THE EFFECT OF MICROPITS AND BIO-LUBRICANTS ON ALUMINUM COLD WORK EXTRUSION PERFORMANCES

NURUL AINI BINTI MOHD. AHYAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

DECEMBER 2016

To my beloved husband and two adorable princess,

and for sure, to my lovely parents

ACKNOWLEDGEMENT

First of all, Alhamdulillah and Syukur to Allah S.W.T for giving me the opportunity and strength to stay in the turf war of Ph.D. I would like to express my special appreciation and thanks to my advisor Professor Dr. Syahrullail bin Samion for being a tremendous mentor for me. I would like to thank you for encouraging my research and for allowing me to grow as a doctoral researcher. Your advice on this research as well as on my career has been priceless. I would also like to thank my co-supervisor, Dr. Fazila binti Zawawi, my lab members, Dr. Norzahir, Dr. Razak, Dr. Nuraliza, Farhanah, Afifah and everyone for helping me even at hardship. I also want to thank you for your brilliant ideas and suggestions, thanks to all of you. I would especially like to thank technicians at Mechanic Fluids Laboratory, Jannah and Mr. Sahlan. All of you have been there to support me when I conducted an experiments and collected data for my Ph.D. thesis.

A special thanks to my family. Words cannot express how grateful I am to my mother, father, mother-in law, father-in-law, brothers, and sisters and for all of the sacrifices that you've made on my behalf. Your prayer for me was what sustained me thus far. I would also like to thank all of my friends who supported me in writing, and incented me to strive towards my goal. At the end I would like express appreciation to my beloved husband and my two princess who spent sleepless nights with and was always my support in the moments when there was no one to answer my queries. Alhamdulillah. Barakallah.

ABSTRACT

Many attempts have been made to replace mineral oil-based with biodegradable lubricant such as vegetable oil in order to reduce environmental impacts. Palm oil based is available in abundance in Malaysia at cheaper price compared to mineral based lubricant but reports on using this oil as an alternative lubricant is hardly found especially in cold metal forming applications. This study aims to evaluate and compare the tribological performances between two different types of palm oil-based and mineral oil-based lubricants using modified die surface geometry (with and without micropits at top and bottom positions, sharp T45 and radius R45 taper angle) during cold extrusion process. All extrusion process parameters were fixed during experiments, i.e. deformation ratio (3:1), speed range (8.1-8.3 mm/s), piston displacement stroke (40 mm), micropit depth (30 μm), diameter (600 μm), distance (1 mm) and 27 percent of area density. Top position of micropit exhibits the lowest friction and extrusion load with finer billet surface in all trials. It is also found that palm stearin (PS) performs better than palm kernel (PK) in terms of extrusion load and billet surface roughness. Similar results also obtained in paraffinic mineral oils experiments where VG460 outperforms VG95. Higher viscosity in both type of lubricants is the main reason that contributes to this performance. Comparing between PS and VG460, the performance of mineral oil-based is still superior than palm oil-based but the difference is very marginal in terms of extrusion load and billet surface roughness. The achievable extrusion load and billet surface finish under PS lubricant are 48.9 kN and 0.11μm respectively. The optimum tribological performance of mineral oil-based VG460 over palm oil-based PS is attributed to the large viscosity difference between VG460 (1347.60 mm^2/s) and the PS (48.29 mm^2/s). Since there is only marginal difference in tribological performance, it can be concluded that palm oil-based has a great potential to be developed further as an environmental friendly lubricant for replacing mineral oil-based type.

ABSTRAK

Terdapat beberapa kajian telah dijalankan untuk menggantikan minyak mineral dengan pelincir yang mesra alam seperti minyak sayuran untuk mengurangkan kesan alam sekitar. Minyak kelapa sawit boleh diperoleh di Malaysia pada harga yang lebih murah berbanding minyak mineral, namun kajian mengenainya untuk digunakan sebagai pelincir alternatif jarang dijumpai terutamanya dalam proses pembentukan logam. Oleh yang demikian, kajian ini dijalankan untuk menilai dan membandingkan prestasi tribologi antara dua jenis pelincir yang diubahsuai geometri permukaan acuannya (dengan dan tanpa micropit di posisi atas dan bawah, sudut bucu tajam T45 dan sudut jejari tirus R45) semasa proses penyemperitan sejuk. Semua parameter proses penyemperitan adalah malar semasa eksperimen, iaitu nisbah ubah bentuk penyemperitan (3:1), kelajuan (8.1-8.3 mm/s), strok anjakan omboh (40 mm), kedalaman micropit (30 μm), diameter (600 μm), jarak (1 mm) dan 27 peratus ketumpatan kawasan. Posisi atas micropit menunjukkan geseran dan penyemperitan beban yang paling rendah dengan permukaan billet yang lebih halus. Kajian juga mendapati bahawa palm stearin (PS) mempamerkan keputusan yang lebih baik berbanding palm kernel (PK) dari segi beban penyemperitan dan kekasaran permukaan billet. Keputusan yang sama juga diperoleh dalam minyak mineral dengan prestasi VG460 melebihi VG95. Kadar kelikatan tinggi dalam kedua-dua jenis minyak pelincir adalah sebab utama yang menyumbang kepada prestasi ini. Minyak VG460 dilihat lebih unggul daripada PS dengan perbezaan yang sangat kecil dari segi beban penyemperitan dan kekasaran permukaan billet. Oleh sebab terdapat hanya perbezaan kecil dalam prestasi tribologi, dapatlah disimpulkan bahawa minyak berasaskan sawit mempunyai potensi yang besar untuk dibangunkan sebagai pelincir mesra alam bagi menggantikan minyak pelincir berasaskan mineral.

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LIST OF SYMBOLS

ρ	-	Density
Ψ	-	Flow pattern
ε	-	Effective strain
$\dot{\varepsilon}$	-	Effective strain rate
Ra	-	Arithmetic mean surface roughness

LIST OF ABBREVIATIONS

PMO	-	Additive free paraffinic mineral oil
RBD	-	Refined, Bleached and Deodorized
VG	-	Viscosity grade
CEO	-	Commercial extrusion oil
PK	-	Refined, bleached and deodorized palm kernel
PS	-	Refined, bleached and deodorized palm stearin
VG95	-	Additive free paraffinic mineral oil viscosity grade 95
VG460	-	Additive free paraffinic mineral oil viscosity grade 460
T45	-	Taper die with 45° chamfered at die half angle
R45	-	Taper die with 5 mm radius at die half angle
NA	-	Non-micropits taper die
P1	-	Micropits taper die pattern 1
P2	-	Micropits taper die pattern 2
LVDT	-	Linear variable differential transducer
ASTM	-	American Society for testing and Materials
JIS	-	Japanese Industrial Standards

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Metal forming is a wide characterization of a number of metal working processes that deform metal stock to create useful parts. It includes extrusion, forging, cold heading, spinning, roll forming and stamping. Forming operates on the materials science principle of plastic deformation, where the physical shape of a material is permanently deformed.

One of the most popular types of metal forming is an extrusion. Extrusion is a bulk-forming process or generally used to produce a long and straight aluminum profile from a cylindrical billet. The extrusion dies that determines the shape and dimensions of the profile are the core of the process since product quality, extrusion productivity and scrap rate depend strongly on the performance of the die. Aluminum extrusions are used in the building industry such as window and door frames, building structures, roofing and curtain walling (European Aluminium Association, 2016) shipping and offshore industry, furniture, and in automotive, aerospace applications and rail vehicles (BOAL Aluminium, 2016).

The surface modification of a tool is one of the important tribological parameters for controlling the metal forming process. The pits, which are also known as oil pockets (Lesniak and Libura, 2007; Gang *et al.*, 2008), cavities (Schubert *et al.*, 2011), dimples (Huang *et al.*, 2012) or micro-pits (Norhayati *et al.*, 2012;

Syahrullail *et al.*, 2014), may reduce friction in two ways: by providing a lift as micro-hydrodynamic bearings (Nilsson *et al.*, 2004), and by acting as a lubricant reservoir (Koszela *et al.*, 2010; Ing *et al.*, 2012). They have also been successfully applied to mechanical seals that expand in real life. Modified surfaces can provide traps for wear debris in dry contacts subjected to fretting wear resistance and can almost double the fretting fatigue life (Koszela *et al.*, 2007).

Surface modification, which also widely known as surface texturing, is among the cheap solutions with small modifications of die ((Tønder, 2011) compared to tool change, hot works and others. In the extrusion die design, pits are increasingly added to balance the metal flow. The balance of metal flow is particularly important for multiple cavity dies or sections with varying thicknesses in order to maintain a uniform velocity profile across the face of the die. Thus, it minimizes the distortion of the extrudate (Li *et al.*, 2003).

No disseminated rules regarding pocket die design are detailed in the available literature, but it remains under consideration as proprietary knowledge among die manufacturers and extrusion companies. Thus far, a number of studies have highlighted the factors associated with maintaining the lubricant flow. Galda *et al.* (2009) examined the influence of surface texture on sliding lubrication by means of a Stribeck curve. The study showed that proper shape and dimensions, as well as suitable area density of oil pockets, could improve the friction characteristics of the sliding pairs in comparison to non-textured surfaces.

The research by Norhayati *et al.* (2012) also found that micro-pits on the taper die sliding surface are able to control the frictional constraint compared to those surfaces without micro-pits. Furthermore, Sudeep *et al.* (2013) concluded that there are significant reductions in the coefficient of friction and vibration at the lubricated concentrated points of contact in surface texturing.

In recent years, a few authors have begun to perform numerical analyses and to compare them with experimental investigations. In 2011 and 2012, Reizer *et al.*

revealed that the results of the simulation of worn surface topography on a block-on-ring tester matched the results obtained from experimental methods. In a study conducted by Ramesh *et al.* (2013), the trends obtained in the experiments matched well with the simulations, thus leading to the conclusion that the texture with 20-30% of area density and 100-200 μm of textured pin width showed a good friction performance.

In order to operate the metal forming process, some amount of lubricant need to be applied on the sliding surfaces. As cited in a studies by Batchelor and Stachowiak (1995), Křupka and Hartl (2007) and Tauviqirrahman *et al.* (2013), the main function of lubrication is to control wear and friction at the interface between interacting surfaces. Mineral oil is the most commonly used industrial lubricant. It is petroleum-based and is used in applications with moderate temperature requirements. There have been several studies in the literature reporting typical applications of mineral oils such as for cosmetics (DiNardo, 2005), bearings (Křupka and Hartl, 2007), and gears (Lawal and Bolaji, 2008; Zhang *et al.*, 2013).

More recently, the application has been studied and extended to various metal forming operations. For example, Caminaga *et al.* (2006) conducted a series of trials in which he mixed a mineral oil with additives and three semi-synthetic oils without chlorine in the cold extrusion process. Cold forging is one of the most popular metal forming processes to be investigated. Jung *et al.* (2008) carried out investigations into a number of mineral oils with different viscosity grades in order to learn the effects of surface roughness on cold forging. By employing the cold extrusion process, Hafis *et al.* (2013) used varying amounts of the additive-free ISO460-paraffinic mineral oil to explore the effect of the lubricant quantity on friction.

1.2 Problem Statement

To date, mineral oils are still widely used as metal forming lubricants. However, the environmental and toxicity issues of these lubricants as well as their rising cost related to a global shortage has led to renewed interest in the development of environmental friendly lubricants (Hsien, 2015).

The presence of lubricant from the die surface is crucial, particularly in cold work forming processes. It has been reported that higher viscosity of the lubricant is one of the important physical properties that able to reduce wear problem (Andersson *et al.,* 2007; Quinchia *et al.,* 2010). It is believed that thicker layer tends to stay longer at the contact surfaces due to the fact that thick lubrication film is generated throughout the forming process (Tang *et al.*, 2013). By indenting several micropits on the sliding surface of the die, the lubricant mass can be maintained throughout the forming process, and therefore the die life can be extended (Bay *et al.,* 2010; Praveen and Geeta, 2013). In the past micropits studies, different types of mineral oils in metal forming processes were evaluated together with varying their micropits physical parameters. There were contradictory results reported in these works in terms of the selection of shape (Qiu and Khonsari, 2011), the diameter (Galda *et al.,* 2009), the length (Koszela *et al.,* 2010), the depth (Huang *et al.,* 2012) and the area density (Sudeep *et al.,* 2013) of micropits. Though the position of micropits on the die surface was studied, however, there was no comparison made by the researchers this far in terms of tribological performances using both mineral oil-based and vegetable oil-based lubricants.

Among the vegetable oil-based, rapeseed oil, canola oil, olive oil and soybean oil are the most potential alternative lubricants for metal forming processes (Gawrilow, 2003; Shashidhara and Jayaram, 2010; Yang *et al.,* 2014; Zareh-desari and Davoodi, 2016). It was reported that rapeseed oil has the longest hydrocarbon chain length and the lowest degree of unsaturation that may contribute to the stronger absorption for lower frictional factor (Zareh-desari and Davoodi, 2016). Hydrocarbon chain in vegetable oil produces saturated fatty acids that may protect the two contacting surfaces from tribological failures including severe wear and friction (Rustan and Drevon, 2005). The main drawback of these oils is very expensive, i.e up to 788.77 USD, 936.99 USD and 4,315.40 USD per metric ton for rapeseed, canola and olive oils respectively (www.indexmundi.com, 2016).

An alternative to these vegetable oils is palm oil where its properties are very similar to rapeseed oil. Palm oil is not only cheaper at the global market price (686 USD per metric ton) but it also has in abundant in Malaysia and not fully exploited as a lubricant. Palm oil can be categorised into several types such as palm olein, palm stearin, palm kernel and palm fatty acid (MPOB, 2016). From these categories, only palm stearin and palm kernel oils have shown great potentials to be used in engineering applications as a lubricant due to their unique properties i.e longer hydrocarbon chain length and among the lowest degree of unsaturation levels (Zareh-desari and Davoodi, 2016). However, there is limited study on these oils as an alternative lubricant in metal forming process.

1.3 Objectives

The main aim of this study is to evaluate the effectiveness of vegetable based against mineral based oils as a lubricant during the cold metal forming process using modified die surface. The specific objectives of this study were as follows:

1. To evaluate the effects of micropits and its position on die surface to the tribological performances during the cold work extrusion process.

2. To compare the tribological performances of palm oil-based and mineral oil-based lubricants during the cold work extrusion process.

1.4 Scopes

The study was conducted within the following limits:

1. The work piece material used for the billet was pure aluminium (AA1100). The average surface roughness of the machined billet was fixed at Ra = 1.46 μm.

2. The cold work forward plane strain extrusion process was conducted at a deformation ratio 3:1, speed range between 8.1 to 8.3 mm/s and with piston displacement stroke of 40 mm.

3. Two types of palm oil-based lubricant were tested, i.e RBD palm kernel and RBD palm stearin. Their performances were compared with three types of mineral oil-based lubricant, i.e commercial extrusion oil, additive free paraffinic mineral oil VG95 and VG460.

4. Two types of taper die with 45 degrees were used in the experiment, i.e die with sharp taper angle and die with 5 mm radius taper angle. The surface roughness of taper die was controlled within 0.04 μm.

5. Measurements of tribological performances were limited to extrusion load, a surface roughness of extruded billet, resultant of relative sliding velocity and effective strain distribution.

6. Micropits design parameters were fixed in both lubricant's environment as follows; depth = 30 μm, diameter = 600 μm, the distance between micropits = 1 mm and 22% of the area density.

1.5 Significance of Study

Sustainability issues are becoming a major concern to world community and it affects all sectors including manufacturing industries. A huge pressure has been put to reduce or even eliminate the use of non-renewable resources such as mineral based oils since it causes pollution to environment and health problem to industrial workers. An alternative to these lubricants is vegetable oil-based. This study evaluates the potential of using palm oil-based lubricants in a cold work extrusion process. The findings from this study may open new opportunities for palm oil to be used as lubricants in many engineering applications that not only environmentally friendly, biodegradable and renewable, but it is also expected to be much cheaper as it is available in abundance in Malaysia. Furthermore, the applications of vegetable oil as a lubricant in manufacturing processes such as cutting, machining and forming could have a great potential in reducing health problems on industrial workers as opposed to mineral oil-based lubricants.

1.6 Thesis Organization

This study consists of five chapters. Chapter 1 introduces the general background of the study, problem statement, objectives, scopes and significance of the study and ends with the organization of thesis. Chapter 2 deals with a review of the literature and relevant research associated with the problem applied in this study. It explains the important of surface modification on taper die sliding contact surfaces and the significant of alternating metal forming lubricant into vegetable oil-based. Chapter 3 provides the description of research methodology and procedures used for data collection and analysis to be carried out. Chapter 4 describes the results and discussion of the collected data as well as the analysis of the results. Finally, Chapter 5 summarizes the research's findings in the form of conclusions and recommendations for future works.

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