously and thus a flattening of the surface when the
energy is higher than the ablation threshold.
Micro-textures can be produced by Excimer laser radiation with high precision and flexibility by using a mask projection technique. A mask is illuminated and its geometrical information is projected onto the surface of the workpiece (see Fig 3.6.a), the irradiated material is then ablated. Fig 3.4 shows examples of laser ablated micro-dimples. Another advantage of laser texturing is that there is almost no heat affected zone in substrate because most of the laser energy is removed immediately with the evaporating material and thus no heat transferred into the workpiece. [55]

The micro-texture explored by Dumitru et al [22] are arrays of micro-dimples whose diameters are in the range of 5–10 micron and depths are in the range of 5–8 micron. The spaces between arrays are about 30 microns. The
micro-texture are ablated by Nd:YAG laser on stainless steel and steel surfaces, through which about 6-time longer life of low friction were achieved.

In the near future, laser processing and coating technologies will most likely be integrated with three dimensional coating architectures that possess very low friction and wear under boundary-lubricated sliding conditions [23].

3.2.2.2 Laser generator and ablation

In our research we used CPA-2110, shown in Fig 3.7, is a 2 kHz amplified Ti:Sapphire laser system which is a product of Clark-MXR, Inc, and available in IWSE department, Ohio-State University, Ohio. The turn-key nature of this extremely compact laser accentuates its productivity and utility. It can run for days without the need to frequently readjust it to optimize performance. The CPA-2110 is the only fully-integrated system on the market today. It includes everything you need to generate high peak power femtosecond pulses in one box i.e. seed laser and its associated diode laser pump, pulse stretcher, Ti:S regenerative amplifier and its associated pump laser, and pulse compressor. It is fully compatible with our NOPA® visible and IR-OPA optical parametric amplifiers (OPAs). For pump-probe experiments requiring two or more synchronized and independently-tunable colors, the CPA-2110 output beam can split to pump as many as five NOPAs that are synchronized to less than 1 femtosecond timing jitter. In Table 3.1 are listed the performance parameters of CPA-2110. [19]

The CPA laser generator was available in laser welding laboratory, welding engineering of IWSE department, Ohio-State University. Here I am expressing my
appreciations to Dr David Farson, faculty of the laboratory, and his student, Dr Hae Woon Choi. They helped us to ablation the micro textures on die surface and roughly analyzed textures.
Fig 3.7: The photo of the CPA laser generator
<table>
<thead>
<tr>
<th><strong>Femtosecond Version</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy</td>
<td>&gt;1 mJ at repetition rates ≤ 1 kHz</td>
</tr>
<tr>
<td></td>
<td>&gt;600 µJ at repetition rates between 1 kHz and ≤ 2 kHz</td>
</tr>
<tr>
<td>Pulsewidth (FWHM)</td>
<td>&lt;150 fs</td>
</tr>
<tr>
<td>TBWP</td>
<td>&lt;1.4 x transform limit (sech²)</td>
</tr>
<tr>
<td><strong>General (as applies to all above versions)</strong></td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>775 nm</td>
</tr>
<tr>
<td>Transverse mode</td>
<td>TEM₀₀</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>User-adjustable up to 2 kHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear, horizontal</td>
</tr>
<tr>
<td>Energy stability</td>
<td>&lt;1% rms</td>
</tr>
<tr>
<td>Beam Diameter</td>
<td>4 - 6 mm</td>
</tr>
<tr>
<td>Beam Divergence</td>
<td>&lt; 100 microradians</td>
</tr>
<tr>
<td>Beam Pointing Stability</td>
<td>&lt; ± 25 µrad/°C</td>
</tr>
</tbody>
</table>

| **Physical Dimensions** |  |
| Laser head              | 48" L x 20" W x 12" H |
| Power supply            | 24" H x 23" W x 38" D |

| **Utility Requirements** |  |
| Electric                | 110 VAC, 60 or 50 Hz, 10 A and 208 VAC, 60 or 50 Hz, 40 A |
| Water                   | Tap water, 4 gpm, <75°F, 30-50 psi |

Table 3.1: Performance parameters of CPA-2110 [19]
Fig 3.8: Laser control and ablation. a) schematic and b) equipment
Fig 3.8 shows the path of laser after leaving from CPA-2110. The X-Y μ-Stepping table is an open-loop and CNC code controlled platform which has X, Y linear motion freedoms and on which the workpiece to be textured is fixed. The laser energy density is controlled by adjusting the angle of BD through which the laser passes. The MS is a controllable shutter through which one can decide whether the laser contacts the workpiece. Different texture patterns can be achieved by specified motions of X-Y μ-Stepping table by properly programming CNC codes.

3.2.3 Texture analysis

Three dies were used in experiments, all with 4 inch (101.6 mm) diameter and 1 inch (25.4 mm) thickness. Two of them were textured by laser ablation using CPA-2110. The texture patterns were concentric circular grooves whose depth and width were controlled by energy density of CPA 2110. Surface topographies of textured dies were measured by a stylus surface analyzer, Surface Profilometer indicated in Figs 3.9 a), 3.9 b) and 3.9 c) show its results. The scanning of stylus probe was in linear lines which approximately pass through center of the circular textured zones, and thus the periodical surface profiles shown in the results indicate concentric texture patterns that are evenly spaced. Based on the Fig 3.9, one can get the groove depths are about 10 and 15 micro-inches (450-600μm) for two different grooves; surface roughness is from 1.4 to 2.4 micron.

Together with SEM pictures shown in Fig 3.10, the spikes in the surface profile plot resulted from the material movement in laser ablation. Those spikes were tiny and they do not affect the tests since they wear off pretty soon due to abrasion.
The SEM images of the textures are shown in Fig 3.10 below, respectively. Through them, one can estimate the width of texture, about 40 µm. Because of issues such as laser focusing, the waviness of the die surface etc., one cannot obtain very accurate ablation width. In addition Fig 3.10 c, that shows there was small bumps of the material on inside edge of the texture as a by-product of from laser ablation. Those bumps are indicated as spikes in the plots of surface profilometer, Figs 3.9 b) and 3.9 c).
Fig 3.9: Surface profilometer and its analysis results on textured surfaces.
Fig 3.9 continued
Fig 3.9 continued
Fig 3.10: SEM images of textures.
Fig 3.10 continued

c)

Fig 3.10: SEM images of textures
### 3.3 Lubricant selected for tests

The role of interface friction and lubrication in the cold forging of aluminum alloys has extensively been studied and reviewed in literatures [8, 10]. In which the lubrication regimes are divided into two categories. When the reductions are low and the aluminum alloys soft, lubrication is often by oils, greases or zinc stearate. However for higher reductions and harder aluminum alloys (5XXX and 7XXX series), conversion coating are needed to entrap lubricants at higher interface pressures, interface speeds and surface expansions. The failure of these lubricants can often result in aluminum pick up, galing and seizure.
Fig 3.11 Choice of lubricant for cold forging of different aluminum alloys [8]
The application of conversion coatings on aluminum billets often involves several steps including mild alkaline cleaning, cold water wash, strong alkaline or acid pickle, cold rinse, coating (zinc phosphate or aluminum fluoride or calcium aluminates) and lubrication (alkaline soap or MoS$_2$) [8].

In their study, Buchner et al. [17] investigated four aluminum forging lubricants: Lubricant A (Dispersion of graphite in water), Lubricant B (Dispersion of graphite in water), Lubricant C (Emulsion of a dispersion of graphite in water and mineral oil) and Lubricant D (Dispersion of graphite in mineral oil), with respect to their lubricating effect and their applicability in the production of parts with long flow paths. The tests were conducted on a custom built testing machine that simulates the conditions in industrial production. The lubricants were assessed considering the change of the coefficient of friction during the test and the influence on tool and workpiece surface. From their results all these new lubricants get into the tool–workpiece interface at the beginning of the process, and pretty soon, tool and specimen are separated by a compact lubrication layer even under high initial surface expansion. Lubricant A seems to be not affected by the surface expansion and its friction stress is high compared to the other lubricants. Regarding the lubricants B to D, the sliding friction stress exceeds the static friction stress and increases until it reaches a maximum. However, the maximum sliding friction stress of lubricants B and C is in the range of that of lubricant A, but the sliding friction stress of lubricant D is about twice this value. The friction stress reaches a steady state for lubricants B
and C. Using lubricant D, the friction stress decreases from its maximum value and reaches a steady state.

### 3.3.1 Selection of lubricant in current study

One of the objectives of this study is to reduce the cost of the application and the environmental hazards associated with the use of acids, alkalis and the resulting sludge, which are two drawbacks with traditional lubrication process. Consequently, there is considerable motivation to find an alternative lubrication method, especially for cold forging harder aluminum alloys. Since the aluminum ring upsetting test is characterized extremely low surface expansion and the hardness of the specimen that were made from AA5050 is medium, according to Fig 3.11, we selected commonly used mineral oils and shop grease as lubricants for the test.

### 3.3.2 Lubricant properties and deposition methodology

Lubricants used in this study are typical shop grease [9] and different SAE (Society of Automotive Engineers) mineral oils. Industry shop grease was melted using a water bath and applied at 75°C (gel state), as shown in Fig 3.12. The melted grease was applied on the dies and ring samples, through which one can achieve same initial lubrication conditions for each test. Four SAE oils were also used 0W-20, 5W-30, 10W-30 and 20W-50. According to SAE, the suffix W means winter and we found the viscosity data of these multi-grade oils as shown in Table 3.2. After extrapolating viscosities at 40 and 100°C to room temperatures, 23°C, the viscosities (Centistokes) of these oils were approximately 54.33, 79.02, 85.43, 207.74 respectively. The application of SAE oils was similar to that of grease.
In order to avoid the contamination of residue from last test, at the beginning of each test the dies were carefully wiped clean, any sticking aluminum was removed by a brush and cleaned with alcohol. Rings were dipped in the candidate lubricant and placed on the die surface for the test to begin. After each test dies were cleaned by alcohol moistened polyester cloth, and there was no metal residue or other debris on die surfaces by eye inspections. Ring samples were kept in alcohol and dried in the air before test.
<table>
<thead>
<tr>
<th>SAE Multi-grade Oil</th>
<th>Viscosity (Centistokes)</th>
<th>Density (kg/m³)</th>
<th>Extrapolation of viscosity to 23°C (Centistokes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40°C</td>
<td>100°C</td>
<td></td>
</tr>
<tr>
<td>0W-20</td>
<td>44.2</td>
<td>8.43</td>
<td>860</td>
</tr>
<tr>
<td>5W-30</td>
<td>64</td>
<td>11</td>
<td>860</td>
</tr>
<tr>
<td>10W-30</td>
<td>69</td>
<td>11</td>
<td>865</td>
</tr>
<tr>
<td>20W-50</td>
<td>166</td>
<td>18.7</td>
<td>872</td>
</tr>
</tbody>
</table>

Table 3.2: Physical properties of SAE oils from
(http://www.pennzoil.com/products.html for SAE 0W-20
http://www.engineeringtoolbox.com/sae-grade-oil-d_1208.html for others)
Fig 3.12: Water bath heating for lubricant
3.4 Die design and Manufacturing

From 1940s, pioneers in metal forming tribology have developed a lot of ways to investigate the frictions during metal forming process, such as spike die extrusion, ring upsetting, backward extrusion, and etc. Among them ring upsetting is the simplest and most reliable method [60]. As shown in Fig 3.13, when a ring is compressed between flat platens, friction resists expansion. The higher the friction, the more is the resistance to expansion. Hence, after upsetting, the hole expands less. And if friction is too high, the hole expansion becomes negative, which means inner diameter becomes actually smaller. Only one independent parameter needs to be measured to calculate friction: Inner Diameter(ID) of the ring. Therefore, the ring-compression test has become a favorite method of lubricant evaluation. Ring samples having the ratio of OD : ID : Height = 6:3:2 are normally adapted in the tests as they are most sensitive to the friction changes [60].
Fig 3.13: Schematic of ring upsetting tests. a) at low friction condition and b) at high friction condition [60], p is the die pressure.
Fig 3.14: Design of ring upsetting die (dimensions in inch unless otherwise specified)
Fig 3.15: Dies and ring sample
3.4.1 Detail design of ring upsetting dies

The design of the ring upsetting dies is shown in Fig 3.14. Top die and bottom die are identical except the bottom one has five thermocouple holes that will be used in future studies in non-isothermal conditions. The outer diameter of the dies is 4 inch or 101.6 mm and the thickness is 1 inch or 25.4 mm. Four counterbore holes are evenly spaced on the boundary of 2.2 inch diameter that is used to connect the die to the press ram with 3/8 inch bolts. On the bottom surface of the die, there is a circular undercut (diameter 2.2 inch) of 0.2 inch in which five small counterbore holes were drilled for embedding thermocouples. The diameters of thermocouple holes are 1 mm (0.039 inch). The distances between tip of thermocouple holes to die surface are all 0.05 inch. Since the die was designed for axis-symmetric forging, thermocouples measure temperature at different positions which can be described by radial distance. The radial distances from axis to center of thermocouple holes are 0 inch, 0.15 inch, 0.2 inch for two pieces, and 0.25 inch, as shown in Fig 3.14. We did not use thermocouples in present research which is done at room temperature. In future research we will investigate the lubrication effects of texture in hot steel forging tests that are non-isothermal. The temperature will be measured through embedding thermocouples.

The material of the dies is H-13 steel which was nitrided and heat treated to hardness about HRC 65. The surface of each die was hand polished to a roughness of Ra 2.0 µm before texturing.
3.4.2 FEM calibration

In order to quantitatively relate the changes of inner diameter to the friction factors, FEM simulations were used for calibration. As shown in Fig 3.16, an axis-symmetric model was created in DEFORM 2D which is a commercial software and a product of Scientific Forming Technologies Corporation. The sizes of ring samples, 1 inch outer diameter, 0.5 inch inner diameter and 1/3 inch height, and material, aluminum alloy 5150, are same as the ones used in experiments. The dies were set as rigid and ram speed was 1 inch/sec which is same as the MTS hydraulic press used in experiment. Series of simulations were run with same setup but different friction factors between die and ring sample. Friction factors were varied between 0.01 and 0.7. The inner diameters at different reduction were measured at the center height of the forged ring, as indicated in Figs 3.16 b) and c). After recording the data of ID and calculating its reduction rate, one can generate a friction map in which each curve represents a distinct value of friction factor. The friction map obtained by above method depends upon the material (flow stress) and dimensions of samples. In our study, there are three different ring samples which were made from aluminum 5050, each sample needs its own map. Fig 3.17 shows the map for samples of 1/3 inch thickness. One can find other maps in section 3.7 where the maps were superimposed with experimental data.
Fig 3.16: Ring upsetting calibrations using FEM simulations.

a)  DEFORM\textsuperscript{TM} 2D simulation model.
Fig 3.16: Ring upsetting calibrations using FEM simulations.
b) ID measurement procedure in low friction simulation (m=0.1)
Fig 3.16: Ring upsetting calibrations using FEM simulations.
c) ID measurement procedure at high friction simulation (m=0.6)
Fig 3.17: The calibration map of friction factor for aluminum 5050 ring samples with 1 inch OD, 0.5 inch ID and 1/3 inch thickness.
3.5 Ring Sample design and preparation

Hu et al. [37] studied two types of workpiece surfaces, random and directional, and found that, for the end face of rings, the amount of liquid lubricant retained increases with decreasing initial roughness on random surfaces (polished and EDMd) which in turn led to decreasing values of friction in aluminum ring upsetting tests. The turned surface, which had greater initial roughness, 2.189 micron of Ra, than the polished surface, 0.167 micron of Ra, showed the lowest value of coefficient of friction because the concentric grooves of a turned surface trapped the lubricant during upsetting preventing squeezing out. Despite the ability of turned surfaces to minimize friction, the trade off was the severe roughening which is an indication of lubricant trapping resulting at high hydrostatic pressures.

The material of ring samples in our tests was aluminum ANSI 5050 which is a aluminum-magnesium alloy. All sample designs were of 0.5 inch (12.7 mm) inner diameter and 1 inch (25.4 mm) outer diameter, with three different thicknesses, 1/3, 1/4, and 1/8 inch. Moreover, based on Hu’s research [37] mentioned above, we turned sample surfaces to increase the sensitivity of the measured friction factor. The typical surface roughness Ra of the turned samples is 2.8 micron. Fig 3.18 shows the SEM picture of a sample is surface texture of sample surface has very little effect on lubrication as it is much smaller than die texture. All samples were made in same batch.
Fig 3.18: SEM picture on ring sample surface
3.6 Upsetting equipment

The upsetting equipment for tests with grease was MTS Servo-Hydraulic Test Frame with maximum force of 50 tons as shown Fig 3.19. The ram speed during forging process was about 1 inch per second. The stroke was pre-set at specified reduction of ring sample height. For those tests with SAE oils, a 350 ton hydraulic press, Savage, was used. The press is shown in Fig 3.20. The ram speed in this test was also 1 inch per second. Since one cannot have the stroke exactly at the pre-set value in hydraulic presses, the real reduction was also manually measured.

Ring samples were concentrically placed on the texture zone before upsetting. Tests were repeated at different upsetting strokes. After tests, the change in the inner diameter of sample was recorded.

A major drawback of the hydraulic press is that one cannot precisely control the final stroke of the ram. However that did not affect our experimental precision as the height of the upset sample was measured to calculate the actual height reduction.
FIG 3.19: MTS SERVO-HYDRAULIC TEST FRAME
FIG 3.20: UPSETTING EQUIPMENT: SAVAGE 350 TON HYDRAULIC PRESS
3.7 Ring upsetting experiments and results

Each die was connected to the ram of MTS Servo-hydraulic test frame using four 3/8 inch bolts through these counter-bore holes, Fig 3.14. Before it was mounted on the ram of the press, die setup was rinsed by alcohol. All ring samples were cleaned by alcohol before tests. The test procedure is listed below:

Step 1: Set the final stroke of the press ram. Due to the properties of hydraulic press, the real final stroke always slightly deviates the set one. This issue can be solved by measuring the real thickness after upsetting to identify the real final stroke.

Step 2: Lubricate the die surfaces by flood spraying specific lubricant. Flood spraying can ensure every test starts at same initial lubrication conditions.

Step 3: Put the rinsed ring sample on the bottom die. Since the ring upsetting tests are axis-symmetric, the sample should be concentric to the textures. This can be done by putting the sample into a collar that concentrically guides the sample.

Step 4: Set the ram speed as 1 inch/second and start the test.

Step 5: Remove the upset sample and rinse die surfaces by flood spraying alcohol and polycystic cloth cleaning.

Step 6: Measure and record inner diameter and sample thickness of upset sample.

All tests strictly followed these 6 steps.
3.7.1 Experimental measurement and conversion

After the tests, changes in sample thicknesses and inner diameters were measured and recorded as indicated in the Table 3.3. The position of the inner diameter is at the middle of the upset height. In some cases the inner diameters were not perfect circle, then 3 or 4 measurements in different radial directions were carried out and their average was recorded. After each test, we inspected the die surface and did not find aluminum residues, or obvious wear of texture surface.

In lubrication condition column of the table 3.3, dry means clean die or not been lubricated (even not the boundary lubrication). When the die was new, we tested some samples without lubrication. As soon as they were lubricated, the dies were not “dry” anymore. As there will be a micro lubricant layer, which is boundary lubrication layer, and that cannot be cleaned by regular laboratory method. Wet means flood lubrication was applied. Three dies, not-textured, fine textured and coarse textured, were used in tests. The lubrication effects of textures were compared with that of not-textured die. In addition, three groups of ring samples were tested. All ring samples were same except thickness with each group having same thickness. The thicknesses for each group are 1/3, 1/4, and 1/8 inch, respectively. All measured data were graphically superimposed on the ring upsetting maps which were generated through FEM calibrations stated in previous section. Fig 3.21 a, b and c show the measurements and mappings for three different sample groups.

In Fig 3.21 each points is coordinated by thickness reduction and inner diameter reduction, through which one can use the map to calculate the friction factor.
Then we obtain Fig 3.22 which is friction factor versus thickness reduction.

Table 3.4 shows the measured data of similar tests using mineral oils, SAE 0W-20, 5W-30, 10W-30 and 20W-50. The data were superimposed with FEM map in Fig 3.23. After converting to the friction factor, the select results are shown in Fig 3.24.
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<th>Final .I.D. (inch)</th>
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Table 3.3: Raw data of ring upsetting tests of grease lubricant
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Sample group III: 1/8 inch thickness

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Continued

Fig 3.21: Ring upsetting test measurements and mappings for grease lubrication. sample thickness 0.333 inch (8.5mm), b) sample thickness 0.25 inch (6.35mm), and c) sample thickness 0.125 inch (3.18mm)
Fig 3.21 continued

![Graph showing the relationship between ring inner diameter reduction and ring thickness reduction for various lubrication conditions.](image)
Fig 3.21 continued

c)
Fig 3.22 Ring upsetting test results for grease lubrication. Sample thickness 0.333 inch (8.5mm), b) sample thickness 0.25 inch (6.35mm) and c) sample thickness 0.125 inch (3.18mm)
Fig 3.22 continued

![Graph showing Grease Lubrication](image)

- **No Texture**
- **Coarse Texture**
- **Fine Texture**

**Thickness Reduction (%)**

**Friction Factor**
Fig 3.22 continued

![Graph showing Grease Lubrication with Thickness Reduction (%) on the x-axis and Friction Factor on the y-axis. The graph compares No Texture, Coarse Texture, and Fine Texture conditions.]
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Table 3.4: Raw data of ring upsetting tests with mineral oils (inch)
Table 3.4 continued

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valvoline 20W-50 @ 23 degree C

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valvoline 5W-30 @ 22 degree C

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Fig 3.23: Ring upsetting test measurements and mappings for mineral oil lubrication using sample of thickness 0.333 inch. a) tests on the dies without texture, b) tests on the dies with coarse texture and c) tests on the dies with fine texture.
Fig 3.23 continued

LUBRICATION WITH COARSE TEXTURE

- m Map
- GREASE
- SAE 5W-30
- SAE 20W-50
- SAE 0W-20
- SAE 10W-30
- BOUNDARY LUBRICATION

HEIGHT REDUCTION (%) vs ID REDUCTION (%) for different lubricants and m values.
LUBRICATION WITH FINE TEXTURE

m=.15
m=.2
m=.3
m=.4

-10
0
10
20
30
25 35 45 55 65

HEIGHT REDUCTION (%)

ID REDUCTION (%)

m Map
GREASE
SAE 5W-30
SAE 0W-20
SAE 10W-30
BOUNDARY LUBRICATION

Fig 3.23 continued
3.7.2 Result discussions

3.7.2.1 Lubrication regimes in metal forming process

In cold metal forming process, the mechanism of lubrication using liquid lubricant can be classified as hydro-dynamic, mixed film and boundary lubrications based on thickness of lubrication film with respective to surface topography [37, 42, and 60]. Hydro-dynamic lubrication mechanism requires a thick film which can totally isolate die and workpiece surfaces. The friction stress is then decided by Reynolds’s equation. Friction is dependent on interface velocity. In Appendix, we applied Reynolds’s equation to our application of ring upsetting test using textured dies and obtained following result:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r h^3}{\eta} \frac{\partial p}{\partial r} \right) = 6V_r \frac{\partial h}{\partial r} + 12V_z
\]  

(3-1)

Where \( V_r \) and \( V_z \) are sliding speeds on radial and Z directions, respectively; \( h \) is film thickness and \( p \) is film pressure and \( \eta \) is lubricant viscosity.

According to Kudo & Azushima [42], because of surface roughness, or texture groove in our special case, if the film is too thin, not all surface area is involved in contact. There exists a series of asperities whose peaks are beyond the height of the lubricant film. The so-called micro-contacts by which all forming loads are supported firstly occur between those asperity peaks and workpiece. Therefore the real area of contact can be calculated as

\[
A_r = F_n / p_r
\]  

(3-2)

Where \( F_n \) is the load given perpendicular to the apparent contact interface and \( p_r \) is the
real pressure prevailing over asperity contacts that is needs to be figured out, theoretically or experimentally. Therefore the real area contact ratio can be calculated:

\[ \beta_r = A_r / A_a \]  

(3-3)

Where \( A_a \) is the apparent contact area. The real area contact ratio \( \beta_r \) increases in bulk deformation. Eventually based on Kudo & Azushima’s approach [42], the actual friction can be found out:

\[ \mu_a = \frac{F_i}{F_\pi} = \frac{\mu_r}{1 + p_p \left( \frac{1}{p_r} - 1 \right)} \]  

(3-4)

Where \( \mu_r \) is coefficient of friction for boundary lubrication at asperity contacts, \( \mu_a \) is overall friction and \( p_p \) is hydro-static pressure in the lubricant pools.

If it is boundary lubrication the friction can be calculated from asperity contact as:

\[ \mu_a = \mu_r = \tau_r / p_r \]  

(3-5)

which causes extreme high friction. (\( \tau_r \) is real frictional stress)

3.7.2.2 The effects of reduction:

When reduction increases, pressure increase accordingly. Lubricant will be squeezed out under higher pressure, common at higher reductions, that results in drastic increase in friction factor if the die does not have textures, shown in Fig 3.22 a, b and c. While friction factor increase mildly for both coarse and fine textured dies
indicated in both Fig 3.22 and Fig 3.23. In addition, in Fig 3.22 c, the data were obtained from upsetting tests of thin samples, 0.125 inch of thickness. It required higher pressure for same reduction comparing to that for thick samples. In that case, since the pressure is higher, the texture lubrication is more obvious. This can be explained by the theory described in Appendix. According to equation A-40 in Appendix, that is ram factor, \[ F_r = \frac{3Z_1}{16Z_1^2}, \] that is one of direct factor affecting final friction. \( Z_1 \) in the denominator is the final stroke which is directly proportional to the thickness reduction.

Comparing Fig 3.22 a, b and c, one can find that the friction factor \( m \) for grease lubrication is small when thickness of initial billet is small. For example, comparing coarse textured lubrication, for the same lubricant and at the same thickness reduction, the friction factor \( m \) is smallest for the test of 0.125 inch samples while it is largest for that of 0.333 inch sample. Same thing happened on the fine texture lubrication. This can also be explained by our theory. The rheology factor described in equation A-39 in Appendix, i.e. \[ F_r = \frac{n}{\sigma_f}, \] is another direct factor affecting the final friction. \( \sigma_f \) in the denominator is the flow stress and can be approximately equal to the pressure. For the thinner ring sample, it needs more pressure to upset to same reduction as compared to thick samples. Then rheology factor becomes small, and that results in smaller friction factor.

3.7.2.3 The effects of texture density

Without lubricants (dry) the friction factors were very much dependent on
the surface area of contact. Friction factor values close to 1.0 were obtained for no-texture surface, see Fig 3.21 a. These decreased to 0.5 and 0.4 for coarse and fine textures. For the non-textured die surface (Fig 3.21 a), grease provided the lowest friction factor for low reduction but the friction increased markedly for higher reduction (45%). With most of the oils, friction factors increase as the viscosity of lubricants decrease with 0W-20 providing friction closer to 0.3 for most reductions (Fig 3.26-29).
Fig 3.24: The friction effects of fine texture for various lubricants
The Fig 3.24 shows lubrication effects of fine texture using mineral oils. Among them SAE 0W-20 has extremely low viscosity which means its low capability of adhering to die surface. Less pressure will causes very thin film. Therefore SAE 0W-20 exhibits boundary lubrication from low reduction to high reduction.

At low reduction, about 30%, the pressure is not very high, and all other lubricants can form hydrodynamic film to achieve pretty low friction factor. The value of friction factor at this lubrication regime depends upon lubricant viscosity. The Fig 3.24 clearly shows, at low reduction, low viscosity oil like 5W-30 has low friction factor, while high one like 20W-50 has high friction factor.

With the increase in reduction, the pressure rises, fine texture grooves do not have adequate persevered lubricants to permeate into the newly expanded surface. Moreover the oil film also becomes thinner, or even broken, because of the surface expansion. Therefore at medium reduction, typically from 38% to 50%, it is mixed film lubrication regime for all three SAE oils, i.e. 5W-30, 10W-30 and 20W-50. The real area contact ratio $\beta_r$ now is important parameter to decide final friction factor. Among them the lubricant with lowest viscosity, i.e. 5W-30, is first squeezed out, which causes $\beta_r$ to dramatically increase and in turn dramatically increases friction.

Same reason, at high reduction, $\beta_r$ is further increased. The boundary lubrication is dominant in the mixed film regime, which is characterized as high friction factor.
Fig 3.25: The friction effects of coarse texture for various lubricants
For coarse texture, metal easily bulges into the texture causing lubricant to
squeeze out. The volume of coarse texture groove is big enough to provide sufficient
lubricant and thus, especially at low reduction from 30% to 35%, squeezed lubricants
form a thick film that causes hydrodynamic lubrications. Moreover low viscosity
lubricants, such as SAE 0W-20, and 5W-30, have less shear stress, which result in
relatively low friction factors as compared to various lubricants at low reduction.

At high reduction, 55% or more, the lubrication regime is mixed film. The
rough texture grooves are two times wider than fine texture, the metal that bulged into
the texture will contact with the bottom of the texture, if the viscosity is not sufficient,
which does not occur in fine texture. This extra contact increases both real contact
ratio $\beta_r$ and prevailing pressure $Pr$, which, in turn, increase the overall friction
factors. In Fig 3.25, when the reduction is high, the friction factor of 10W-30 is higher
than that of 20W-50. The high viscosity of 20W-50 can withstand more pressure, and
thus less contact area in the bottom of textures.

Comparing to the lubrication effect of fine texture, the permeated film in
course texture lasts longer. Hydrodynamic and mixed film lubrication is possible up to
55% of reduction for coarse texture, while 45% for fine texture. This is especially
suited to applications of low viscosity lubricants and high reduction deformation.
Fig 3.26: The comparison of friction effects of textures using SAE 0W-20 oil
3.7.2.4 The combination effects of viscosity and texture density

The viscosity of SAE 0W-20 is pretty low, only about 54.33 Centistokes at room temperature. Fig 3.26 shows its lubrication effect using both coarse and fine textures as compared to non-texture lubrication. Without help of texture, this kind of low viscosity lubricant cannot stick to the die surface and is easily squeezed out. Thus, as indicated in Fig 3.26, boundary lubrication appears at low reductions.

However both coarse and fine textures can continually provide lubricant when it is being squeezed out. Since the coarse textures carry more lubricant because of their relatively larger volume, the permeated film is thicker than that of fine texture. Therefore with coarse texture, SAE 0W-20 can achieve better lubrication at high reduction. However at high reduction, about 50% reduction as shown in Fig 3.26, the high pressure pushes more metal into texture groove, moreover, the viscosity of SAE 0W-20 is too low to withstand high pressure that is common at high reduction. This causes the extra contact at bottom of textures, which increases real area contact ratio.

According to equation 3-4, the overall friction factor increase.
Fig 3.27: The comparison of friction effects of textures using SAE 5W-30 oil
The viscosity of SAE 5W-30 is about 79.02 Centistokes at room temperature. This is still too low to stick to the die surface without helps of texture. With textures, both coarse and fine, one can avoid boundary lubrication present when using dies without texture. At low reduction, below 45%, both textures form the permeated films. Usually each texture groove forms one film. Comparing to SAE 0W-20, the viscosity of 5W-30 is slightly higher that makes it harder to be squeezed out at low reduction. Thus the permeated films are not long enough to join together. In fine texture pattern, there are more texture grooves in same size of die surface, and thus more permeated films, which causes much lower real area contact ratio and eventually low friction factor at low reduction as shown in Fig 3.27.

With the increase of the reduction, so increases in pressure, more lubricant is squeezed out causing the length of permeated films to grow for of both textures. For the fine texture, at about 48% reduction as shown in Fig 3.27, textures may run out the lubricant because of their limited volumes, the permeated film breaks down when the surface further expands. This results in the dramatic increase of real area contact ratio and thus increase of friction factor at high reduction. In contrast, coarse texture hold more lubricant, break down of the permeated film does not occur until 55% reduction.
Fig 3.28: The comparison of frictions effects of textures using SAE 10W-30 oil
The viscosity of SAE 10W-30 is relatively high, about 85.43 Centistokes at room temperature. It can achieve hydrodynamic/mix film lubrication at low reduction without helps of textures. However, with the increase in reduction, lubricant cannot stick to the die surface if there is no texture, which causes the increase of friction factor at high reduction.

Similar to that of SAE 5W-30, at low reduction below 50%, both textures form the permeated films. And fine texture gets the lower friction factor because fine texture pattern has more texture grooves in same size of die surface, and thus more permeated films, which causes much lower real area contact ratio and eventually low friction factor at low reduction as shown in Fig 3.28. The viscosity of SAE 10W-30 is higher than that of 5W-30. So that it can withstand more pressure. That may be the reason why mixed film lubrication regime is longer for SAE 10W-30, about 55% reduction, compared to 48% for 5W-30.

At high reduction, more than 55%, both textures run out of lubricant and break in films appears. But according to texture pattern design, fine texture has low real area contact, i.e. the value $\beta_r$ is smaller than that of coarse texture. This reflects lower friction factor for fine texture than that for coarse one at high reduction. Same reason for why friction factor is highest when one using dies without texture.
Fig 3.29: Comparison of friction effects of textures using SAE 20W-50 oil
The viscosity of SAE 20W-50, about 207.34 Centistokes at room temperature, is much higher than other lubricants. It is difficult to squeeze out. Therefore at low reduction, below 28% reduction, hydrodynamic lubrication is present for all cases with and without textures. With an increase of reduction, its behavior is similar to those of SAE 5W-30 and 10W-30, i.e. fine texture provides more independent permeated films and cause low friction factor. The difference exists at high reduction. Since its high viscosity, it is hard to squeeze the lubricant out for both coarse and fine textures as they form permeated films at high reduction. But the volume of coarse texture is larger and thus it forms thicker film compared to that of fine texture. This may be the reason why friction factor of coarse texture is lower than that of fine texture at high reduction.

3.7.2.5 Photographic evidences for lubrication regimes

After the deformation, ring surfaces were photographed to study the presence of different lubrication mechanisms such as full film, thin film and boundary regimes. Some of these photographs are included in Figs 3.30 and 3.31. Since these regimes are often associated with interface pressures, displacements and velocities, the nodal data of these parameters were extracted from numerical simulations for five locations at the interface: A= at the I. D., B= half way between the I.D. and mid location, C= mid location, D= halfway between the mid location and the outer diameter (O.D.) and E= at the O. D.

Examination of ring surfaces after different reductions is an indirect method of investigating the presence of dominant lubrication regimes. For example from Fig
3.28 it is seen that for the same lubricant, SAE 10W-30, the fine textured surface provide lower friction factor over the entire reduction range. This is due to the establishment of a thin film lubrication regime along the interface. In Fig 3.30 are included the photos for the three ring surfaces. It is seen that the lubricant film breaks down for the blank (non-textured) surface at the bottom periphery; the film is retained for the coarse textured surface and is continuous and wide for the fine textured surface. The lack of film creates a shiny luster in the middle area of the ring surface that is characterized by circumferential marks.

For the coarse textured die surfaces, grease lubrication provided the lowest friction factors that were stable up to higher reductions. For most oil based lubricants, the results were similar (between 0.2 and 0.25) except at higher reductions the lower viscosity lubricants performed better. In the case of fine textured dies, grease again performed well up to medium reductions. Most oils had similar performance with lower viscosity lubricants providing more stable performance. The presence of thick film lubrication is even clearer in Fig 3.31 that compares two different lubricants for the coarse texture die at 65% reduction. It seen that the higher viscosity lubricant provides more stable film and better control of metal flow.

The establishment of thin film lubrication at the inner and outer extremities of the ring can be better understood by examining interface pressures and sliding velocities at different locations along the ring-die interface. It is seen that the interface pressure is similar along the interface and only increases with increase in reduction, reaching a value of 45 ksi (310 MPa) for 65% height reduction (Fig 3.32). This
pressure results in the breakdown of the lubricant film in the non-textured surfaces resulting in higher friction. This breakdown is greater at location B as the interface where velocity is almost zero (hydrostatic case). Locations C and D also have lower velocities that prevent film formation in the non-textured case. However, grooves in the textured surface entrap lubricant preventing lubricant squeeze-out. This enhances film stability. For the two extreme locations, A and E, the interface velocity is high enough to prevent film failure.
Fig 3.30: corresponding ring surfaces at about 62% height reduction lubricated SAE 10W-30 oil with: Non-Texture (left), coarse texture (center) and fine texture (right)
Fig 3.31: Ring surfaces at about 65% reduction with coarse texture for different lubricants: 0W-20 (left) and 20W-50 (right)
Fig 3.32: Pressure at the interface (friction factor 0.2) for different points at the interface for various reductions (A= I.D., C= midpoint, E= O.D.)
Fig 3.33: Radial velocity as a function of reduction at different locations at the interface (A= I.D., C= midpoint, E= O.D.)
CHAPTER 4

STEEL PLANE STRAIN UPSETTING TESTS USING LASER MICRO-TEXTURED DIES

4.1 Introduction

Plane strain is another research friendly approach to develop and verify theories. Plane strain deformations frequently appear in the cold steel forming processes such as bending, drawing, rolling etc. Similar to the ring upsetting dies, micro textures laser ablated on the die surface act as the lubricant reservoirs which continuously provide lubricant during processes characterized with high pressure and surface expansion.

The concept of experimentally measuring friction in plane strain deformation was proposed by Pawelski et. al [51]. As shown in Fig 4.1, during upsetting, the metal flows differently for the locations close to punch and to the anvil. This difference is the cause for different friction factors, m1 and m2 on the interface of punch-coupon and that of anvil-coupon. This difference in surface friction causes the bending of the coupon after upsetting. The tilting angle, $\alpha$, is only related to the difference of friction factor, i.e. m1-m2, geometry of the coupon, and amount of reduction, i.e. $(h1-h0)/h0$. [51]
Fig 4.1: The concept of plane strain upsetting tests proposed by Pawelski et. al [51].
They also calculated that the titling angle can be expressed as

\[ \alpha = \frac{3}{2} \Delta m \ln \frac{h_0}{h_1} \]  

(4-1)

Where \( \Delta m \) is the difference of the friction factors, \( m_1 \) and \( m_2 \); \( h_0 \) and \( h_1 \) are initial and final thicknesses, respectively, as shown in Fig 4.1.

In our study, we ablated micro textures on the surface of the anvil and put macro-grooves on the surface of the punch. Macro grooves have latch effect that will completely resist metal flow, as we discussed in Chapter 3. Therefore the friction factor between punch and coupon, \( m_1 \), is approximately equal to 1. Moreover, to the largest extent, it raises the sensitivity between measuring variable \( \alpha \) and friction factor \( m_2 \).

### 4.2 Die design and calibration

#### 4.2.1 Plane strain upsetting die design

The key component of the bottom die is the anvil as shown in Fig 4.2. On its working surface parallel and linear micro grooves were ablated using laser CPA-2100, that was described in Chapter 3. Before texturing anvils, which were made from H-13, were nitrided and heat treated to HRC 65 on the surface. There are two kinds of textures characterized by different densities which are similar to those in ring upsetting dies. Moreover all parameters used in laser ablation are the same as those used in ring upsetting dies, and thus the texture grooves should be same also.

Some shims were used to control the stroke of the ram and thus control the reduction of the coupons. Shims and anvil were bolted together and then snap fit into the rectangular cavity in the ring which was positioned by two dowel pins, indicated
Similarly on the top the punch, shown in Fig 4.4, an anvil was also snapp fit into the rectangular cavity of the top ring, which was also positioned by same dowel pins as with the bottom die. Through the arrangement time punch and anvil always stay aligned. In addition, on the working surface of punch some macro and linear parallel grooves were ablated. The objective of those grooves is to resist the metal from flowing on the punch surface, i.e. so called latch effect discussed in chapter 3. Therefore metal will stick to the punch surface and thus its friction factor will approximately be equal to 1.

Pictures in Fig 4.5 show what were look like of both top die (a) and bottom die (b) after they were mounted on the press.

4.2.2 FEM calibration

Equation 4-1 only gives us a relationship between titling angle and difference of friction factors on both sides of the couple. Here we use FEM to find the relation between the friction factor differences to the measured titling angle. The numerical model which is dedicated to the tests was created in DEFORM, as shown in Fig 4.6.

A series of simulations with varying “m” value between coupon and bottom anvil were run. The “m” value between top punch and coupon was fixed to 1, since the properly designed macro grooves on punch resists material from being displaced. To further verify this, one simulation in which the top “m” value was 0.75 instead of 1 was run and it was found that the tilting angle was far away from our real test results,
as shown in Table 4.1. All simulation data were extracted at 40% reduction, and are shown in figure and table below.

Data that are friction factor between anvil and coupon verses titling angle can be obtained at low reduction, i.e. 16%. Therefore we got the map between titling angle and m at 16% and 40% reductions, respectively, as shown in Fig 4.7. After the maps were made, one can obtain the friction factor by substituting the measured tilting angles to the map.
Fig 4.2: Design of the anvil. a) Schematic and b) Design drawing
Fig 4.3: Assembly of bottom die
Fig 4.4: Assembly of top die
Fig 4.5: Dies on press. a) Top die and b) Bottom die
Fig 4.6: The schematic of FEM simulation
### Table 4.1: Data extracted from simulations

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<tr>
<td></td>
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<td>0.5</td>
<td>8.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>9.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>10.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2</td>
<td>11.14</td>
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<td>11.70</td>
</tr>
<tr>
<td>0.7</td>
<td>0.1</td>
<td>6.54</td>
<td></td>
</tr>
</tbody>
</table>
**Fig 4.7:** The Map between tilting angle and m value on anvil, obtained from DEFORM simulations
4.3 Texture fabrication and analysis

The laser equipment used to ablate the texture on anvils was the same as that for in ring upsetting tests, i.e. CPA-2100 shown in Fig 3.3. Before ablation, the anvil’s working surfaces were polished to approximate Ra=200 micro inch. Anvils were made from H-13 and nitrided and heat treated to HRC 65 on the surface. Since all laser parameters were same, texture details for plane strain upsetting dies are the same as those for ring upsetting dies described in Chapter 3.

4.4 Coupon analysis

The dimension of the rectangular coupon is 0.45 by 1.1 inch (or 11.4 by 27.9 mm) and the thickness is 0.13 inch (or 3.2 mm). The width of the punch’s working area is 0.19 inch (4.8 mm), the length of the coupon is long enough to ensure plane strain deformation during upsetting. Coupons were made from medium carbon steel 1040. Fig 4.12 shows the coupon before (a) and after (b) test.
4.5 Lubricant preparation and deposition methodology

Lubricants used in this study are PPS and different SAE (Society of Automotive Engineers) oils. PPS is mixture 80% in weight mineral oil and 20% Poly Phenylene Sulfide (whose molecular weight is 10000). Goto [30] investigated its lubricities in metal forming applications, and showed that PPS was able to withstand high pressure in both low and high temperatures, and he suggested PPS as a replacement for traditional zinc phosphate plus soap steel forging lubricant, for environment protection considerations. However Goto did not quantitatively determine interface friction due to the limitation of his experimental methodology [30]. However the tests adopted in this research can obtain the friction factor by measuring titling angle of the tested coupons.

Four SAE oils, 0W-20, 5W-30, 10W-30 and 20W-50, were also used as lubricant. At 23°C (room temperature), the absolute viscosities of these oils were approximate as 0.05, 0.08, 0.12, 0.18 N-s/m², respectively. Besides, the vegetable oil was also investigated, since its environment friendly property.

At the beginning of each test the anvil was carefully wiped and rinsed using alcohol. Coupons were dipped in the candidate lubricant and placed on the anvil surface for the test to begin. Other coupons were kept in alcohol and dried in the air before test.
4.6 Plane strain upsetting experiments and results

Before tests, all anvils and coupons were dipped into alcohol. The procedures of the test are listed below:

Step 1: Set the final stroke of the press ram. Due to the properties of hydraulic press, the real final stroke always slightly deviates from the set one. This issue can be solved by measuring the real thickness after upsetting to identify the real final stroke.

Step 2: Install the anvils and lubricate it by flood spraying specific lubricant. Flood spraying can ensure every test starts at same initial lubrication conditions.

Step 3: Put the rinsed coupon on the anvil. And make sure that the coupon is aligned with textures.

Step 4: Set the ram speed as 1 inch/second and start the test.

Step 5: Remove the upset coupon and rinse die surfaces by flood spraying alcohol and polycystic cloth cleaning.

Step 6: Measure and record titling angle and thickness of upset coupon. All tests are strictly followed these six steps.

4.6.1 Experimental measurement and conversion

The experimental variables are reduction, texture type and lubricant. There were two reductions, 16% and 45% (approximately); three texture types, no texture, coarse texture and fine texture. The lubricants that used in tests were PPS, Vegetable oil, and four mineral oils, i.e. SAE 0W-20, 5W-30, 10W-30 and 20W-50.
The only measurement variable in this test is the titling angle of the upset coupons. The measurement was carried out at three different positions for each tested coupon, position A, B and C, as shown in Fig 4.12c, using a digital protractor, shown Fig 4.2d. The measurement was also perpendicular to the material flow direction and not close to the extreme ends of the coupon, where they were not in plane strain deformations. The distance between two measurements next to each other was about 10 mm, and therefore, the span of measurement, position A to C shown in Fig 4.12c, was about 20 mm (about 75% of original coupon length). The average of these three measurements was recorded as the final results of these tests. We found that the measurements at those positions of each tested coupon were very close. For most cases, the digital protractor whose precision is 0.01 degree could not detect the differences, or they were naturally equal. This fact provided the evidence that our test was stable and reliable.

Table 4.2 above shows the lubrication effect of PPS lubricant. Table 4.3 shows the lubrication effect of Vegetable oil. In addition, four SAE oils, 0W-20, 5W-30, 10W-30 and 20W-50, were also used as lubricants. At 23°C (room temperature), the absolute viscosities of these oils were approximate 0.05, 0.08, 0.12, 0.18 N-s/m², respectively. Based on this, we can plot the friction factors, converted from measured titling angles, verses viscosity, seeing Fig 4.8 to 4.11.

Fig 4.8 and 4.9 show the comparisons between texture types at different reductions. While Fig 4.10 and 4.11 show the comparison of each texture style at different reductions.
<table>
<thead>
<tr>
<th>Lube</th>
<th>Measured angle</th>
<th>Converted m value</th>
<th>Measured angle</th>
<th>Converted m value</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16% REDUCTION</td>
<td>40% REDUCTION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPS</td>
<td>3.70</td>
<td>0.31</td>
<td>10.27</td>
<td>0.29</td>
<td>Coarse</td>
</tr>
<tr>
<td></td>
<td>3.70</td>
<td>0.31</td>
<td>10.45</td>
<td>0.27</td>
<td>Fine</td>
</tr>
<tr>
<td></td>
<td>3.68</td>
<td>0.32</td>
<td>10.18</td>
<td>0.30</td>
<td>No texture</td>
</tr>
</tbody>
</table>

Table 4.2:  Lubrication of PPS
<table>
<thead>
<tr>
<th>Lube</th>
<th>Measured angle</th>
<th>Converted m Value</th>
<th>Measured Angle</th>
<th>Converted m Value</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetable oil</td>
<td>3.70</td>
<td>0.31</td>
<td>8.40</td>
<td>0.50</td>
<td>Coarse</td>
</tr>
<tr>
<td></td>
<td>4.20</td>
<td>0.19</td>
<td>9.30</td>
<td>0.43</td>
<td>Fine</td>
</tr>
<tr>
<td></td>
<td>3.68</td>
<td>0.32</td>
<td>7.50</td>
<td>0.55</td>
<td>No Texture</td>
</tr>
</tbody>
</table>

Table 4.3: Lubrication of Vegetable Oil
Fig 4.8: Comparisons of texture effects at low reduction (16%) for oils
Fig 4.9: Comparisons of texture effects at medium reduction (40%) for oils
Fig 4.10: Lubrication effect of coarse texture for different reduction
Fig 4.11: Lubrication effect of fine texture for different reduction
4.6.2 Result discussion

The most outstanding character of PPS lubrication is that one can achieve pretty good lubrication at medium reduction, i.e. 40%. From Table 4.2, lubrication effect of PPS seems not to be sensitive to the texture size at both low and high reductions.

From Table 4.3 one can find out that its lubrication effect of vegetable oil is too high, especially at higher reduction, in industry in spite of its environment friendly properties.

Figs 4.8 and 4.9 show the lubrication effects of SAE oils. For SAE oils, there exists a critical viscosity at which the lubrication effect is worst no matter what surface textures are used. This issue was appeared at both the low reduction (16%) and at medium reduction (40%). With the viscosity increase, the friction factor “m” increases to a peak value, typically about 0.4 and then decreases to a lower value, and finally slowing increase. However texture does play an important role in improving lubrication for all range of viscosities.

The analytical analysis is based on theoretical model described in Appendix, i.e. equations A-59, 62 and 63. In order to solve those equations, same FEM simulation technique, i.e. specifying calculated friction factor in friction window, which is described in section 3.7.3.3 of this dissertation was applied. The results at higher reduction were also listed in Fig 4.9.

At medium reduction, 40%, when the pressure has increased, both fine and coarse textures improve lubrications (low friction factors achieved as compared to
that without texture). Coarse texture exhibited outstanding lubrication effect at high viscosity while fine texture works better at low viscosity. With the increase of viscosity, the lubrication effect was diminished, especially for fine texture. At low reduction, fine texture exhibit outstanding lubrication effects no matter whether the viscosity is high or low. This probably is caused by low pressure that was not enough to squeeze out extra lubricant, and thus thick film lubrication existed. While the coarse texture only shows fair lubrication effect. When there was no texture or fine texture, as the reduction increases, the frictional effect become severe. One can find out this by comparing associated curves indicated Fig 4.8. However, at relative high viscosities, coarse texture may achieve constant lubrication as shown in Fig 4.10 below. The curves Fig 4.10 are the same as those indicated in Fig 4.9, except differently plotted.

FEM simulations based on theoretical calculations also reflect those trends described above at medium reduction. The differences in comparison to the experimental results may result from the same reasons described in section 4.7.

Figs 4.12 b and c show punch side and anvil side of the coupon after about 45% reduction, respectively. On the mid-zone, anvil-side where plane strain has occurred, there is no texture marks comparing to both ends, this is clear evidence that a thick film formed during upsetting. This film provided better lubrication in tough metal forming conditions.
Fig 4.12: Pictures of coupon. a) before test, b) upset coupon, punch side, c) upset coupon, anvil side and d) angle measuring device
CHAPTER 5

CONCLUSIONS

5.1 Summary

This dissertation was completed in the Center for Excellence in Forging Technologies, Ohio-State University. In this dissertation, an integrated approach, applying micro-texture on specific tooling surfaces to achieve friction control during metal forming process which is characterized as high pressures, is proposed and implemented.

The research was based on two experiments, aluminum ring upsetting and steel plane strain upsetting tests. In each experiment, FEM simulations, which were done in commercial software DEFORM®, were used to calibrate the measured results, i.e. ID change of upset rings and titling angle, to friction factor. Based on the calibrated setups, the lubrication effects of laser textured die surfaces were investigated. Ring upsetting tests were carried out using three different die textures (machined, coarse and fine) and five different lubricant candidates. After tests, the ID changes of ring samples were measured; friction factors were calculated; and ring surface finish and interface parameters were studied to explain the observed behavior.
The effectiveness of laser textured die surfaces in reducing interface friction and preventing lubricant film failure in the cold deformation of steel were also investigated. Plane strain upsetting tests were carried out using three different die textures (blank, coarse and fine) and six different lubricant candidates. Calculated friction factors were studied to explain the observed behavior. The lubrication regimes and its typical friction factors at different reductions for all SAE oil lubricants are summarized in Table 5.1 and 5.2 for both aluminum ring upsetting and steel plane strain upsetting tests. Based on results of both tests, it is concluded that laser ablation textures do indeed control interface friction and prevent film failure even at high reductions.

Moreover, in the appendix, we also developed theoretical models for micro-texture lubrications in both ring upsetting and plane strain tests. Theoretical models first analyzed the deformation of the bulk material and thus calculated the pressure and surface sliding speed which are the input variables of the Reynolds’s equation for the entrapped lubricant. Then the amount of the lubricant which was squeezed out is calculated. After calculating the permeated film thickness, the weighted average of the friction factor through all contact area is outputted as the final friction factor of the micro-texture lubrication.

**5.2 Conclusions**

Both texture patterns can considerably reduce the friction factors no matter what lubricants were used in tests. Without lubricants the friction factors were very much dependent on the surface area of contact. Friction factor values close to 1.0
were obtained for no-texture surface in clear condition. These decreased to 0.5 and 0.4 for coarse and fine textures. This reduction is due to lower area of contact due to texture. For the non-textured die surface, grease provided the lowest friction factor for low reduction but the friction increased markedly for higher reduction (45%). With most of the mineral oils friction factors increase as the viscosity of lubricants decrease with 0W-20 providing friction closer to 0.3 for most reductions.
<table>
<thead>
<tr>
<th></th>
<th>Low Red.(&lt;35%)</th>
<th>Medium Red.(35-55%)</th>
<th>High Red.(&gt;55%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA E 0W-20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Mixed 0.26</td>
<td>Boud. 0.29</td>
<td>Boud. 0.29</td>
</tr>
<tr>
<td>Coarse Texture</td>
<td>Hy. Dyn 0.21</td>
<td>Hy. Dyn 0.23</td>
<td>Mixed 0.236</td>
</tr>
<tr>
<td>Fine Texture</td>
<td>Mixed 0.24</td>
<td>Mixed 0.24</td>
<td>Mixed 0.24</td>
</tr>
<tr>
<td>SAE 5W-30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Boud. 0.26</td>
<td>Boud. 0.26</td>
<td>Boud. 0.26</td>
</tr>
<tr>
<td>Coarse Texture</td>
<td>Mixed 0.22</td>
<td>Mixed 0.22</td>
<td>Mixed 0.23</td>
</tr>
<tr>
<td>Fine Texture</td>
<td>Hy. Dyn 0.2</td>
<td>Mixed 0.24</td>
<td>Boud. 0.25</td>
</tr>
<tr>
<td>SAE 10W-30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Hy. Dyn 0.23</td>
<td>Mixed 0.24</td>
<td>Boud. 0.29</td>
</tr>
<tr>
<td>Coarse Texture</td>
<td>Hy. Dyn 0.23</td>
<td>Hy. Dyn 0.23</td>
<td>Mixed/Boud 0.26</td>
</tr>
<tr>
<td>Fine Texture</td>
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<td>Hy. Dyn 0.22</td>
<td>Mixed/Boud 0.25</td>
</tr>
<tr>
<td>SAE 20W-50</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Hy. Dyn 0.24</td>
<td>Boud. 0.26</td>
<td>Boud 0.27*</td>
</tr>
<tr>
<td>Coarse Texture</td>
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<td>Mixed 0.25</td>
</tr>
<tr>
<td>Fine Texture</td>
<td>Hy. Dyn 0.19</td>
<td>Mixed 0.23</td>
<td>Boud. 0.26</td>
</tr>
</tbody>
</table>

* Value is estimated

Table 5.1: Summary of lubrication effect of SAE oils in aluminum ring tests

Note of abbreviations (for both table 5.1 and 5.2):

Red.: Reduction
Lub. Reg.: Lubrication regime
Typ. m: Typical friction factor
Boud.: Boundary Lubrication regime
Mixed: Mixed film lubrication regime
Hy. Dyn: Hydro-dynamic lubrication regime
<table>
<thead>
<tr>
<th></th>
<th>Low Red. (~16%)</th>
<th>Medium Red. (~40%)</th>
<th>Lub. Reg. Typ. m</th>
<th>Lub. Reg. Typ. m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAE 0W-20</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Hy. Dyn</td>
<td>0.22</td>
<td>Boud.</td>
<td>0.4</td>
</tr>
<tr>
<td>Coarse Texture</td>
<td>Hy. Dyn</td>
<td>0.16</td>
<td>Mixed</td>
<td>0.32</td>
</tr>
<tr>
<td>Fine Texture</td>
<td>Hy. Dyn</td>
<td>0.13</td>
<td>Mixed</td>
<td>0.32</td>
</tr>
<tr>
<td><strong>SAE 5W-30</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Mixed</td>
<td>0.34</td>
<td>Boud.</td>
<td>0.43</td>
</tr>
<tr>
<td>Coarse Texture</td>
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<td>0.38</td>
<td>Boud.</td>
<td>0.41</td>
</tr>
<tr>
<td>Fine Texture</td>
<td>Hy. Dyn</td>
<td>0.28</td>
<td>Boud.</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>SAE 10W-30</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Texture</td>
<td>Mixed</td>
<td>0.37</td>
<td>Boud.</td>
<td>0.41</td>
</tr>
<tr>
<td>Coarse Texture</td>
<td>Mixed</td>
<td>0.33</td>
<td>Hy. Dyn</td>
<td>0.32</td>
</tr>
<tr>
<td>Fine Texture</td>
<td>Mixed</td>
<td>0.33</td>
<td>Mixed/Hy. Dyn</td>
<td>0.39</td>
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<tr>
<td><strong>SAE 20W-50</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>Mixed</td>
<td>0.36</td>
<td>Boud.</td>
<td>0.44</td>
</tr>
<tr>
<td>Coarse Texture</td>
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<td>0.36</td>
<td>Mixed</td>
<td>0.35</td>
</tr>
<tr>
<td>Fine Texture</td>
<td>Hy. Dyn</td>
<td>0.16</td>
<td>Boud</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Table 5.2: Lubricity summary of SAE oils in steel forming tests
Both coarse and fine texture can form thick lubricant films, and thus achieve hydrodynamic lubrication at low reduction (below 35%) with medium and high viscosity. But the friction factor of fine texture lubrication is lower than that of coarse ones, since fine texture pattern provides more lubricant pools, and thus more permeated films. However coarse texture can achieve hydrodynamic lubrication for low viscosity oil, such as SAE 0W-20 which exhibits boundary lubrication effect in fine texture lubrication. In addition, the permeated thick film formed by coarse texture lasts to higher reductions compared to that of fine texture. Lubrication with thick film is up to 55% reduction for coarse texture, while it is from 38% to 50% reduction depending on the viscosity of the lubricant for fine texture. Coarse texture especially suited for applications with low viscosity lubricants and high reduction deformation. Fine texture does not have good lubrication effects for low viscosity liquid lubricant, such as SAE 0W-20 oil.

At high reduction, 55% or more, the lubrication regime is mixed film for both texture patterns. For fine texture, friction factor increases with an increase of real contact ratio, $\beta r$, which increases with the reduction. Therefore, at high reduction characterized by high real area contact ratio, the boundary lubrication may appear for fine texture lubrication. Moreover, based on the photo evidence of deformed rings, the textures, both coarse and fine, enlarge the life of the lubrication film. The lubricant squeezed out from texture forms the permeated films which perform the same function as regular films. Therefore the mixed film lubrication can last to more than 55% reduction for oil lubrication of aluminum ring upsetting tests, while it is only up
to about 35% when there is no texture. For the steel upsetting tests, the textures also significantly improve the life of lubrication film.

On the other hand, the coarse texture grooves are two times wider than fine texture, the metal that bulges into the texture will contact with the bottom of the texture, if the viscosity is not sufficient. This does not occur with fine texture. The extra contact will increase both real contact ratio $\beta_r$ and prevailing pressure, which, in turn, increase the overall friction factors for coarse texture lubrication. However this will not occur if the viscosity is high, such as SAE 20W-50, since high viscosity lubricant entrapped in the texture can withstand more pressure and thus less contact area at the bottom of textures. Therefore coarse texture exhibits better lubrication effect at high reduction with the use of high viscosity lubricant.

In section 3.1.1 and 3.1.2, we reviewed literatures on the tribology application of micro-textures. Many of these investigations were not done in metal forming area and moreover, their experimental backgrounds, lubricants and etc were not consistent. Therefore the absolutely values of friction obtained from their researches do not make sense for comparing the results of this research to theirs. However the percentage of friction reduction may be used for comparing results. The percentage of friction reduction ranges from 2% to 40%. Among them Neudecker et al. [48] with focus on tools for metal forming and stamping, have shown that the kinetic coefficient of friction can be reduced by up to 14%, while Hu et al. [37] studying ring upsetting test with textured samples resulted friction reduction was about 40%. While in our research, the percentage of friction reduction is about 38% at reductions lower than
35% for aluminum ring upsetting test with grease lubrication and even more for higher reductions. The percentage of friction reduction for SAE oils of aluminum ring upsetting tests ranges from 7.7-20.8% for low reductions; about 8-15% at medium reduction; and 7.5-18.6% at the reduction greater than 55%. For the steel plane strain tests, the friction reduces 10.8-55% at low reduction while 7-20% at medium reduction. If PPS was used as lubricant in steel plane strain tests, friction only reduces 3% at low reduction and 10% at medium reduction.

5.3 Significances and contributions of the research

The significance of this research lies on the finding that one can use environmental friendly lubricants, such as SAE oil, in metal forming process with the help of texture. The benefit arising from micro groove textures on a metal forming tool surface is a combination of several effects that include improving the lubricant supply and reducing and controlling surface friction at the contact between plastic deforming metal and hard tool surface. Surface textures can act as oil reservoirs, which transport or retain oil that is released in emergency situations, and thereby provides support to the formation of oil film at the interface.

Scientific and experiential contributions pertain to the following fields: 1. Understand fluid lubrication mechanisms and thus provide an approach to optimize lubrication in metal forming processes, through which one can make good quality parts with less lubricant use and thus less pollution. 2. Provide the knowledge for texture pattern designs and implementation on hardened tool surfaces, through which
one will enable to locally control lubrication and thus, in turn, to improve quality of products. 3. Using the finite element analysis to calibrate the experimental measurement to the friction and thereby reduce the measurement conversion errors. Finally, 4. The work may provide basic knowledge and data for friction control which is important for net-shape or near net-shape forming.

5.4 Applications of the research

The application of this research may exist in two fields, industry and academia. In industry, the data obtained from the experiments can provide the knowledge that implementing texture on tool surface can reduce friction in metal forming process and thus reduce forming tonnage and scrap rate. Moreover, with the help of the texture, one can select environment friendly lubricant to replace the regular ones without impairing the lubrication effects. In addition, comparing with current industry technique that is to fabricate micro textures on workpiece especially in sheet forming), the present approach is at lower cost and is more stable and reliable.

In academia, this research provides the data and the knowledge for lubrication reduction and control through which researchers can design friction at specified zones on tooling surfaces. The results of this research also show how the lubrication regimes change at different reductions during metal forming, and thus provides knowledge on how to support surface lubrication after regime changes. In addition this research can also be applied to friction control on sheet metal forming,
rolling and etc processes, through which one can partially control metal flow to improve product quality and reduce scrap rate.

5.5 Limitations of present research and suggested future work

The main limitations of this research are on following felids:

1. The current experiments were carried out under slow sliding speed conditions. The interface sliding speed is important in lubrication film evolution. The lubrication film can last longer under slow sliding speed, and therefore the current results cannot be applied to those metal forming processes with high sliding speed, such as backward extrusion.

2. The current research did not consider temperature variation and assumed the room temperature through out whole metal forming process. The efficiency of the lubrication mechanisms depend on lubricant viscosity very much which is related to temperature. Therefore this research may not be applied to non-isothermal metal forming process such as hot rolling, or hot forging.

3. In the experiments, it was hard to directly measure lubrication film. Only indirect method such as method of photo-graphics to check evidences of different lubrication regimes after the experiment was adopted. Direct measurement of film thickness will be more accurate.

4. In the FEM calibration of the designed dies, we assumed the friction was constant in whole process, which does not reflect the real lubrication of metal forming. Any error in modeling would severely affect the inverse calculation of friction.
5. The process of laser ablation was hard to control which caused the big deviation between fabricated texture pattern and its design.

Based on limitations of current research and to have a full understanding of textured lubrication strategies in metalworking processes, the following tasks considering various aspects should be further investigated:

1. Extending this research to different texture patterns and lubricants including the improvement of the current method to take into account the suspension effects of the lubricant, such as water based graphite, numerically and experimentally. The current experimental results already insight into the relations between texture pattern and lubricant’s rheology properties. There exists an optimal texture pattern for each special lubricant. This should be further investigated.

2. More analytical and experimental studies on the elevated temperature conditions. The lubricant properties will not be constant any more and the experiments need special equipment that can keep the tiny specimen hot during the experimental process.

3. Integrations between current commercial FEM software and analytical models and experimental results. The available commercial metal deformation FEM software does not have lubrication module in spite of its importance because of lacking of models and data. The next generations of FEM software in metal forming processes will be character as more accuracy, faster, and more reliable, which makes integrating the module of lubrication process un-avoided.

4. Current study is able to be extended to bio-friendly lubricants that can be
applied to more severe cold forging processes such as backward extrusion. If successful, laser micro texturing technology can extend oil lubrication to applications that currently require expensive and environmentally unfriendly conversion coatings.
Appendix

ANALYTICAL ANALYSIS OF MICRO TEXTURE IN FORGING LUBRICATION

A.1 Micro textured lubrication for axis symmetry forging

The texture for axis symmetry forging is a series of circular grooves as shown in Fig A.2. The radial coordinate of the inward and outward edges of the groove are \( r_a \) and \( r_c \), respectively. The geometry of grooves can be described as \( H(r) \) and \( dH/dr \). Both bottom die and top die have same textures. The ram speed of top die is \( \dot{Z}_l \) and stroke is \( Z_l \). The initial billet height is \( Z_0 \). The bulk material strength is \( \sigma_f \). The lubricant is supposed to be incompressible and its viscosity is \( \eta \) and, for cold forging, one may consider the pressure effect of viscosity. According to Barus equation, there is:

\[
\eta = \eta_0 e^{\alpha p}
\]  \hspace{1cm} (A-1)

Where \( \eta_0 \) is the viscosity at atmosphere pressure; \( p \) is liquid pressure in the trapped volume; and \( \alpha \) is pressure coefficient.

In the forging process, the workpiece metal bulges into groove under high
pressure and forces the lubricant to permeate into the contact zone between die and workpiece metal, which brings mixed film lubrication, instead of boundary lubrication, to that zone. The amount of metal deviation from die surface is expressed as $\delta(r)$, where $\delta(r)$ is negative in texture grooves and positive in permeation areas, as shown in Fig A.2. In addition, the radial coordinate of the end of permeation area is $r_d$ which is varied with stroke $Z_1$; and $r_f$ is radial coordinate of the end of bulk deformation zone. Fig A.1 shows whole derivation procedure of the analytical models for axisymmetric forging lubrication using circular micro-groove textures. The model was basically based on the forging slab analysis method and Reynolds’s equation for entrapped lubricant.
Fig A.1: The derivation procedure of analytical lubrication model for axisymmetric forging
Fig A.2: Schematic of micro textured lubrication for axis symmetry forging
Compared to the depth of the texture groove, \( H(R) \), the film thickness caused by lubricant permeation is relatively small, only few microns. We then therefore assume the permeating film to have constant thickness, i.e. \( \delta(r) \) [42]. Therefore the film thickness can be shown as

\[
h(r) = H(r) + \delta(r), \quad \text{when } r_e \leq r \leq r_i;
\]

\[
h(r) = \delta(r), \quad \text{when } r_e < r \leq r_i;
\]

\[
h(r) = 0, \quad \text{where boundary lubrication occurs}
\]

The Reynolds equation for axis symmetry forging can be reduced as

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( \frac{rh^5 \partial p}{\eta \partial r} \right) = 6V_r \frac{\partial h}{\partial r} + 12V_z
\]

For axis symmetry forging we have

\[
\varepsilon_r = \varepsilon_\theta
\]

And thus

\[
\sigma_r = \sigma_\theta
\]

Since there is

\[
\varepsilon_r + \varepsilon_\theta + \varepsilon_z = 0
\]
It is easy to find

\[ \varepsilon_r = -\frac{1}{2} \varepsilon_z \]  

(A-7)

And thus

\[ \varepsilon_r = -\frac{1}{2} \varepsilon_z \]  

(A-8)

But

\[ \varepsilon_z = \ln \frac{Z_1 - 2\delta}{Z_0} \approx \ln \frac{Z_1}{Z_0} \]  

(A-9)

And

\[ \varepsilon_z = \frac{\dot{Z}_1 - 2\delta}{Z_1 - 2\delta} \approx \frac{\dot{Z}_1}{Z_1} \]  

(A-10)

Then

\[ V_z = -Z_1 \varepsilon_z \approx \dot{Z}_1 \]  

(A-11)

And

\[ V_r = r \varepsilon_r = -\frac{r}{2} \varepsilon_z = \frac{r}{2Z_1} \dot{Z}_1 \]  

(A-12)
In the texture groove since the friction between liquid and deforming metal $\tau=0$, and also considering the yield condition then the normal pressure can be found as

$$p = \sigma_f = \text{const} \quad [60]$$

Therefore left hand side of the Reynolds equation is equal to zero and hence we get

$$V_r \frac{\partial h}{\partial r} + 2V_z = 0$$

(A-14)

Insert $V_r$ and $V_z$ into above we get

$$\left( 2 - \frac{r}{2Z_i} \frac{\partial h}{\partial r} \right) Z_i = 0$$

(A-15)

Then

$$\frac{\partial h}{\partial r} = \frac{4Z_i}{r}$$

(A-16)

Therefore

$$h(r) = 4Z_i \int_{r_a}^{r} \frac{1}{r} dr + C = 4Z_i \ln \frac{r}{r_a} + C$$

(A-17)

In texture groove we have

$$h(r) = H(r) + \delta(r)$$

(A-2)

then we get
\[ \delta(r) = 4Z \ln \frac{r}{r_u} - H(r) + C \]  

(A-18)

Also consider the boundary condition

\[ H(r_a) = \delta(r_a) = 0 \]  

(A-19)

Eventually we get

\[ \delta(r) = 4Z \ln \frac{r}{r_u} - H(r) \]  

(A-20)

At the entrance of the film, where \( r = r_c \), the film thickness is

\[ h = \delta(r_c) = 4Z \ln \frac{r_c}{r_u} \]  

(A-21)
Fig A.3: Free body diagram of the Slab method analysis in permeating film area
In the permeating film area, one can use slab analysis to find out the film pressure. As shown in Fig A.3, the resultant force in radial direction is zero, that is

$$\sum F_r = 0 \quad (A-22)$$

Then we get:

$$\sigma_r r d \theta (Z_1 - 2\delta) - (\sigma_r + d\sigma_r)(r + dr)(Z_1 - 2\delta)d\theta - 2\sigma_\theta \sin \frac{d\theta}{2} (Z_1 - 2\delta)dr + 2 \tau r d\theta dr = 0 \quad (A-23)$$

For axis symmetry there exists

$$\sigma_r = \sigma_\theta \quad (A-5)$$

Under yield condition there also exists

$$\sigma_r + p = \sigma_f \quad (A-24)$$

And thus:

$$d\sigma_r = -dp \quad (A-25)$$

In addition we have:

$$\tau = m\sigma_f \quad (A-26)$$

Simplify A-23 by inserting conditions A-5, 25, and 26, we can get:
\[ r(Z_1 - 2\delta)dp = -2m\sigma_f r\,dr \]  \hspace{1cm} (A-27)

Or

\[ \frac{\partial p}{\partial r} = \frac{2m\sigma_f}{Z_1 - 2\delta} \]  \hspace{1cm} (A-28)

The film thickness is assumed as constant, that is

\[ \frac{dh}{dr} = 0 \]  \hspace{1cm} (A-29)

And the film thickness can be found at the entrance of the film, that is

\[ h = \delta(r_c) = 4Z_1 \ln \frac{r_c}{r_a} \]  \hspace{1cm} (A-21)

From which one can get

\[ \dot{h} = 4Z_1 \ln \frac{r_c}{r_a} \]  \hspace{1cm} (A-30)

Reynolds equation in film area is thus reduced as

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( \rho h^3 \frac{\partial p}{\partial r} \right) = 12\dot{Y}_z = 12\dot{\delta} \]  \hspace{1cm} (A-31)

After Integral, we get
At film entrance where \( r = r_c \), there exists

\[
\frac{d}{dr}(r_c) = 0
\]  
(A-33)

Then it is easy to find out \( C = 0 \). Insert equation A-28 into A-32 and notify \( h = d \) and \( C = 0 \) at film area.

\[
\frac{rh^3}{\eta} \frac{2m \sigma_f}{Z_i - 2h} = 6h(r^2 - r_c^2)
\]  
(A-34)

Rearrange it and we have:

\[
m(r) = \frac{3\left(\frac{\dot{h}(r^2 - r_c^2)}{Z_i - 2h}\right) \eta(Z_i - 2h)}{\sigma_f rh^3}
\]  
(A-35)

After inserting equation A-21 and A-30, the friction factor at film area can be computed as

\[
m(r) = \frac{3}{16} \frac{\eta Z_i}{\sigma_f Z_i^2} \frac{1 - 8 \ln \frac{r_c}{r_a}}{\ln^2 \frac{r_c}{r_a}} \frac{r^2 - r_c^2}{r}
\]  
(A-36)

We define \( W \) as modified width of the texture groove,

\[
W = \ln r_c - \ln r_a = \ln \frac{r_c}{r_a}
\]  
(A-37)
$W$ includes information of both texture position and width. And also define width factor as

$$F_w = \frac{1 - 8W}{W^2} \quad (A-38)$$

Rheology factor as

$$F_r = \frac{\eta}{\sigma_f} \quad (A-39)$$

and Ram factor

$$F_m = \frac{3Z_i}{16Z_i} \quad (A-40)$$

Eventually one gets

$$m(r) = F_r F_m F_w \frac{r^2 - r_c^2}{r} \quad (A-41)$$

From volume conservation, one can compute film length. First one needs to compute the volume of lubricant that is squeezed out:

$$Vol = \left| \int_{r_a}^{r_b} r \delta(r) dr \right| = \left| \int_{r_a}^{r_b} \left[ 4Z_i \ln \frac{r}{r_a} - H(r) \right] dr \right| = \int_{r_c}^{r_a} rhdr \quad (A-42)$$

Right hand side of above equation is

$$\int_{r_c}^{r_a} rhdr = \frac{h}{2} (r_a^2 - r_c^2) \quad (A-43)$$
Insert equation A-21 to replace \( h \), one gets

\[
\int_{r_i}^{r_e} rhdr = 2Z_i \ln \frac{r_e}{r_a} (r_i^2 - r_e^2)
\]

Therefore \( r_d \) which reflects the length of permeating film can be found out

\[
r_d = \left( \frac{\int_{r_i}^{r_e} \frac{r}{r_a} \left[ 4Z_i \ln \frac{r}{r_a} - H(r) \right] dr}{2Z_i \ln \frac{r_e}{r_a}} \right)^{\frac{1}{3}}
\]

Since

\[
\int r \ln \frac{r}{r_a} dr = \frac{r^2}{4} \left(2 \ln \frac{r}{r_a} - 1\right)
\]

Therefore

\[
r_d = \left[ \frac{1}{2 \ln \frac{r_e}{r_a}} \left( r_e^2 - r_a^2 + \frac{1}{Z_i} \int_{r_i}^{r_e} rH(r) dr \right) \right]^{\frac{1}{3}} = \left[ \frac{1}{2W} \left( r_e^2 - r_a^2 + \frac{V_g}{2 \pi Z_i} \right) \right]^{\frac{1}{3}}
\]

where \( V_g \) is the volume of single texture groove. The average friction factor of textured die for forging can be computed as:

\[
m_o = \frac{1}{r_f} \int_0^{r_f} rm(r) dr
\]
Fig A.4: The derivation procedure of analytical lubrication model for plane strain forging
Fig A.5: Schematic of micro textured lubrication for plane strain forging
A.2 Micro textured lubrication for plane strain forging

Plane strain is another frequently applied metal forming in industry. Fig A.4 shows whole derivation procedure of the analytical models for plane strain forging lubrication using linear micro-groove textures. As shown in Fig A.5 strain in Y direction, equaling to zero, is always the second principle stress. The micro textures are a series of parallel grooves whose direction is in Y axis. Analysis parameters and assumptions are same as those in axis symmetry forging.

From the property of plain stain deformation we have

\[ \varepsilon_x = -\varepsilon_z = \ln \frac{Z_1 - \delta}{Z_0} \quad (A-49) \]

Or

\[ \dot{\varepsilon}_x = -\dot{\varepsilon}_z = \frac{\dot{Z}_1 - \dot{\delta}}{Z_1 - \delta} \quad (A-50) \]

Therefore velocity in X direction is

\[ V_x = x \dot{\varepsilon}_x = x \frac{\dot{Z}_1 - \dot{\delta}}{Z_1 - \delta} \quad (A-51) \]

And velocity in Z direction is

\[ V_z = (Z_1 - \delta) \dot{\varepsilon}_z = \dot{Z}_1 - \dot{\delta} \quad (A-52) \]
For the lubricant liquid the Reynolds equation for plane strain situation can generally be expressed as

\[
\frac{\partial}{\partial x} \left( \frac{h^3}{\eta} \frac{\partial p}{\partial x} \right) = 6V_x \frac{\partial h}{\partial x} + 12V_z \tag{A-53}
\]

Analysis deforming material just above the micro texture groove, one can find out the pressure, that is

\[
p = 2.57 \sigma_f = \text{const} \tag{A-54}
\]

Which means the left hand side of the Reynolds equation is zero, that is

\[
V_x \frac{\partial h}{\partial x} + 2V_z = 0 \tag{A-55}
\]

Since liquid film in texture can be found out as

\[
h(x) = H(x) + \delta(x) \tag{A-56}
\]

Or

\[
\frac{\partial h}{\partial x} = \frac{dH}{dx} + \frac{\partial \delta}{\partial x} \tag{A-57}
\]

After inserting equation A-51, 52, and 57, equation A-55 become

\[
x \frac{\dot{Z}_1 - \dot{\delta}}{Z_1 - \delta} \left( \frac{dH}{dx} + \frac{\partial \delta}{\partial x} \right) + 2 \left( \dot{Z}_1 - \dot{\delta} \right) = 0 \tag{A-58}
\]
Simplifies above:

\[ \frac{\partial \delta}{\partial x} = - \left[ \frac{2(Z_f - \delta)}{x} + \frac{dH}{dx} \right] \]  \hspace{1cm} (A-59)

Differential equation A-59 does not have analytical solution. One has to numerically solve it. In the equation \( dH/dx \) is known geometry of the textures and \( Z_f \) is the known ram stroke. The boundary condition for equation is

\[ \delta(x_a) = 0 \]  \hspace{1cm} (A-60)

After solving equation with boundary condition A-60, the permeated film thickness can be found out as

\[ h = \delta(x_c) \]  \hspace{1cm} (A-61)

In the film area, since both film thickness and pressure are constant, the speed of \( V_z \) is derived as zero, which means the film does not grow thickness, but it does grow length based on volume conservation.

\[ \int_{x_a}^{x_c} \delta(x) dx = \delta(x_c) (x_d - x_c) \]  \hspace{1cm} (A-62)

Thus the film length is

\[ l = x_d - x_c = \int_{x_a}^{x_c} \frac{\delta(x) dx}{\delta(x_c)} \]  \hspace{1cm} (A-63)
A.3 Result interpretations and discussions

Equation A-38 is the width factor of the texture lubrication. It shows the relations to mixed film lubrication from both position and width of micro textures. Fig A.6 graphically shows the width factor, from which one can find wider texture has better lubrication effect. This is true, since the texture act as lubricant reservoir in forging process. However if textures are too wide, they are not micro textures any more. Textures become the die impressions into which metal will be squeezed and thus cause forging defects. The efforts trying to improve forging quality through meliorating lubrication become meaningless.

Fig A.7 shows the friction factor varies for individual texture groove and permeating film. Among them, $m_0$ is the friction factor for boundary lubrication which is top limit of forging lubrication, and $F$ is defined as

$$F = \frac{1}{F_m F_w} \quad (A-64)$$

The texture groove acts as lubricant reservoir and the friction shear stress is the viscosity stress between deforming metal and liquid, which can be ignored comparing with that of between die and deforming metal. In the film area the curve in Fig A.5 reflects equation A-41. The friction factor increases from inward to outward until it reaches that of in boundary lubrication.

Rhelogy factor indicates in equation A-39 shows some ideals about the effects of lubricant and strength of the bulk material. Considering the pressure effect of lubricant, Taylor expansion of equation A-1 is
\[ \eta \approx \eta_0 \frac{e^{\alpha \sigma_f}}{\sigma_f} \left[ 1 + \alpha \left( p - \sigma_f \right) \right] \approx \eta_0 \frac{e^{\alpha \sigma_f}}{\sigma_f} \]  \hspace{1cm} (A-65)

And then the rheology factor, equation A-39 can be approximately expressed as

\[ F_r \approx \eta_0 \frac{e^{\alpha \sigma_f}}{\sigma_f} \]  \hspace{1cm} (A-66)

which shows how metal strength and lubricant together affect friction factor.

The ram factor, defined in equation A-40, is another factor for friction caused by forging process itself. From the forging process, there is

\[ Z_1 = Z_0 - \dot{Z}_1 t \]  \hspace{1cm} (A-67)

in which \( t \) is upsetting time. Hence the ram factor can be rewritten as

\[ F_m = \frac{3 \dot{Z}_1}{16 \left( Z_0 - \dot{Z}_1 t \right)^2} \]  \hspace{1cm} (A-68)

From which one can find out that the ram speed dramatically decrease lubrication effects. In addition, one is also able to find out the lubrication effect is worse and worse in the forging process. This is common sense in forging industry.

In addition, the length of the squeezed film also affects the lubrication. Equation A-47 reflects how texture properties such as texture position, width and volume, affect the film length.
Fig A.6: Width factor and modified width
Fig A.7: Lubrication effect of Individual texture
LIST OF REFERENCES


