Study of Additive for Aluminum Cold Rolling Lubrication

Li Fang
University of Windsor

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Study of Additive for Aluminum Cold Rolling Lubrication

By

Li Fang

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2014

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Study of Additive for Aluminum Cold Rolling Lubrication

by

Li Fang

APPROVED BY:

______________________________________________

A. Fartaj
Department of Mechanical, Automotive and Materials Engineering

______________________________________________

X. Nie
Department of Mechanical, Automotive and Materials Engineering

______________________________________________

A. Riahi, Advisor
Department of Mechanical, Automotive and Materials Engineering

April 24, 2014
DECLARATION OF ORIGINALITY

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ABSTRACT

The performance of lubricants and additives was studied through simulated ball on disc experiments on aluminum alloys AA3003 and AA5182. Experiments covered five lubricant base oils with two additives at two additive concentrations. Comparison of lubricants was carried out based on measurements of the coefficient of friction (COF), surface damage and lubrication failure temperature. With lubricant applied during the cold rolling process, a protective layer containing carbon and oxygen forms on the alloy surface; the performance of lubricants is affected by both additive type and additive concentration. Lubricants’ anti-wear property is sensitive to changes in additive concentration; that is with an increase in additive concentration, the wear decreases. For lubricants’ anti-friction properties, only fatty alcohol shows a decrease in coefficient of friction when the additive concentration increases. With lower concentration of additive, higher lubrication critical temperature was observed. Generally, coefficient of friction is insensitive to aluminum material changing.
DEDICATION

To my father,

You are always the goal, guide and model of my life

To my mother,

Thank you for the silent support year after year

To my wife,

Your care is so warm

To my son, Dean

You are the happiest thing happen to me. Hope you know how meaningful you are to me
ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to Dr Riahi, for his guidance, support and encouragement during this journey. His continuous drive for research, mentorship and interest in me are much more than appreciated. My thanks to Dr Alpas and Dr. Edrisy, for their continual support, valuable suggestions and taking a chance on me. My sincere appreciation is extended to Dr K. Januszkiewicz for his comments, support and vital suggestions during this work.

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## NOMENCLATURE

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<th>Abbreviation</th>
<th>Description</th>
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</thead>
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<tr>
<td>COF</td>
<td>Coefficient of Friction</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersive X-Ray Spectroscopy</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>NP</td>
<td>Normal Paraffin</td>
</tr>
<tr>
<td>HK</td>
<td>Hydro treated Kerosene</td>
</tr>
<tr>
<td>WO</td>
<td>White Oil</td>
</tr>
<tr>
<td>HF</td>
<td>Hydrocarbon Fluid</td>
</tr>
<tr>
<td>IP</td>
<td>Iso-Paraffin</td>
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CHAPTER I

INTRODUCTION

1.1 Background

Aluminum alloy is one of the most commonly used material in human daily life because of its remarkable properties. First, it is lightweight, aluminum alloy weighs only 1/3 as much as equal volumes of general used iron or steel. With its lighter weight, aluminum alloy exhibits high strength, for 7XXX series of aluminum alloy, the ultimate tensile strength achieves over 600MPa. The high strength-to-weight ratio of aluminum alloy is extremely attractive, for instance, in the aerospace and automotive industries. In today’s automotive industry, cars with aluminum-made engines and body frames exhibit high performance.

An engines made from aluminum provides both excellent acceleration performance because of its light weight and stable service because of its good heat conduction. Vehicles with aluminum alloy body frames take advantage of the material’s high strength at low temperature. As the temperature is reduced, the strength of the aluminum alloys increases, making the vehicle suitable for more environmental conditions. The oxidability of aluminum helps it to resist corrosion naturally. When aluminum is exposed to air, an oxidized film quickly forms on the surface and protects the surface from corrosion. Compared with other metals, aluminum alloy is soft, and the high ductility gives aluminum
alloy more flexibility. The usual forming methods such as extrusion, stamping or rolling have been found to be appropriate for aluminum of a complex shape or extreme thickness.

Among all of the methods of shaping and forming, rolling is the most widely used. As indicated by Wilson in 1997, about 70% of the tonnage of all metals is rolled at least once during production [1]. According to the working temperature, rolling is categorized as hot rolling or cold rolling. If the working temperature of the rolling process is above the metal’s recrystallization temperature which is about 0.5-0.7 of the metal’s melting temperature, the rolling process is defined as hot rolling. Accordingly, the working condition for cold rolling is below metal’s recrystallization temperature. For hot rolling, larger deformation can be achieved in comparison to cold rolling, since the metal remains soft and ductile. However, the product surface finish achieved with hot rolling is inferior to that of cold rolling due to the oxidation, adhesion and material loss that are enhanced by the high temperature. For the final product, a good appearance is required and for the accurate control of dimensions, as in metal sheet or foil, cold rolling is necessary.

Due to strain hardening, the ductility of material decreases while the strength increases though the cold rolling process. In terms of the product’s thickness, three kinds of rolling products can be further identified. A rolled aluminum product with a thickness above 6.3 mm is defined as aluminum plate; this is usually used in heavy duty applications. If the thickness of the aluminum product is less than 0.2mm, it is defined as aluminum foil.
Finally, products between 0.2 mm and 6.3 mm in thickness are defined as aluminum sheet; most cold rolling products fall into this category. [2]

During the cold rolling process, both the roller and rolling sheet will experience high frictional force and plastic deformation, which may cause undesired scuffing and other negative effects on the surface appearance. By introducing lubricants into the cold rolling process, a protective layer forms on the material’s surface, preventing direct metal-to-metal contact, thus, high friction is expected to be eliminated. Another common problem in cold rolling is the rise in temperature. With some hard materials, a temperature rise of about 80°C has been observed due to a high degree of plastic deformation and friction. The high temperature at the interface of contact causes softening of the material and further adhesion may occur. The flow of lubricant in cold rolling remove the heat and acts as a coolant to reduce the temperature.

Commonly used lubricants in cold rolling are mineral oil or synthetic lubricant. Based on the structural difference, mineral oils are generally classified as aromatic, naphthene and paraffin. Paraffinic lubricants have been found to contain long-chain hydrocarbons with a straight or branched shape, which theoretically perform best for protection of surface protection. For the purpose of improvement in lubricant performance or enhancement in a certain ability, different additives are used; this is discussed in detail in the following literature review below.
1.2 Thesis Objective

The basic mechanisms of the cold rolling process and the benefit of lubrication on aluminum cold rolling have been well studied. However, only limited research has been conducted on lubricant additives. Thus, the present research focuses on the additives for aluminum cold rolling. As known, there are huge numbers of additives and lubricant base oils that are used for different types of manufacture. With different combinations of base oil and additives, the lubrication performance may be different. Thus, five commonly used base oils have been selected for the research. Moreover, as economical and practical additives, fatty alcohol and fatty acid are applied to the base oils at two concentrations. The selection of base oils and additives was carried out helpful guidance of the research industry partner.

There are two objectives set for this research. First, the effect of additive’s type and concentration on lubricant performance was tested. The lubricant’s performance was evaluated as anti-friction performance, anti-wear performance and critical temperature. As the study on additive proceed, the performance of different lubricant base oil was also learned as another part of the research’s objective.

1.3 Organization of Thesis

This thesis is arranged into six chapters; a brief synopsis of each chapter is give below

Chapters 1 introduces the thesis, giving background information on the research and its objectives.
Chapter 2 provides the literature review regarding the research. The review first focuses on basic knowledge concerning cold rolling. General cold rolling processes, rolling mechanisms and important parameters of cold rolling are explained. Previous research on lubrication in cold rolling is also studied in the literature review. Basic knowledge about lubrication is first given, followed by a discussion of parameters influencing the cold rolling process.

Chapter 3 explains the design and methodology of the experiments. This includes the experimental setup devised for this research, the conditions under which the experiments were carried out, the parameters monitored, the materials used and the planning of the experimental process.

Chapter 4 provides the experimental results in detail. The arrangement of experimental results followed by the arrangement of experiments. Explanation of the numerical data analysis, SEM and WYKO images is given in detail.

Chapter 5 discusses the results given in Chapter 4. Numerical data are analyzed by reformatting them in plots for trend observation. Several conclusions are made in this chapter.

Chapter 6 provides a summary of the entire thesis. It reviews the results obtained from the research and the discussions in the previous chapters.
2.1 Introduction to the Review

As introduced in Chapter 1, due to the outstanding properties of aluminum alloy, it is one of the most widely used materials in many industrial areas. The demand for high quality aluminum products has experienced a huge increase in the last several decades and will keep increasing. Cold rolling as the basic shaping treatment method of aluminum alloy directly affects a product’s surface finish and properties. For the purposes of improving product surface quality, lubricants are widely used in aluminum forming manufacture. With the application of lubricants, friction between the roller and rolling sheet is expected to decrease, and the temperature rise during rolling process should theoretically be limited. However, there are many factors influencing lubrication performance, such as rolling speed, degree of reduction and lubricant viscosity. A briefly study of the cold rolling procedure will be given first, followed by more detailed research on rolling and lubrication theory.

2.2 Rolling Theory

In metalworking, rolling is a metal-forming process in which metal stock passes through a pair of rolls. Rolling is classified according to the temperature of the metal rolled. If the temperature of the metal is above its recrystallization temperature, then the process is termed hot rolling. Conversely, if the temperature of the metal is below its recrystallization temperature, the process is termed cold rolling. Cold rolling increases
material’s strength, via strain hardening, up to 20%. Since cold rolling offers less thermal expansion and oxidation scales than hot rolling, it can achieve a superior surface finish and dimensional tolerances. According to the product thickness, the rolling product can be classified as plate, sheet or foil. In addition, according to the shape of the rolled material, the rolling process can be classified as flat rolling, foil rolling, ring rolling and so on.

2.2.1 Aluminum Cold Rolling Procedure

Rolling is a basic process for producing strip and sheet that can be used in many industries. A hot-rolled aluminum strip is cooled to room temperature and fed into a cold roll mill line. The strip is then passed several times between a series of rollers until it is gradually reduced to the desired gauge and wound into a coil. According to the product thickness and capacity requirements, different mill setups are used. The commonly used mills in industry are single-stand two mill (Figure 1 (a)), four mill (Figure 1 (b)), six mill, cluster mill (Figure 1(c)) or tandem mills. Due to the limited thickness reduction per pass and production capacity, single-stand two mills are usually only used in small manufacture or laboratories. Commonly used rolling mills in industry start from four mills and up. In a four-high mill, as shown in Figure 1 (b), only the two smaller rolls (work rolls) are normally driven because this can achieve greater reduction in a single pass than for large rolls; the larger rolls, known as back-up rolls, rotate merely due to the friction against the work rolls. The object of the back-up rolls is to prevent excessive distortion of the work rolls under the roll load. Without the back-up rolls, distortion would be excessive because of the small
diameter of the work rolls [3] With more back-up rolls installed, the roll assemblies could bear more force; thus, more reduction could be achieved with each pass. It is for this reason that six-mills and cluster mills were introduced.

**Figure 1** Schematic of (a) single-stand two high mill (b) single-stand four high mill and (c) cluster mill

For higher productivity, a continuous cold rolling line with two- or three-stand tandem mills would be used. The capacity of such a line would be about 300,000 tons and higher per year. For special application such as polish rolling material to a bright finish, a two high mill with limited reduction at low throughput speeds may be used [4]. Annealing or other intermediate heat treatments could also be used in the cold rolling process depending on the degree of rolling and final thickness desired for particular applications to modify mechanical features of the cold-rolled coils [5]. At finishing stage, cold-rolled aluminum coils are flattened to a precise thickness by running them through a tension leveling process then slitters are used to achieve a precise width to the coil. In some companies a protective
film will be applied to the product as the last step of the whole cold rolling process. [6]

2.2.2 Rolling Geometry

In the rolling process, the metal goes through the work rolls and is deformed by the rolling pressure. During rolling, the material is deformed in three dimensions, as shown in Figure2.

![Figure 2 Three-dimensional view of the strip rolling process](image)

The material thickness is reduced from $y_1$ to $y_2$, by the ratio $\xi = y_1/y_2$, which is called the draft coefficient. The material width changes from $B$ to $b$, with a spread coefficient of $\psi = b/B$. The material length increases from $L$ to $L_1$, with an elongation coefficient of $\lambda = L_1/L$.

The constant mass flow is given by

$$y_1 BL = y_2 bL_1 \quad (1)$$

The reduction ratio $\varepsilon$ is defined as

$$\varepsilon = \frac{y_1 - y_2}{y_1} \times 100\% \quad (2)$$

In cold rolling, the strip width spread can be neglected as the width is much greater than
the thickness; thus, the plastic deformation mainly occurs along the length and thickness direction.

2.2.3 Roll Force and Torque

The maximum amount of thickness reduction that may be achieved in a single rolling pass is mainly determined by the maximum roll separating force (force applied to the rolls in vertical direction) and maximum torque [7]. Theoretically, to calculate the rolling force and torque for flat products on smooth rolls of equal diameter, a general equation is used which is based on Roberts’ assumption, which states that where deformation occurs in the roll bite the rolling pressure is equal to the resultant resistance to deformation of the material being rolled. Under this circumstance, the rolling force is merely the product of the contact area and rolling pressure. Thus the rolling force is given by [8]:

$$P_1 = \sigma_y A_c = \sigma_y B_m L_e = \sigma B \left( \sqrt{\frac{\sigma y_1 \varepsilon}{2}} + \varphi \left( \frac{P_1 D}{E} + \frac{\varphi^2 \mu D P_1 (2-\varepsilon)}{2E y_1 (1-\varepsilon)} \right) \right)$$  \hspace{1cm} (3)

The torque exerted by each spindle without considering bearing losses is

$$T = \frac{DH\sigma}{4} \left[ \varepsilon \left( 1 + \frac{\sigma y_1}{\sigma} \right) + \left( \frac{\sigma y_1 - \sigma y_2}{\sigma} \right) \right]$$  \hspace{1cm} (4)

where $B_m$ is the mean width of the material, $L_e$ is the projected arc of contact between the roll and material, $D$ is the diameter of work rolls, $\varphi$ is a dimensionless constant with a value of 1.08, $\varepsilon$ is the reduction ratio, $E$ is the elastic modulus of the work roll, $\mu$ is the effective friction coefficient in the roll bite and $\sigma y_1$ and $\sigma y_1$ are tensile stresses from the entry and exit tensions.

Experimentally, Al-Salehi et al. (1973), Christensen et al. (1986), and Saeed et al
measured roll separating force and torque for different kinds of material such as steel, aluminum and copper under different reductions and rolling conditions. Three conclusions can be drawn from their research. First, the roll-separating force and torque increase with reduction of thickness. Second, under the same rolling conditions, the roll-separating force and roll torque for rolling a harder material are larger than those for rolling a softer material. Third, for a roller with a larger diameter, a larger roll separating force and torque are expected [9-11]. The reason for these phenomena can be explained, in that a small roll diameter results in small roll contact area, and consequently a low absolute value of the roll-separating force and torque required for achieve a certain thickness reduction [12].

2.2.4 Interfacial Frictional Forces

Friction plays an essential role in the cold rolling process. All the deformation energy is transmitted from the work rolls to the strip material by shear stresses set up on the running surfaces. This implies that the greater the friction between the roll and strip, the more easily the strip can be rolled. However, if the friction is too high it may impede the flow of the material in the bite; moreover, the quality of the rolled product will be poor.

In Figure 3, a typical geometry of roll bite was given which shows pressure distribution predicted from rolling theory; at neutral point N.P., shear stress (τ) along the arc of contact is reversed. In Figure 4 roll pressure and friction stress distribution during cold rolling of dry Al-1100-T0 aluminum strips at different reductions is given. It can be observed that the ratio of friction stress to normal pressure in the roll gap during cold rolling varies from...
entry to exit [12-14].

Figure 3 Geometry of roll bite [9]

Figure 4 Roll pressure and friction stress distribution during cold rolling of dry Al 1100-T0 aluminum strips [15]

The significant parameters affecting interfacial frictional forces involve the reduction
and the relative velocity between the work roll and the rolled strip. In Figure 4 it can be observed that as the thickness reduction increases, so do the frictional stress, normal pressure and of course the average frictional coefficient [9,10,16]. The adhesion theory of friction presented by Rabinowicz reasonably explains this phenomenon, since as the reduction increases, so do the interfacial normal forces; hence, the real contact area approaches the apparent one [17]. In Lim’s research, he pointed out that the speed of rolling is another significant parameter that affects friction: As rolling speed increases the average coefficient of friction (COF) decreases. This phenomenon is explained by Yan and others in that the increase in speed leads to shorter contact times, in addition, high speeds causes high interface temperatures, which soften or melt asperity on contact material then, the region of melt lubrication is achieved [17-20].

2.2.5 The Coulomb Friction Law

The Coulomb friction law is the most commonly used method to characterize friction. This law says that friction stress increases in proportion to normal pressure with a constant of proportion called the coefficient of friction [21]:

$$|\tau_i| = \pm \mu p$$  \(5\)

where \(\tau_i\) is friction stress, \(\mu\) is the coefficient of friction and \(p\) is normal pressure. Friction stress is defined as positive between the exit of the roll bite and the neutral point and negative between the entry and the neutral point. However, friction stress cannot exceed the shear yield strength of the workpiece. This places an upper limit on the friction stress.
for processes involving plastic deformation. For a constant $\mu$, the interface shear stress $\tau_i$ must increase at the same rate as the interface pressure. The condition of sliding friction is:

$$\tau_i = \mu p < k \quad (6)$$

When $\tau_i$ reaches the value of $k$, it will take less energy for the material to shear inside the body of the work piece. In this condition, it is assumed that the term friction coefficient is no longer applicable, since there is no relative sliding movement at the interface. This is described as sticking friction and the condition is written as:

$$\tau_i = \mu p > k \quad (7)$$

In both expressions, $k$ is the shear yield strength of the rolled material. In the rolling process, reducing the friction increases the reduction in thickness obtainable with a given roll load. The lower the friction between the rolls and working metal, the lower the sub-surface resistance to deformation, and consequently, the lower the roll load required to effect a given reduction will be. Based on this, therefore, lower friction is better for rolling. However, a certain level of friction must be maintained to carry the work metal through the rolls.

2.2.6 Forward Slip

Forward slip has been studied by several researchers and is considered an important factor in the control of strip velocity and tension for multi-stand tandem mills. During the rolling process, reduction in the roll gap mainly leads to an extension of the rolling stock length but not width. Therefore, forward slip is defined in terms of the exit velocity of the
strip and the surface speed of the roll.

The common method of measuring forward slip in the laboratory is to mark the roll sheet with two parallel lines or points at a known distance $l$, then measure the distance between the impressions created by the marks on the strip, $l_1$. Forward slip can be calculated from equation (1) [22, 23].

$$s_f = \frac{l_1 - l}{l} \quad (8)$$

In Wang et al’s research, they concluded that a few basic models could be used to predict coefficient of friction from forward slip measurement: namely Ekelund’s formula, Robert’s formula, Ford’s formula, Sims’s formula, Inhaber’s formula and Hsu’s formula. According to their experimental results, Hsu’s expression in equation (9) predicts the closest coefficient of friction [24].

$$\mu = \mu_0 V \left[ 1 - \frac{H(1-r)(1+S_h)}{h_i} \right] \quad (9)$$

According to Zhang and Lenard, measurements of forward slip during strip rolling in industrial settings may be the most effective means of arriving at an understanding of frictional resistance at the roll-strip interface. They tested three aluminum alloys in order to study the dependence of forward slip in material and process parameters. The key results of their study are shown below [23]:

15
Figure 5 The effect of speed and reduction on forward slip for 1100-H14/5052-H34/6061-T6 alloy; without lubrication

As Figure 5 shows, as the reduction increases, the forward slip also increases under all testing conditions; however, the effect of speed and strength of material on the forward slip appears does not appear to be significant, confirming the data reported by Roberts [8] and
2.2.7 Temperature Distribution

During cold rolling, due to plastic work and interfacial friction forces, a temperature rise in both the roller and strip could be expected. M. Pietrzyk and J. G. Lenard have made several general conclusions on the temperature rise in cold rolling aluminum against steel. First, as the number of rolling passes increase, the temperature rises. Second, temperature increases in tandem with thickness reduction. Examples of these phenomena are shown in Figures 6 and 7, respectively. Third, via comparison between low carbons steel and pure aluminum, it can be observed that the temperature rise in harder metal is much greater than that in the soft metal [25,26].

**Figure 6** The effect of number of rolling passes on temperature rise during cold rolling.
Figure 7 The effect of reduction on temperature rise during cold rolling

A plot of roll temperatures in the depth direction for cold rolling from research of Chang is shown in Figure 8. Due to the frictional forces at the interface between the roll
and the sheet, the temperature near the roll surface is observed to be higher, this drops rapidly from the roll surface to the interior in the depth direction. This phenomenon was confirmed by A. A. Tseng et al and M. Pietrzyk [25,26]. The boundary of the temperature change is called the thermal boundary layer. In this layer, thermal stress is important; outside the boundary layer, however, mechanical stresses become more important [27].

![Figure 8 Roll temperatures in the depth direction for the cold rolling](image)

2.3 Lubrication

The lubricating conditions in the roll gap exert a profound effect on the surface appearance of the strip. Unless reductions are very low, rolling with dry rolls or with inadequate lubrication causes local welding and hence scuffing of the surface; in extreme cases, the strip ultimately tears apart. Better lubrication eliminates the scuffing, and the rolls then carry out have a burnishing action on the strip and give the smooth bright finish.
usually desired in cold rolled products.

In rolling operations, the internal friction due to plastic deformation and the surface friction due to slip both generate considerable amounts of heat. While reducing friction, the rolling lubricant also reduces the heat when flowing over the surface acting as coolant. Other results of lowering the friction are the reduction of power consumption, lowering the wear rate of the rolls, and decreasing the load on the roll bearings. Perry [28] has concluded several requirements for rolling oils as follows:

(1) They must reduce coefficient of friction. This decreases the roll load and the power consumption, as well as the heat generated and the rate of wear of the rolls. It also helps to control the surface finish.

(2) In some cases, they must act as coolants.

(3) They must spread uniformly and evenly across the rolls; otherwise, the work metal may roll unevenly, resulting in non-uniform thickness and possibly wrinkling.

(4) They must not corrode the rolls or work metal, and in fact, should give a measure of anti-corrosion protection to the rolled material, which may otherwise corrode while waiting for subsequent processing.

(5) They must be inoffensive to the operatives, and be economic in use.

2.3.1 Lubrication Regimes

In metal-forming processes, any of several different regimes of lubrication can occur at the tooling-work piece interface. Different regimes can arise as a result of slight changes
in the lubricant and work piece properties, temperature, geometry or surface texture. These regimes are characterized by $\lambda$, which is the ratio of lubricant film thickness $h$ to the combined composite surface roughness $R_s$ of the strip and roll

$$\lambda = \frac{h}{\sqrt{R_s^2 + R_s^2}} \quad (10)$$

According to Wilson and Hutchings there are three main regimes: the hydrodynamic regime (often referred to as the full film regime), the mixed regime (also known as the partial elastohydrodynamic regime) and the boundary regime [29,30]. The lubrication regimes may be illustrated though reference to the Stribeck curve. Here, the coefficient of friction is plotted against the modified Sommerfeld number defined as:

$$S = \frac{\eta \Delta v}{p} \quad (11)$$

where $\eta$ is the dynamic viscosity, $\Delta v$ is the relative velocity and $p$ is the pressure. A schematic diagram of the Stribeck curve is shown in Figure 9, with the boundary, mixed and hydrodynamic mode of lubrication identified.
The brightness of the surface is sometimes used to classify the lubrication mechanism. If the strip undergoes free deformation, this is, if the lubrication mechanism is hydrodynamic, the reflection in the rolling direction corresponds to that in the transverse direction. Azushima [31] proposed a parameter representing the lubrication mechanism: specifically $\alpha = \frac{R}{R_{90}}$ where $R$ is the reflection in the rolling direction and $R_{90}$ is the reflection in the transverse direction. When $\alpha = 1$ the lubrication mechanism is hydrodynamic; when $\alpha < 1$, it is of the mixed type.

Hydrodynamic Lubrication:

In hydrodynamic lubrication regime, the tool and work piece surfaces are separated by lubricant film of sufficient thickness to avoid asperity interaction. According to the thickness of the lubricant film, the sub-regimes can be classified as thick and thin film.
In the thick film regime, as shown in Figure 10(a), the surfaces are separated by a continuous lubricant film which is much thicker than either the roughness of the conjugated surfaces or the molecular size of the lubricant. This occurs when the mean lubricant film thickness is greater than about 10 times the root mean square (RMS) composite roughness of the surfaces involved. Since the thickness of lubricant film is so high, surface roughness and asperity orientation will have little influence on lubrication and the lubricant can be modeled as a continuum between smooth surfaces. Thus, friction is determined by the shear resistance of the lubricant film under the conditions at the interface.

In the thin film regime, as shown in Figure 10(b), the mean lubricant film thickness is approximately 3-10 times the RMS composite roughness of the surfaces. In this regime, the surface roughness and asperity orientation have a significant influence on the lubricant flow. However, the film thickness is almost always greater than the lubricant molecular size, and the asperity contact carries a negligible fraction of the total load between the two surfaces. The frictional behavior is similar to that in the thick film regime, except that lubricant flow has to be modified according to the surface topography [30].

For applications requiring high surface finish quality, hydrodynamic lubrication is not generally preferred. Due to the high lubricant film thickness mechanism of hydrodynamic lubrication, the friction will be too low, causing skidding of the rolls or requiring very large inlet and outlet tensions. The occurrence of skidding has been ascribed to hydrodynamic
lubrication by Reid and Schey. When skidding happens, surface roughening will occur due
to the different deformations of individual grains. Moreover, the surrounding grains may
influence the movement. The surface then roughens and grains with pockets of lubricant
are formed [32].

Mixed Lubrication:

In cold rolling, the lubrication system must be carefully designed to provide adequate
lubricant film thickness, thereby avoiding the problems of severe metal-to-metal contact.
On the other hand, if the film thickness is too high, a poor surface finish may result, as
discussed above. In addition, the friction between the strip and rolls must be sufficient to
draw the strip through the rolls. In order to resolve all of the conflicting constraints, the
cold rolling process must generally operate using the mixed lubrication regime.

As shown in Figure 10(c), the mean film thickness is reduced to less than three times
the RMS composite roughness using this regime. A considerable fraction of the load will
be carried by asperity contact with the remainder of the load carried by the lubricant in the
roughness valleys.

According to the analysis of the contact between two surfaces in a mixed lubrication
regime by Chang, Tsao and Sutcliffe, in the mixed lubrication regime, the formation of a
lubricant layer at the interface is influenced by both surface roughness and asperity
orientation. With a rough surface, more valleys are available for lubricant entrapment as a
result of more effective lubricant retention on surfaces. Moreover, transverse asperity tends
to carry more lubricant flow, as its aligned asperity lies perpendicular to the relative motion, while longitudinal asperity allows more lubricant to leak through the roughness channels [33-35].

![Diagram of lubrication modes](image)

**Figure 10** (a) Thick film regime ($\lambda>10R_s$), (b) thin film regime ($3R_q<\lambda<10R_s$), (c) mixed Regime ($1<\lambda<3R_q<10R_s$)

**Boundary Lubrication:**

As shown in the Stribeck curve, under very high contact pressure or low sliding speeds, lubrication can be characterized as a boundary regime. Here, lubricants act by forming adsorbed molecular films on the surfaces; repulsive forces between the films then carry much of the load and intimate contact occurs between unprotected asperities. Two fundamental types of adsorption are recognized depending on whether the association at the surface or interface is physical or chemical in character. For physical adsorption, the lubrication ability provided by adsorbed molecules varies markedly with the constitution of the molecule [36, 37]. The molecules adsorbed on surface may be nonpolar or polar.
Polar molecules will orient themselves on surface and the lubrication performance is directly affected by molecular weight. The molecules are weakly held to the surface only by van der Waals’ molecular forces of attraction. Molecules are continuously attaching themselves to and detaching themselves from a surface automatically. As the temperature rises, thermal oscillations increase and the equilibrium are disturbed in the direction of desorption. When the temperature decreases, the rate is disturbed in the direction of adsorption. Thus, physical adsorption is characterized by reversibility. The concentration of adsorbed molecules decreases with higher temperature and physical agitation [38, 39]. Lubrication dependent on physical adsorption is limited to low load, sliding speed and temperature, which are the conditions of the boundary lubrication regime.

Compared with physical adsorption, chemical adsorption shows higher temperature of adsorption and is generally not completely reversible. Frequently, adsorption seems to be physical at low temperatures and changes to chemisorption at higher temperatures [40]. In boundary lubrication when molecules are first physically adsorbed on a metal and then valence electrons are exchanged, chemisorption has occurred. The metal ions do not leave their lattice, and the adsorbed portion retains some of the physical properties of the original unreacted molecule. The most typical example of chemisorption could be that of fatty acid with metal, forming soaps exceptionally low shear-strength solids. The organic part of the soap molecule remains as a long-chain hydrocarbon similar to acid [41-43]. Temperature is the primary factor in chemisorption; chemisorbed films are lubricated effectively up to
their melting point. The failure of lubrication is a result of the disorientation, softening or melting of the solid film despite even though the molecules remaining anchored to the surface [39].

Figure 11 illustrates the mechanism of operation of a typical boundary lubricant, namely a long-chain carboxylic acid on metal surface. The molecular chains tend to align perpendicularly to the surface, stabilized by their mutual repulsion and form dense layers of hydrophobic chains typically 2 to 3nm long. When the two layers come together, most of the normal load is carried by the interaction of the hydrocarbon chains. The frictional force in boundary lubrication regime is lower than for unlubricated sliding and less severe wear than unprotected contact. The molecular weight and the length of hydrocarbon chain directly affect the performance of boundary lubricant [30].

**Figure 11** Boundary regime: polar end-groups on the hydrocarbon chains are bound to the surface

### 2.3.2 Effect of Viscosity on Lubrication

As discussed above, lubricant film thickness is an important factor that affects the transition of lubrication regimes. Wilson and Walowit developed founded the model of inlet film thickness in the deformation zone with back and forth tension during lubricated
rolling. The film inlet thickness \( h_a \) can be estimated using the equation of Wilson and Walowit: [44]

\[
h_s = \frac{6\eta_0 \alpha \bar{\mu}}{\theta_0 \left[1 - e^{-\alpha Y}\right]}
\]  \hspace{1cm} (12)

where \( \bar{\mu} \) is the average entraining velocity, \( \theta_0 \) is the inlet angle between the strip and roll, \( Y \) is the plain strain yield strength of the strip, \( \alpha \) is the pressure-viscosity coefficient and \( \eta_0 \) is the viscosity of the lubricant at ambient pressure. This equation has been widely used by researchers to determine the film thickness. According to Wilson and Walowit’s equation, lubricant film thickness is directly proportional to viscosity of lubricant. In other words, a lubricant with higher viscosity should provide a thicker film to protect metal surface.

This hypothetical prediction was confirmed by Sun Jianlin and Kunikai Matsui’s research. They studied several lubricants with various viscosities and the experimental observation showed that mean lubricant film thickness increases with viscosity and lubrication becomes more hydrodynamic in character as the lubricant viscosity increases. A lubricant with higher viscosity has higher resistance to flow, and therefore it is harder to be squeezed out from the contact zone. With a stronger lubricant film formed on contact surfaces, a decreased roll force and friction could be expected with increased lubricant viscosity. In S. Zhang’s and J.G. Lenard’s research they also found forward slip decreases with lubricant’s viscosity [45,46].
2.3.3 Effect of Rolling Speed on Lubrication

According to rolling theory described in Chapter 2.2, as the rolling speed increases, friction exhibits a decreasing trend. With lubricant applied, the same phenomenon occurs; this can be attributed to more oil being entrapped in the roll gap along the contact arc, followed by more entrapment and squeezing out of the lubricant. Consequently, friction along the arc of contact decreases at higher speeds. Furthermore, according to the speed and the amount of lubricant entrapped, a change in the lubrication regime can be expected [47].

Sakai pointed out in his research that since there is more lubricant entrapped due to high rolling speed, the surface deforms more freely with entrapped lubricant oil at higher speeds than at lower speeds. It is expected, therefore, that the resulting surface-roughness will become somewhat greater at higher speeds [48].

Zhang and Lenard also did experiments to study the effects of speed on friction in cold rolling. According to their research, Kondo and Sakai’s conclusions on the effect of rolling speed on lubrication have been confirmed. These researchers also found that there were no significant changes in the roll-separating force at different speeds. The explanation of this phenomenon they stated is because the speed affects the force in two ways: first by reducing the friction and the force through the entrapment of more oil in the roll gap and increases the force for strain-rate sensitive materials through augmented hardening; the force increasing or decreasing depending on which phenomenon is dominant [49].
2.3.4 Effect of Reduction on Lubrication

The effect of reduction on cold rolling under lubrication condition basically follows the rolling theory: With increasing reduction, roll force, forward slip and coefficient of friction all show increasing trend. The most obvious reason for this phenomenon is that due to the reduction increase, lubricant film thickness decreases since more lubricant will be squeezed out from the entrapment zone because of the higher pressure. However, with application of lubricant, the effect of reduction on rolling process will become more complex than it is in basic rolling theory.

Following Lenard and others, details of the results of increasing reduction are depicted in Figure 12. The first phenomenon concerns the effect of straining as the rolling pass proceeds and the attendant strain hardening of the metal. The increasing resistance to deformation will require more expenditure of energy to flatten the asperities and thus, will cause the true area of contact to approach the apparent area at a slower rate. Fewer sites for the formation of adhesive bonds will be available. A material that is more strain hardening will therefore experience a lower magnitude coefficient of friction than one with a lower strain-hardening exponent.

The metal that has hardened will also possess asperities that are harder to break. If this metal is in contact with another to which it has a high chemical affinity, the resistance of relative motion will probably increase, since this is the bond that will have to be broken to overcome frictional resistance.
The asperities of a softer metal will flatten with relative ease compared to those of a harder metal. More sites for bonds may then be available and the coefficient of friction will likely be higher than for a hard metal subjected to the same load.

When lubricants are introduced into the conjunction, their response to the increased pressure and temperature will affect the tribological system in a significant manner. In general, increasing pressures increases the lubricant’s viscosity, which will result in lower resistance to relative motion. Higher temperatures will lower the viscosity, causing higher frictional resistance [50-57].

The last contributor, resulting from larger reduction, is the increased angle of bite. This will make more oil available for entry into the contact zone. After successful entrainment, further reduction of the coefficient of friction may occur [58].

**Figure 12** Effect of reduction on the mechanisms that affect the coefficient of friction
2.3.5 Lubrication Base Oil

The most widely used oils used in cold rolling are mineral oil (also known as petroleum oil) and synthetic oils. Most lubricating oils of mineral origin are found to contain a rich amount of different hydrocarbon species. The various hydrocarbon species found in crude petroleum provide sufficiently viscosity to maintain a lubricant film under operational condition, and also flow as a fluid to avoid high power losses due to frictional drag and promote heat transfer. Moreover mineral oil has low volatility, which is compatible with the desired viscosity and makes it resistant to thermal decomposition and oxidative degradation. The inexpensive cost is another reason why mineral oil is commonly used as a lubricant. On the other hand, petroleum consists mainly of hydrocarbons and a portion of non-hydrocarbon material which contains sulfur, nitrogen and/or oxygen, hydrogen and carbon is also often used in some heavy duty rolling processes.

The hydrocarbons from crude petroleum may be classed broadly as cyclic and noncyclic. These may be further subdivided into saturated and unsaturated compounds. The three classes can be typified by the structures below, which are commonly seen in lubricants.
Oil with long straight-chain hydrocarbons is called paraffinic oil. Such oils can further be classified as linear paraffins and isoparaffins depending on whether also consist of branched-chain hydrocarbons in addition to straight-chain ones. Naphthenic oils consist of hydrocarbons in ring structures. Aromatic oils consist of hydrocarbons that contain totally unsaturated six-member rings. A mixture of paraffinic, naphthenic and aromatic molecules is very common in petroleum oils. The general rule for classifying hydrocarbon compounds could be summarized as follows: If the molecule contains an aromatic ring, it is called an aromatic compound regardless of the presence of the naphthene and paraffin group. If it does not contain an aromatic ring but has a naphthene ring with or without paraffinic chains, it is termed a naphthene. Only when it contains neither an aromatic nor a naphthene ring is it called paraffin. [59-61]

Synthetic oils are used as lubricants under conditions where mineral oils would be unsuitable, for example under extreme temperature conditions. Typical synthetic oils are organic esters, which lubricate over a wide temperature range and are used, for example, in gas turbine engines; polyglycols, which have excellent boundary lubricating properties.
and decompose at high temperature without leaving solid residues; and silicones, which are chemically very stable, can operate at extreme temperature and are electrically insulating. In addition, synthetic oils costs more than common mineral oils, thus are usually used on in specialized and demanding applications.[30, 45, 62]

As mentioned above, viscosity is a major factor in lubricant performance. The viscosity of mineral oil depends strongly on its composition, with higher viscosity being associated with higher molecular weight. Other properties that affect an oil’s suitability as a lubricant are the temperature and pressure dependence of its viscosity. The following formula shows the relationship between oil viscosity, pressure and temperature [46, 52].

\[ \eta = \eta_0 \exp(\gamma P - \alpha T) \]

where \( \eta_0 \) is the viscosity under normal atmospheric pressure, \( \gamma \) is the pressure coefficient and \( \alpha \) is the temperature coefficient.

2.3.6 Lubrication Additives

When base fluids of mineral oil are no longer sufficient to meet the high requirements of material process, with advances in modern additive technology, both the physical and chemical properties of the base oil can be modified; consequently, the lubrication performance will be improved. In industry, the lubrication additive is found to be the most worthwhile choice for improving the performance of lubricants.

Based on the purpose for their use, there are three main types of additives that can be identified, namely surface-protective additives, performance enhancement additives and
lubricant-protective additives. Examples of different types of additives are shown in Table 1.

The most common surface-protective additives are antiwear (AW)/extreme pressure (EP) additives which have engage in a chemical reaction with the metal surface to form a strong tribofilm in order to reduce friction wear and prevent scoring and seizure, anticorrosion and rust inhibitor which has preferential adsorption of polar compounds on metal surface and therefore prevent corrosion and rusting of metal parts; detergent and dispersant additives, where detergent provides soft-core to reverse micelle formation, solubilizes organic acids and neutralizes strong acids induced by blow-by gases and reduces lacquer, while dispersant keeps the surface free of deposits and contaminants dispersed in the lubricant, and disperses sludge, carbon and other precursors to prevent agglomeration by dispersing particles in fluid; and friction modifier additives, which act by forming thin layers on the friction surface due to physical adsorption in order to reduce friction.

Performance additives include pour point depressants enable lubricant to flow at low temperature and modify wax crystal formation to reduce interlocking, while viscosity index improver expand with increasing temperature to counteract oil thinning and reduce the rate of viscosity change with temperature.

Finally, commonly used lubricant-protective additives are antioxidants and antifoamants. Anti-oxidants retard oxidation decomposition, decompose peroxides and terminate radicals, thereby preventing or slowing down oxidation of the base at high
temperatures. On the other hand, *anti-foamants* prevent lubricants from forming a persistent foam and reduce surface tension. [63-65]

**Table 1** Examples of Commonly used additives

<table>
<thead>
<tr>
<th>Additive Type</th>
<th>Typical Compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Protective Additives</strong></td>
<td></td>
</tr>
<tr>
<td>Anti-wear (AW)/ extreme Pressure (EP)</td>
<td>Zinc dithiophosphates, organic phosphates, chlorine and sulfur compounds, sulfides and disulfides, crown ethers, calcium carbonate-benzoate hard-cors RMs</td>
</tr>
<tr>
<td>Anti-corrosion and rust inhibitor</td>
<td>Zinc dithiophosphates, sulfonic acids compounds, phosphoric acid derivatives, nitrogen compounds, fatty acid amides, carboxylic acid derivatives, Ca carbonate-benzenesulfonate hard-core RMs</td>
</tr>
<tr>
<td>Detergent and dispersant</td>
<td>Detergent: Sulfonates, phosphonates, phenates and salicylates, ash-free bases-calixarenes; Dispersant: Succinimides, succinate esters, Mannich bases and phosphorus compounds types, macroyclic bicyclic and polycyclic polyamines</td>
</tr>
<tr>
<td>Friction modifier</td>
<td>Fatty alcohol, fatty amines, amides phosphoric acid esters organometallic modifier, molybdenum compounds</td>
</tr>
<tr>
<td><strong>Performance additives</strong></td>
<td></td>
</tr>
<tr>
<td>Pour point depressant</td>
<td>Polymethacrylates, long-chain alkyl phenols, polyacrylamides</td>
</tr>
<tr>
<td>Viscosity index improver</td>
<td>Polysobutenes, polymethacrylates, olefin co-polymers, polyalkylstyremes</td>
</tr>
<tr>
<td><strong>Lubricant protective additives</strong></td>
<td></td>
</tr>
<tr>
<td>Anti-oxidant</td>
<td>Aromatic amines, hindered phenols, sulfurized phenols dithiophosphates, crown ethers</td>
</tr>
<tr>
<td>Anti-foamant</td>
<td>Silicone polymers, organic copolymers</td>
</tr>
</tbody>
</table>

In addition to the additives mentioned here, there are many more additives that could
be identified. Effective additive should be used alone or in combination for different applications and conditions. For example, in hydrodynamic lubrication, since the thickness of the lubricant film is important for friction control, viscosity index improvers are necessary to prevent an excessive decrease in film thickness with augmenting temperature. On the other hand, strong additive adsorption is needed for boundary regime or mixed regime to avoid direct metal-to-metal contact.

2.4 Short Summary of Literature Survey

The basic mechanism of cold rolling was first studied as a foundation for further study on cold rolling lubrication. The maximum amount of thickness reduction that can be achieved in a single rolling pass is mainly determined by the maximum roll-separating force and maximum torque, which are affected by reduction and the rolling material [6,8-10]. Friction plays an essential role in the cold rolling process, and directly affects the surface quality of the cold rolling product. Two main parameters have been found to affect friction, namely thickness reduction and rolling speed. In order to calculate the friction, the Coulomb Friction Law was studied [20]. The relationship between frictional stress and normal pressure introduced by the Coulomb Friction Law could be used in the calculation of the experimental results. Two common phenomena in cold rolling were also introduced. The first one was forward slip, defined as the material’s extension in length caused by reduction of thickness [21, 22]. The second was the temperature rise caused by material deformation and friction. The distribution of temperature rise was learned to be high at
interface and to decrease with depth of material [24, 25].

The main purpose of using lubricants in cold rolling process is to limit the high friction and reduce temperature in order to improve the surface quality. Three lubrication regimes were reviewed, as specifically boundary, hydrodynamic and mixed lubrication. The performance of lubrication is influenced by several factors, including rolling speed and level of reduction. Friction will decrease with an increase in rolling speed, while it will increase with thickness reduction. For different lubricants, the lubrication performance will be affected by the structure of lubricant and the viscosity. In order to improve the lubricants’ performance, additives have been introduced. Various types of lubricant additives have been studied, and it was shown that different lubricant additives can be applied for different purposes,
CHAPTER III.
DESIGN AND METHODOLOGY

3.1 Friction Measurement

The rolling process was simulated using a tribometer with a ball on disc configuration run with heat injection on the ball; this the setup is shown in Figure 14. The configuration was designed to fabricate and retrofit to the tribometer in order to characterize the thermo-mechanical properties of lubricants in a conventional way.

The disc samples were tightly secured in the tribometer, as shown in Figure 14(a). The disc was then set to rotate counter-clockwise at a speed of 30 rpm, which was equivalent to a sliding speed of 0.039 m/s. This speed was chosen because it can maintain a boundary lubrication regime which this research is focused at.

The schematic of coefficient of friction measurement tribometer is depicted in Figure 15. Force is applied by an adjusted spring to a stainless steel beam that connects the support bearing to the ball holder. The thickness in the middle of the stainless steel beam has been reduced to make it sensitive to the bend caused by frictional force. The installed cantilever load cell is used to detect the change in frictional force at a frequency of 8 times per second. Since heat is applied to the ball during the experiments, holes have been drilled on the steel beam for heat dissipation.

In the experiment, lubricant was introduced using a 3 ml syringe, acting as an oil reservoir; its configuration can be observed in Figure 14(b). It was first filled with 3 ml of
the appropriate lubricant type and the tip of the syringe needle was held at the center of the
disc to provide uniform oil distribution on the disc surface via centrifugal force.

3.2 Experimental Material

The cylindrical disc samples were made from AA 3003 and AA5182 aluminum alloys
provided by Novelis Global Technology Centre; details of their composition are given in
Table 2. The aluminum alloy samples were cut into cylinders of 25 mm diameter and 12
mm thickness. The base of each disc was polished with grinding papers ranging up to
P1500 grit which is 12.6μm. An AISI 52100 steel bearing ball of 10 mm in diameter was
used as the counter-face. The balls and the discs were ultrasonically cleaned in acetone
before each test. The material of both the rotating disk and the ball are commonly used in
the aluminum industry.

Five kinds of lubricant base oils were selected for this research, specifically, Normal
Paraffin (NP), Hydro treated Kerosene (HK), White Oil (WO), Hydrocarbon Fluid (HF)
and Iso-Paraffin (IP). For each lubricant base oil, two kinds of additives were employed:
namely fatty alcohol and fatty acid; these were added at two concentrations, specifically
0.022% and 2.2%, for the improvement of lubrication performance. Details on the
combinations of lubricant base oils and additives are shown in Table 5.

3.3 Electrical Resistance Measurement

Electrical resistance between the rotating aluminum alloy disc and steel ball were
monitored during each experiment to identify and failure in lubrication. The standard
electrical resistance between disc and ball was set up as 100 ohm; as lubrication failure begins, the buffer for metal-to-metal contact decreases, and this is displayed as a drop in electrical resistance.

3.4 Temperature Measurement

The effect of temperature change during the cold rolling process on lubricants’ performance was of interest for this project; therefore, heat was applied by the cartridge heater to the steel ball up to 250°C. The thermocouple’s tip was also attached at the ball holder though in contact with the steel ball directly. After each experiment, the tribometer was cooled to room temperature before the next experiment was conducted. The temperature at which lubrication starts to fail is referred to as the critical temperature ($T_c$) of lubrication.

3.5 Data Analysis Method

As discussed previously, data on frictional force, electrical resistance of rotating disc and temperature were monitored and transmitted to a data acquisition unit (InstruNet acquisition unit), which then sent the data to a computer. According to the data collected by cantilever load cell, frictional force was confirmed; in addition the applied normal force to the rotating disc is known, and coefficient of friction could be calculated based on Coulomb Friction Law. To intuitively observe all parameters, coefficient of friction, temperature and electrical resistance were then be combined in an excel sheet and plotted in one graph. This schematic can be seen in Figure 16. For each lubricant at least three
experiments were carried out to obtain repeatable results for average calculation; typical experimental results will be given in the results chapter 4.

3.6 Experimental Plane

The research in this project was divided into three stages. In the first stage, aluminum alloy AA3003 was studied with two kinds of lubricant: Normal Paraffin and Hydro-treated Kerosene with or without additives under two loads: namely 4.05N and 7.8N. According to the results from Stage One, 7.8N load was chosen for second stage since the higher load seems more effectively to show lubrication’s failure. Therefore, at the second stage all lubricants (Normal Paraffin, Hydro-treated Kerosene, Hydrocarbon Fluid, White Oil and Iso-Paraffin with or without additives) were tested under 7.8N load and again with AA3003. At the last stage, the effect on lubrication of changing the rolling material was studied by switching the material from AA3003 to AA5182; here the same experimental condition were used as in second stage. The experimental plane is illustrated in Figure 17 for better understanding.
Figure 14 Experimental Set-up for the tribometer: (a) showing ball on disc configuration

(b) showing oil dispensing mechanism
Figure 15 Schematic of Coefficient of Friction Measurement Tribometer

Figure 16 Schematic diagram of the friction measurement system
Figure 17 Illustration of Experimental Plane

Table 2 Composition of SAE 52100 steel, wt-%

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<tr>
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<th>Mn</th>
<th>Si</th>
<th>S</th>
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Table 3 Composition of alloy under investigation, wt-% (AA3003)

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Table 4 Composition of alloy under investigation, wt-% (AA 5182)

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### Table 5 Combinations of lubricant base oils and additives

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<th>Additive Concentration</th>
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<td>N/A (Neat Oil)</td>
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</tr>
<tr>
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</tr>
<tr>
<td></td>
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CHAPTER IV.
RESULTS

4.1 Results of AA3003 under 4.05N

Aluminum Alloy AA3003 was first tested under 4.05N with two base oils: Normal Paraffin and Hydro-treated Kerosene with or without additives. The combined experimental data were plotted into one graph and the experimental data on lubricants showing the failure of lubrication will be illustrated. The detailed coefficient of friction and critical temperature results are shown in Table 6.

Experimental results of Normal Paraffin and Hydro-treated Kerosene base oil without additives showed high coefficient of friction and low critical temperature of lubrication, the typical experimental results are shown in Figure 18 and 19, respectively. For Normal Paraffin base oil, the average coefficient of friction was 0.5660, and lubrication failed as soon as the experiment started at room temperature (25°C). For Hydro-treated Kerosene, the electrical resistance dropped at 149.84°C, indicating the failure of lubrication, and the coefficient of friction increased sharply after the failure of lubrication; the average coefficient of friction was calculated to be 0.5225. For base oil, Hydro-treated Kerosene exhibited better performance at 4.05N.

With additive applied, the performance of both Normal Paraffin and Hydro-treated Kerosene’s obviously improved. For Normal Paraffin with 0.022% concentration fatty acid additive, the average coefficient of friction decreased to 0.287 and no obvious sign of
lubrication failure was detected. Hydro-treated Kerosene with the same additive also did not show evidence of lubrication failure and the average coefficient of friction was calculated to be 0.223. The improvement of lubrication performance is similar for both lubricant base oils with 0.022% concentration of fatty alcohol additive. The average coefficient of friction for Normal Paraffin with 0.022% fatty alcohol added is 0.2512 and 0.2240 for Hydro-treated Kerosene. For both lubricants there was no evidence of lubrication failure. With lower additive concentration, Hydro-treated Kerosene has a better performance than Normal Paraffin. Figure 20 shows the experimental results for Normal Paraffin with 2.2% fatty acid additive; the average coefficient of friction was decreased to 0.2110 with the increase in additive concentration. However, the critical temperature of lubrication dropped to 150.76℃. The average coefficient of friction for Hydro-treated Kerosene with 2.2% fatty acid was measured to be 0.2661, and lubrication failed at 155.08℃ (shown in Figure 21). For Normal Paraffin and Hydro-treated Kerosene with 2.2% fatty alcohol, the average coefficient of friction were calculated as 0.2260 and 0.2673 respectively. No failure of lubrication was detected for either lubricant. At a higher additive concentration of 2.2%, Normal Paraffin exhibited better performance.

4.2 Results of AA3003 under 7.8N

All lubricants (Normal Paraffin, Hydro-treated Kerosene, Hydrocarbon Fluid, White Oil and Iso-Paraffin) with or without additives (Fatty Acid and Fatty Alcohol) were tested under 7.8N, since higher load was expected to show the failure of lubrication more
effectively for comparison. WYKO image was used to measure the wear track width which is shown in Table 7 with other experimental results. Both the plots with combined experimental data and WYKO images for all lubricants will be displayed in illustration.

For neat oil, Normal Paraffin showed the highest average coefficient of friction of 1.4755; lubrication failed as soon as steel ball and rotating disc came in contact at room temperature (25°C). The WYKO image indicated the widest wear track of 1.137mm, and the result is illustrated in Figure 22. In Figure 23 shows that the electrical resistance of Hydro-treated Kerosene dropped at the beginning of experiment, the average COF was calculated to be 0.9340 and wear track width was 0.913mm. The experimental result for Hydrocarbon Fluid is plotted in Figure 24. Although no obvious drop of electrical resistance was observed, a jump of coefficient of friction was detected at around 106°C repeatedly for three tests, which is regarded as evidence of lubrication failure; the average COF was measured to be 0.7880 and the wear track width was 0.927mm. For neat White Oil, as shown in Figure 25, the result of electrical resistance first dropped at 66.57°C, followed by a sharp increase of COF; the calculated average COF was the lowest of base oils at 0.5181, and wear track width was 1.084mm. Failure of Iso-Paraffin (IP) neat oil was observed at 53.19°C with the drop of electrical resistance displayed in Figure 26. Average coefficient of friction of IP base oil was 0.6610. A comparison of base oils will be conducted below.

With the addition of 0.022% fatty acid, the lubricants’ performance improved in terms
of critical temperature; the same trend was observed at 4.05N. No obvious drop in electrical resistance was observed for any of the lubricants, which indicates that the critical temperature for all lubricants is 250°C. Other than the critical temperature, additive also increased lubricants’ anti-friction performance except for White Oil. With the 0.022% fatty acid additive, the average COF for Normal Paraffin decreased to 0.6654 with a wear track width of 0.858mm (Figure 27); for Hydro-treated Kerosene (Figure 28) the average COF dropped to 0.6606 with wear track width of 0.927; Hydrocarbon Fluid showed lowest average COF at 0.4769 and the smallest wear track width of 0.756mm (Figure 29). Furthermore, Iso-Paraffin had an average COF at 0.4937 and a wear track width of 0.950mm (Figure 30). Finally, as mentioned above, only White Oil (Figure 31) showed an increasing trend in coefficient of friction with 0.022% fatty acid, shifting from 0.5181 to 0.5923. The wear track width was measured as 0.950mm.

With fatty alcohol additive concentration of 0.022%, Normal Paraffin does not show signs of lubrication failure in Figure 32; the average coefficient of friction was calculated to be the highest again, at 0.7667, and the wear track width was 0.953mm. For the Hydro-treated Kerosene, no sign of lubrication failure was showed in Figure 33 neither, the average coefficient was 0.7520 and the wear track width was 0.956mm. For Hydrocarbon Fluid showed in Figure 34, electrical resistance exhibited a short-lived drop at the beginning of the experiment, but soon recovered. The recovery of electrical resistance may have been caused by the re-formation of oxidation at the contact surface. At around 60°C
electrical resistance dropped again formally until the end of the experiment; the coefficient of friction was calculated to be 0.5170 and wear track width is measured as 0.887mm. Figure 35 shows the experimental results for White Oil with 0.022% fatty alcohol additive; the average coefficient of friction was computed to be 0.5856, with no failure of lubrication detected. Furthermore, the wear track width was 0.858mm. Figure 36 shows results for Iso-Paraffin with 0.022% alcohol additive of average COF at 0.4900 without any failure of lubrication, and the wear track width was 0.844mm. Both the coefficient of friction and wear track width of Iso-Paraffin was the lowest of all lubes at this concentration.

Figure 37 shows results of Normal Paraffin with 2.2% concentration of fatty acid additive, lubrication failed at the beginning of experiment, average coefficient of friction was calculated to be 0.6218 and measured wear track width is 0.802mm. Figure 38 shows results of Hydro-treated Kerosene with the same additive, lubrication also failed at the beginning of experiment, average coefficient of friction was calculated to be 0.7094 and measured wear track width was 0.861mm. For Hydrocarbon Fluid with 2.2% fatty acid additive showed in Figure 39, electrical resistance started to drop at the beginning and increased with the procedure of experiment till the end. Average COF of 0.4880 and the smallest wear track of 0.726mm were observed. For White Oil with 2.2% fatty acid in Figure 40, no lubrication failure was detected according to the electrical resistance and average COF was 0.6093 and the wear track was 0.940mm wide. In Figure 41, Iso-Paraffin showed formally failure of lubrication at 148.61°C with several shorted-lived drops at
previous. The average COF was calculated to be the lowest at 0.3895 and the wear track width was 0.867mm.

With a 2.2% concentration of fatty alcohol additive, Normal Paraffin and Hydro-treated Kerosene both showed low critical temperature for lubrication failure at room temperature of about 25°C. The detailed experimental results for these lubricants are given in Figures 42 and 43, respectively, with a calculated average coefficient of friction of 0.5937 for Normal Paraffin which exhibited the largest drop compared to the base oil, and 0.6584 for Hydro-treated Kerosene. Figure 44 shows the experimental results of Hydrocarbon Fluid with 2.2% fatty alcohol. Lubrication failed at 63.71°C when a sudden drop in electrical resistance occurred; the average COF was 0.5038, and the wear track width was 0.789mm. White Oil with 2.2% fatty alcohol showed high critical temperature of lubrication failure as illustrated in Figure 45, with no evidence of a drop in electrical resistance until drop till the end of the experiment. The calculated average COF was 0.6396 and wear track width was 0.746mm wide. For Iso-Paraffin with 2.2% fatty alcohol (Figure 46), it performed best for anti-friction purpose with calculated average COF of 0.4393; however, the electrical resistance result indicated that lubrication failed at the beginning of experiments.

4.3 Results of AA5182 under 7.8N

In the third stage of experiments material was switched from AA3003 to AA5182 for the same experimental condition which is 7.8N load and heat applied up to 250°C. As for
AA3003, all experimental data were plotted into one graph for identification of lubrication failure and coefficient of friction calculation. Due limitations of space, the plots will not be displayed one by one, but the detailed experimental results are shown in Table 8.

For neat oil, Normal Paraffin again showed the highest average coefficient of friction among all lubricants, at 1.1093 and lubrication failed as soon as the experiment started at 25°C. For Hydro-treated Kerosene, the drop in electrical resistance indicated a low critical temperature of lubrication at room temperature and average COF was calculated to be 0.8550. Observation of experimental result of Hydrocarbon Fluid indicated that electrical resistance dropped at 186.7°C and average coefficient of friction was 0.6559. For neat White Oil, electrical resistance dropped as soon as the experiment started, the calculated average COF was 0.5403. Failure of Iso-Paraffin neat oil was observed at 84.04°C, with an average coefficient of friction of 0.5872.

Similar to the previous results for AA3003 under 4.05N and 7.8N loads, almost all lubricants with 0.022% fatty acid additive showed high critical temperature of lubrication at 250°C; the exception to this was White Oil with AA5182. The average COF for Normal Paraffin was calculated to be 0.6238, for Hydro-treated Kerosene was 0.5692, for Hydrocarbon Fluid is 0.4907 and 0.5013 for Iso-Paraffin. As mentioned above, White Oil was an exception for both critical temperature and average friction coefficient. The lubrication of White Oil with 0.022% fatty acid failed at 89.52°C and the average COF increased to 0.5974 from 0.5403.
With 0.022% concentration of fatty alcohol additive, no obvious drop in electrical resistance was detected for Normal Paraffin and the average coefficient of friction was calculated to be 0.8529. Neither was any sign of lubrication failure was observed for Hydro treated Kerosene, and the average coefficient was 0.6749. For Hydrocarbon Fluid, electrical resistance dropped at 104℃ and coefficient of friction was calculated to be 0.5556. The average coefficient of friction of White Oil with 0.022% fatty alcohol was computed to be 0.5830 with no failure of lubrication detected. Results for Iso-Paraffin with 0.022% alcohol additive indicated an average COF at 0.6099 without any failure of lubrication.

With 2.2% fatty acid additive, Normal Paraffin, Hydro-treated Kerosene and Hydrocarbon Fluid all showed low critical temperature of lubrication at 25℃. The average COF results were calculated to be 0.5685 for Normal Paraffin, 0.6876 for Hydro-treated Kerosene and 0.4213 for Hydrocarbon Fluid. For White Oil with 2.2% fatty acid, no lubrication failure was detected according to the electrical resistance and average COF was 0.3684. For Iso-Paraffin, lubrication failed at 71.21℃ with average COF of 0.3895.

With 2.2% concentration of fatty alcohol additive, Normal Paraffin and Hydro-treated Kerosene both showed low critical temperature for lubrication failure at room temperature of about 25℃. The average coefficient of friction for Normal Paraffin was calculated to be 0.6074, while it was 0.6584 for Hydro-treated Kerosene. Lubrication of Hydrocarbon Fluid with 2.2% fatty alcohol failed at 152.73℃ and the average coefficient of friction was
White Oil and Iso-Paraffin both showed high critical temperature with 2.2% fatty alcohol additive. The average coefficient of friction for White Oil was 0.6033, while for Iso-Paraffin the result was 0.3787.

### Table 6 Experimental Results of AA3003 under 4.05N

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<tr>
<th>Oil Name</th>
<th>Additive</th>
<th>Additive Concentration (%)</th>
<th>Load (N)</th>
<th>Coefficient of Friction</th>
<th>Critical Temperature (°C)</th>
<th>Standard Deviation of COF</th>
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**Figure 18** Typical experimental results of Normal Paraffin base oil against AA3003 under 4.05N with heat applied to 250℃

**Figure 19** Typical experimental results of Hydro-treated Kerosene base oil against AA3003 under 4.05N with heat applied to 250℃
Figure 20 Typical experimental results of Normal Paraffin with 2.2% concentration fatty acid additive against AA3003 under 4.05N with heat applied to 250°C

Figure 21 Typical experimental results of Hydro-treated Kerosene with 2.2% concentration fatty acid additive against AA3003 under 4.05N with heat applied to 250°C
Figure 22 (a) Typical experimental results of Normal Paraffin base oil against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 23 (a) Typical experimental results of Hydro-treated Kerosene base oil against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 24 (a) Typical experimental results of Hydrocarbon Fluid base oil against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 25 (a) Typical experimental results of White Oil base oil against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 26 (a) Typical experimental results of Iso-Paraffin base oil against AA3003 under 7.8N with heat applied to 250°C  (b) WYKO image of wear track
Figure 27 (a) Typical experimental results of Normal Paraffin with 0.022% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 28 (a) Typical experimental results of Hydro-treated Kerosene with 0.022% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 29 (a) Typical experimental results of Hydrocarbon Fluid with 0.022% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 30 (a) Typical experimental results of White Oil with 0.022% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 31 (a) Typical experimental results of Iso-Paraffin with 0.022% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 32 (a) Typical experimental results of Normal Paraffin with 0.022% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 33 (a) Typical experimental results of Hydro-treated Kerosene with 0.022% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C  (b) WYKO image of wear track
Figure 34 (a) Typical experimental results of Hydrocarbon Fluid with 0.022% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 35 (a) Typical experimental results of White Oil with 0.022% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250℃ (b) WYKO image of wear track.
Figure 36 (a) Typical experimental results of Iso-Paraffin with 0.022% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 37 (a) Typical experimental results of Normal Paraffin with 2.2% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C  (b) WYKO image of wear track
Figure 38 (a) Typical experimental results of Hydro-treated Kerosene with 2.2% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 39 (a) Typical experimental results of Hydrocarbon Fluid with 2.2% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 40 (a) Typical experimental results of White Oil with 2.2% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 41 (a) Typical experimental results of Iso-Paraffin with 2.2% fatty acid additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 42 (a) Typical experimental results of Normal Paraffin with 2.2% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 43 (a) Typical experimental results of Hydro-treated Kerosene with 2.2% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 44 (a) Typical experimental results of Hydrocarbon Fluid with 2.2% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 45 (a) Typical experimental results of White Oil with 2.2% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
Figure 46 (a) Typical experimental results of Iso-Paraffin with 2.2% fatty alcohol additive against AA3003 under 7.8N with heat applied to 250°C (b) WYKO image of wear track
CHAPTER V.
DISCUSSION

5.1 Effect of Load

For Normal Paraffin and Hydro-treated Kerosene with or without additives, experiments were carried under loads of both 4.05N and 7.8N. The detailed experimental data are listed in Tables 6 and 7. In Figures 47 and 48, the coefficient of friction results for both applied loads are plotted. There is an obvious trend for coefficient of friction which increased with the increase of applied load from 4.05N to 7.8N. This increasing trend was observed for both Normal Paraffin and Hydro-treated Kerosene and is independent of additive type and also the additive concentration.

By looking at the effect of load on critical temperature of lubrication, as shown in Figures 49 and 50, critical temperature decreased with the increase in applied load for most lubricants. For Normal Paraffin with the lower concentration additive at 0.022%, the difference in load did not affect the critical temperature; however, with the additive concentration increased to 2.2%, the effect of load could be observed. For Hydro-treated Kerosene, only with 0.022% fatty acid additive was not affected by the increase in load. Thus, an increase in load can accelerate the failure of lubrication, but for different lubricants, such the acceleration may not occur.

5.2 Comparison of Base Oils

Figure 51 gives the comparison of base oils, comprising results of coefficient for
friction, wear track width and critical temperature of lubrication failure. The first suggestion that can be made based on the results shown in Figure 83 is that Normal Paraffin has exhibits the worst performance as base oil because it has the highest coefficient of friction and wear track width, as well as the lowest critical temperature. White Oil base oil had the lowest coefficient of friction, however, its wear track width was the second highest. Although Hydro-treated Kerosene had the lowest wear track width, its critical temperature was the lowest and the COF value was the second highest. This means that either Hydrocarbon Fluid or Iso-Paraffin can be selected as the best oil. First, the wear track widths for both base oil is similar. Iso-Paraffin has a lower coefficient of friction of 0.6610, while that of Hydrocarbon Fluid which is 0.78880. Nevertheless, Hydrocarbon Fluid base oil has a higher critical temperature, which is almost double that of Iso-Paraffin. Thus far, which is the best base oil between the two is unclear. The only conclusion that can be made in the comparison of the base oils is that Normal Paraffin exhibited the worst performance among all the tested lubricants.

5.3 Influence of Additive Application

After looking at the performance of different base oils, the influence of additive application on the lubricants’ performance is studied. First, the addition of additive improved the lubricants’ anti-friction property. This observation was confirmed for all lubricants except for White Oil. For the lubricants’ anti-wear property, the additives also showed obvious improvement on Normal Paraffin, Hydrocarbon Fluid and White Oil. With
the application of additive, Normal Paraffin exhibited the most remarkable improvement in terms of both anti-friction and anti-wear performance. For Normal Paraffin base oil, that had the highest coefficient of friction and the widest wear track. With 2.2% concentration of fatty alcohol additive, the coefficient of friction results dropped 0.8818 and the wear track width reduced 0.344mm. In Figure 22 (b) and (c), both the WYKO and SEM images shows severe and wide wear on the sliding track; in comparison, Figure 42 (b) and (c) shows Normal Paraffin with 2.2% fatty alcohol added, and the wear track surface shows a much smoother finish. For White Oil, additive unexpectedly increased the coefficient of friction. For White Oil, with 2.2% fatty alcohol, the coefficient of friction had the highest growth among all additives. However, the wear track width was reduced by about 0.338mm, representing the largest drop in all White Oil lubricants. A comparison of the surface finish is provided in Figure 25 for base oil and Figure 45 for lubricant with 2.2% fatty alcohol applied. For Hydro-treated Kerosene, the low additive concentration of 0.022% did not improved the wear track surface, but it did improve lubricant’s anti-friction performance.

In conclusion, with the application of an additive to base oils, at least one property of the lubricant is improved, whether this is the anti-friction or the anti-wear property.

5.4 Effect of Additive Type

Above, the influence of additive application was studied; since there were two types of additives used in the experiments, the effect of switching additive typed will be discussed in the present section. In Figure 54 to 57, the coefficient of friction results and
wear track width for lubricants with additives are shown with the base oil’s results as reference. The plots are separated by additive concentration in order to compare the difference according to additive types. In Figure 54, with the additive at 0.022% concentration, Normal Paraffin, Hydro-treated Kerosene and Hydrocarbon Fluid reacted better with fatty acid for a lower coefficient of friction than with fatty alcohol; on the other hand, White Oil and Iso-Paraffin reacted better with fatty alcohol. The lowest coefficient of friction result was achieved using Hydrocarbon Fluid with fatty acid. In Figure 55, with additive at 2.2% concentration, Normal Paraffin and Hydro-treated Kerosene reacted better to fatty alcohol than of fatty acid, while Hydrocarbon Fluid, White Oil and Iso-Paraffin reacted better to fatty acid. At this concentration, the lowest coefficient of friction was achieved by Iso-Paraffin with fatty acid. The lowest coefficient of friction at 0.022% and 2.2% concentrations were both achieved via fatty acid. For Hydrocarbon Fluid, fatty acid was the better additive for anti-friction purposes at both additive concentrations; for the other lubricants the better additive alternated with the increase in additive concentration.

Figure 56 and 57 show the results of wear track width separated by additive concentration. With additive at 0.022% concentration, Normal Paraffin, Hydro-treated Kerosene and Hydrocarbon Fluid reacted better with fatty acid, on the other hand, White Oil and Iso-Paraffin reacted better with fatty alcohol. The smallest wear track width was achieved by Hydrocarbon Fluid with fatty acid. For 2.2% additive concentration, only Hydrocarbon reacted better with fatty acid while others all reacted better with fatty alcohol.
The smallest wear track with at 2.2% concentration was observed for Normal Paraffin with fatty alcohol.

Combining the observation from both coefficient of friction and wear track width results, fatty acid is the best additive for hydrocarbon fluid for both anti-friction and anti-wear purposes, no matter what the additive concentration is. For the other lubricants, the performance is not affected by the additive type directly; with the change in additive concentration the appropriate additive type also changes.

5.5 Effect of Additive Concentration

In Figures 58 to 61, the coefficient of friction results and wear track widths for lubricants with additives are divided in to two sections by additive type to compare the effect of additive concentration. Figure 58 shows the experimental results for lubricants with fatty acid additive. With fatty acid additive concentration increased from 0.022% to 2.2%, only Normal Paraffin and Iso-Paraffin show improvement in terms of anti-friction performance. For comparison with the additive concentration shown in Figure 59 for fatty alcohol, all lubricants’ performance improved with the increase of additive concentration except for White Oil.

In Figures 60 and 61, wear track width results show the effect of additive concentration. For both additives shown in both figures, wear track width decreased with the increase of additive concentration. For fatty alcohol additive displayed in Figure 61, the decrease in wear track width is more obvious.
Combining the observation from both coefficient of friction and wear track width results several conclusions can be made related to the effect of additive concentration. First, lubricants’ anti-wear property is more sensitive to changes of additive concentration; a decreasing trend of wear track width could be predicted for an increase in additive concentration, regardless of additive type. For lubricants’ anti-friction properties, only fatty alcohol shows a decrease of coefficient of friction while additive concentration increase which indicates that the lubricant’s anti-friction property is influenced by both additive type and concentration. The second observation is also confirmed in the discussion of the effect of additive type.

5.6 Comparison between AA3003 and AA5182

Figures 62 to 65 show the comparison of coefficient of friction trend between AA3003 and AA5182. For lubricant base oils both materials show the same rank of lubricant. For additive concentration at 0.022%, the difference is evident in White Oil with fatty acid. For AA3003, the coefficient of friction result for White Oil with 0.022% fatty acid was higher than the result for base oil; however, the opposite trend was exhibited for AA5182. For additive concentration of 2.2%, the same trend appeared for White Oil with fatty acid additive. This phenomenon indicates that, for White Oil with fatty acid additive on AA5182, a different reaction may occur than with AA3003. Further study of this chemical mechanism is needed to explain this occurrence. Besides the White Oil with fatty acid additive, other lubricants showed the same trend for AA3003 and AA5182, which indicates
that coefficient of friction result is not sensitive to the change in material and the same lubrication mechanism could be expected for both materials.

5.7 Surface Analysis

By reviewing all tested lubricants with additives applied, Iso-Paraffin with 2.2% acid showed the lowest coefficient of friction (0.3895), Hydrocarbon Fluid with 0.022% acid showed the lowest coefficient of friction at 0.022% additive concentration (0.4769) and Normal Paraffin with 0.022% alcohol showed the highest coefficient of friction (0.7667). Surface morphology of such samples have been studied in order to the difference in performance. One suggestion is that lubricant with better performance is supposed to have a thicker or stronger protective layer forming on the sample surface which could have a higher concentration of protective elements such as carbon. In order to eliminate the effect of severe wear caused by long sliding distance or high temperature, the lubricants mentioned above have been tested again under the same load but only with 5 turns sliding distance and no heat injection. EDS mapping was taken on the finished sample for detecting of carbon and oxygen. Figure 66 (a) shows the carbon concentration detected by EDS on an unlubricated sample, rare carbon could be observed. Meanwhile, Figure 66 (b) shows the oxygen concentration on the unlubricated sample, where it was found that oxygen was mainly concentrated along the sliding track, which indicates that the oxidation layer was wiped off during the experimental process. Figures 67 to 69 show the EDS mapping for Iso-Praffin with 2.2% acid, Hydrotreated Fluid with 0.022% acid and Normal Paraffin with
0.022% alcohol, respectively. Through the observation of the carbon and oxygen on the surface, it can be concluded that with lubricant applied, a carbon and oxidation layer forms uniformly along the surface for protection. By comparing the numerical concentration of carbon in the lubricated samples, it was found that for IP+2.2% acid it is 8.147%, for HF+0.022% acid is 6.47% and for NP+0.022% alcohol it is 4.86%. Although the numerical concentration is not accurate, it shows a reliable trend base on the same conditions for each lubricant. The ranking of carbon concentration follows the rank of coefficient of friction which confirms the prediction that the lubricant with better performance will have a higher concentration of protective elements formed on surface by lubrication.
Figure 47 Effect of Load on coefficient of friction for Normal Paraffin

Figure 48 Effect of load coefficient of friction for Hydro-treated Kerosene
**Figure 49** Effect of load on critical temperature for Normal Paraffin

**Figure 50** Effect of load on critical temperature for Hydro-treated Kerosene
Figure 51 Comparison of base oils

Figure 52 Influence of additive on coefficient of friction
Figure 53 Influence of additive on wear track width

Figure 54 Comparison of additives on coefficient of friction at 0.022% concentration
Figure 55 Comparison of additives on coefficient of friction at 2.2% concentration

Figure 56 Comparison of additives on wear track width at 0.022% concentration
Figure 57 Comparison of additives on wear track width at 2.2% concentration

Figure 58 Comparison of additives concentration on coefficient of friction for fatty acid
Figure 59 Comparison of additives concentration on coefficient of friction for fatty alcohol

Figure 60 Comparison of additives concentration on wear track width for fatty acid
Figure 61 Comparison of additives concentration on wear track width for fatty alcohol

Figure 62 Coefficient of friction trend of AA3003 at 0.022% additive concentration
Figure 63 Coefficient of friction trend of AA5182 at 0.022% additive concentration

Figure 64 Coefficient of friction trend of AA3003 at 2.2% additive concentration
Figure 65 Coefficient of friction trend of AA5182 at 2.2% additive concentration

Figure 66 EDS Mapping on surface of unlubricated AA3003 sample under 7.8N without heat slide for 5 turns (a) carbon indicated by red (b) oxygen indicated by green
Figure 67 EDS Mapping on surface of Iso-Paraffin+2.2% Alcohol against AA3003 sample under 7.8N without heat slide for 5 turns (a) carbon indicated by red -8.147% (b) oxygen indicated by green

Figure 68 EDS Mapping on surface of Hydrocarbon Fluid+0.022% Alcohol against AA3003 sample under 7.8N without heat slide for 5 turns (a) carbon indicated by red -6.47% (b) oxygen indicated by green
Figure 69 EDS Mapping on surface of Normal Paraffin+0.022% Alcohol against AA3003 sample under 7.8N without heat slide for 5 turns (a) carbon indicated by red - 4.86% (b) oxygen indicated by green
CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS

Performance of lubricants and additives was studied through simulated ball on disc experiments working under boundary lubrication regime with aluminum alloys, AA3003 and AA5182. Experiments covered five lubricant base oils (Normal Paraffin, Hydro-treated Kerosene, Hydrocarbon Fluid, White Oil and Iso-Paraffin) with two additives (fatty acid and fatty alcohol) at two additive concentrations (0.022% and 2.2%). Comparison of lubricants was carried out based on the measurements of coefficient of friction, surface damage and lubrication failure temperature. The results can be summarized as follows:

1) Change of applied load was confirmed to influence lubrication directly. With the increase in applied load, coefficient of friction was observed to increase, regardless of the additive applied. For certain additives and concentrations, the lubrication failure temperature will not be impacted by increase in applied load.

2) Comparison of base oils showed that Normal Paraffin is the worst base oil for the measurement of COF and wear track width, while White Oil achieved the lowest coefficient of friction, and Hydro-treated Kerosene showed best anti-wear performance. Meanwhile Iso-Paraffin and Hydrocarbon Fluid exhibited even performance.

3) The addition of additives improved the lubricants’ anti-friction property. This observation was confirmed for all lubricants except for White Oil.
4) Not all lubricants showed improvement in anti-wear performance; only Normal Paraffin, Hydrocarbon Fluid and White Oil showed decreased wear track width with all additives.

5) The performance of lubricants was not directly affected by the additive type; with the change in additive concentration the appropriate additive type also changed.

6) Fatty acid is the best additive for hydrocarbon fluid for both anti-friction and anti-wear purpose no matter what the additive concentration.

7) Lubricants’ anti-wear property is more sensitive to the change in additive concentration; a decreasing trend in wear track width could be predicted for an increase in additive concentration, regardless of the additive type.

8) For lubricants’ anti-friction properties, only fatty alcohol showed a decrease of coefficient of friction while additive concentration increased, which indicates that the lubricant’s anti-friction property is influenced by both additive type and concentration.

9) With lower additive concentration, higher lubrication critical temperature was observed.

10) Generally, coefficient of friction is insensitive to changes in aluminum material.

11) EDS mapping indicated that lubricants form a protective layer on aluminum surface that contains rich carbon and oxygen. With higher concentration of such protective elements formed on the surface, better performance of lubricants could be expected.
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NAME: Li Fang
PLACE OF BIRTH: Dalian, China
YEAR OF BIRTH: 1988
EDUCATION:
Bachelor of Applied Science, General Mechanical Engineering
University of Windsor
Windsor, ON, Canada
2007-2011
Master of Applied Science Engineering Materials
University of Windsor
Windsor, ON, Canada
2011-2013