FRICTION AND WEAR BEHAVIOUR OF ALUMINIUM CHROMIUM NITRIDE COATING AND PALM OIL METHYL ESTER LUBRICATION

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UMS
UNIVERSITI MALAYSIA SABAH

THESIS SUBMITTED IN FULFILLMENT FOR THE DEGREE OF MASTER OF ENGINEERING

SCHOOL OF ENGINEERING AND INFORMATION TECHNOLOGY
UNIVERSITI MALAYSIA SABAH
2013

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DEGREE : **MASTER OF ENGINEERING**

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ACKNOWLEDGEMENT

First and foremost I would like to glorify The Almighty Lord for His grace and rich blessings.

A Master Degree is designed to be the sole contribution of one individual. Even so, there are many people who have been of great help to me over the last two years. I would like to acknowledge them. Special thanks to my wife, parents and family members for their continuous prayers and support. They are the main motivation that drives my life endeavours.

I wish to express my deepest gratitude and appreciation to my supervisor, Assoc. Prof. Dr. Willey Liew Yun Hsien for his support, advices, encouragements, discussions throughout the research and he contributed significantly to the success of this work. His teachings and experiences shared were invaluable and someone whom I look up to for qualities of a good researcher. Most importantly, he has been instrumental in improving my writing skills.

I would like to extend my appreciation to my co-supervisor, Mr. Mohd Azlan bin Ismail, for his support, suggestions and discussions and for all his help. Also, thanks to Mr. John Paulus for his assistance in carrying out the machining tests as well as to Mr. Afifi Nasir and Mr. Farhan Johar of Institute of Tropical Biology and Conservation (ITBC) and Mr Azli Sulid of School of International Tropical Forestry, UMS for their assistance in surface analysis using the scanning electron microscope (SEM) and to all the technical staff in Mechanical Engineering Department of School of Engineering and Information Technology (SEIT), UMS, for their technical support. I would also like to acknowledge the financial support of the Ministry of Higher Education of Malaysia (MyBrain15 Program) and the research funding from the Fundamental Research Grant Scheme (FRG0215-TK1/2010 and FRG0210-TK1/2010).

I would finally like to thank all my friends and New Life group members of Kota Kinabalu Seventh-Day Adventist Church, for their friendship and prayers.

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ABSTRACT

FRICTION AND WEAR BEHAVIOUR OF ALUMINIUM CHROMIUM NITRIDE COATING AND PALM OIL METHYL ESTER LUBRICATION

This thesis investigates the effectiveness of POME (palm oil methyl ester) as lubricant additive using four-ball and milling tests. Examination on the friction and wear behaviour of AlCrN coating and its comparison to that of TiN coating by using the ball-on-disk and reciprocating tests is also done. Comparative study on the coatings in air and vacuum environment was aimed to provide important insight on the effect of oxidation on the friction behaviour of the coatings. Other important factors such as load, sliding velocity and temperature effects on the coatings were also investigated. Compared to flood lubrication, small quantity of mineral oil sprayed in mist form was more effective in reducing the coating delamination and delaying the occurrence of tool cracking and fracture in the milling tests. The effectiveness of mineral oil in suppressing coating delamination and delaying the occurrence of cracking and fracture could be enhanced by the presence of POME. The mechanism by which the POME suppresses these wear mechanisms could be explained by the results obtained in the four-ball wear tests. The presence of POME brought a reduction in the friction coefficient, severity of welding of the asperities and wear scar, and increased the critical load for welding to occur. In the ball-on-disk tests carried out in vacuum, (i) TiN gave lower COF (coefficient of friction) than AlCrN, showing that the surface of TiN was more lubricous, and (ii) the COF of both coatings were lower than that produced in air. In ambient air, AlCrN gave lower COF than TiN with high wear debris retention on the sliding interface due to the effect of oxidation. In the reciprocating tests, increasing the temperature from room temperature to 150 °C resulted in a reduction in the COF. Higher nominal load resulted in lower COF while higher speed resulted in higher COF. The presented results have shown promising use of POME as additive component in oil lubricant as well as provided fresh insight on the superior oxidation behaviour of AlCrN.

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ABSTRAK

Tesis ini mengkaji keberkesanan POME ('Palm Oil Methyl Ester') sebagai bahan tambah dalam pelincir minyak mineral dengan menggunakan ujian Four-Ball dan ujian pemotongan logam secara kisaran, serta menguji sifat geseran dan kehausan bahan penyalut PVD AlCrN, dan perbandingannya dengan bahan penyalut TiN dengan menggunakan ujian Ball-on-disk dan Reciprocating, juga dijalankan. Kajian perbandingan terhadap bahan-bahan penyalut ini dalam udara dan vakum adalah bertujuan untuk memberikan pengertian yang penting terhadap kesan pengoksidaan ke atas sifat geseran bahan-bahan penyalut tersebut. Faktor-faktor lain seperti kesan daya, halaju geseran dan suhu juga dikaji. Jika dibandingkan dengan pelincir bendalir cecair, penggunaan sedikit kuantiti pelincir minyak mineral yang disembur dalam bentuk kabus adalah lebih berkesan dalam mengurangkan kikisan pada penyalut mata alat serta menangguhkan pembentukan retak dan rekahan. Keberkesanan pelincir minyak mineral ini boleh ditingkatkan dengan kehadiran POME. Mekanisme perlindungan terhadap retak dan rekahan yang dibawa oleh POME dijelaskan daripada data ujikaji yang diperolehi daripada ujian Four-ball yang menunjukkan penyusutan kepada nilai pekali geseran, fenomena kimpalan pada permukaan kasar, dan kesan kehausan serta meningkatkan daya kritikal untuk kejadian kimpalan sesama berlaku. Ujian Ball-on-disk dalam keadaan vakum menunjukkan (i) TiN menghasilkan pekali geseran yang lebih rendah, menunjukkan yang permukaan TiN adalah lebih licin, dan (ii) pekali gesearan untuk kedua-dua bahan penyalut adalah lebih rendah berbanding dengan yang dihasilkan dalam udara. Ujian dalam udara menunjukkan yang AlCrN menghasilkan nilai pekali geseran yang lebih rendah berbanding TiN disebabkan oleh kesan pengoksidaan yang lebih efektif. Dalam ujian Reciprocating, peningkatan suhu ke 150 °C dari suhu bilik menyebabkan penyusutan nilai pekali geseran. Peningkatan nilai daya juga menghasilkan nilai pekali geseran yang rendah sementara peningkatan halaju menghasilkan nilai pekali geseran yang lebih tinggi. Keseluruhan data ujikaji yang diperolehi telah menunjukkan keputusan yang memberangsangkan bagi penggunaan POME sebagai komponen dalam bahan pelincir minyak untuk aplikasi pemotongan logam serta memberikan pengertian yang baru berkenaan dengan keunggulan sifat pengoksidaan bahan penyalut AlCrN.

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the reciprocating tests under various sliding frequency and nominal load of 5 N at temperatures of (a) 25°C and (b) 150°C.

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LIST OF SYMBOLS

σ	Normal stress	[Pa]
$\varnothing$	Diameter	[mm]
D	Tool diameter	[mm]
F	Frictional force	[N]
k	Shear flow stress of the chip	[-]
μ	Coefficient of friction	[-]
N	Rotational speed	[RPM]
η	Viscosity	[cSt]
τ	Shear stress	[Pa]
V_B	Flank Wear	[mm]
v	Sliding speed	[m/min]
W	Load	[N]

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LIST OF ABBREVIATIONS

Al	Aluminium
Al_2O_3	Aluminium Oxide, Alumina
AlCrN	Aluminium Chromium Nitride
AlCrSiN	Aluminium Chromium Silicon Nitride
ASTM	American Society for Testing and Materials
AW	Anti-Wear
BS	British Standard
CCD	Charge-coupled device
COF	Coefficient of friction
Cr_2O_3	Chromium Oxide
Cu	Copper
DIN	Deutsches Institut fur Normung ("German Industry Standard")
DLC	Diamond-like carbon
EP	Extreme Pressure
HRC	Rockwell C Hardness
HV	Vickers Hardness
IP	Institute of Petroleum
IR	Infrared
LVDT	Linear Variable Displacement Transducer
MPa	Mega Pascal
POME	Palm Oil Methyl Ester
PVD	Physical Vapour Deposition
RPM	Rotation per minute
SDBL	Shell Dormus BL
SEM	Scanning Electron Microscopy/ Microscope
TiAIN	Titanium Aluminium Nitride
TiN	Titanium Nitride
TiO_2	Titanium Oxide
Si	Silicon
vol%	volume percentage
ZDDP	Zinc Dialkyl Dithiophosphate

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CHAPTER 1

INTRODUCTION

1.1 Background of Palm Oil Product Diversification in Malaysia

Malaysia is often viewed as a country that evolved from dependence on tin and rubber to export-oriented manufacturing dominated by electronics assembly, but the commodity that actually made the country to the technological frontier is palm oil. Electronic firms are specialized in labour-intensive assembly based on technology imported from their parent plants overseas and engaged in contract activities without extending their reach to higher-value-added segments. In contrast, palm oil firms are an integral part of value chains in which Malaysian companies play a significant role. Palm oil is now a major pillar of Malaysia's industrialization and it holds a considerable lead in global markets (Rasiah, 2006).

To ensure a sustainable growth of palm oil industry in the country and remains competitive in the global market, palm oil industry in Malaysia in recent years has been shifting to palm oil product diversification from a conventional commercial cultivation as its main export focus until more years to come. In this regard, the country's Third Industrial Master Plan (IMP3) supports and reinforces this focus (MITI, 2006). Research and development (R&D) effort, therefore, became more critical; in particular, to explore and develop new palm oil based products for higher value added in the palm oil chain.

Currently, about 80 percent of current world palm oil output is consumed for food use, but non-food uses has increasingly become important, contributing to greater demand and higher prices for palm oil (Teoh, 2010). The usage in soap, detergents and surfactants, cosmetics, pharmaceuticals and some household and industrial products has been growing because of the move away from petroleum-based products and hence opens up non-traditional demand for palm oils. Recently, it has been promoted as a biofuel feedstock in compression ignition engines (diesel engines) with the production of palm oil methyl ester (POME).

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In various investigations, there are sufficient evidences that POME presence as additive in the mineral oil (as base oil) has improved the lubrication performance and majority of the work was done in biodiesel engine application (Masjuki and Maleque, 1996a, 1996b, 1997; Maleque et. al, 2000; Kalam and Masjuki, 2002). POME has an ester functional group which is a classic example of additive in lubricants for metalworking fluids (Canter, 2007); hence it has the desired qualities required for lubrication purposes. The aforementioned quality that POME had for lubrication purposes is further reviewed in Section 2.2.6. In addition to the country's diversification effort on palm oil products, a more widespread research on the potential use of palm oil methyl ester for industrial lubricant in machining application would be beneficial. This strategic thinking forms the foundation in part of this thesis research which aims at understanding the effect of POME as a lubricant additive in enhancing the lubricating performance in machining process, particularly in reducing the tool wear that consequently would improve the industrial cost-saving and output by increasing production throughput time through reductions of machine breakdowns and tool change.

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1.2 Problem Statement

Additives perform a wide variety of functions and represent an important and necessary contribution to the overall properties and performance of the lubricants. Without additives, even the best base fluids are deficient in some features. Hence, the performance of a finished lubricant depends collectively on the base oil, additives and formulation.

In lubricated machining, the source of lubricant additives is large, and yet, new additives continue to be developed. This will help future lubricants meet the increasingly demanding conditions that manufacturers require. Furthermore, environmental issues will require more environmental-friendly additive design to meet the global regulations driven by global warming and ethical corporate policies and government strategies to encourage biodegradable materials. When the fluid has to be environmentally acceptable, the formulation has to be ashless (not containing metals) and only environmentally harmless additives can be used. While the first requirement is relatively easy to achieve, as broad variety of ashless additives exists in the market, the latter can be a problem, as currently there are only a few additives available, in which full ecotoxicological data have been assessed and disclosed from additive suppliers (Habereder et. al, 2009).

The environmental and toxicity issues of petroleum-based oils as well as their rising cost related to a global shortage and remediation efforts due to its poor biodegradability have led to renewed interest in the development of environmental friendly oils based on vegetable oils as lubricants and industrial fluids. Petroleum-based oils are, for the most part, non-polar, whereas triglycerides of vegetable oil are highly polar thus they have an affinity to metal and protect the surface. Owing to this character, vegetable oils and their derivatives are ideally suited for lubrication applications. Conversely, their low thermo-oxidation stability is the main limitation (Fox and Stachowiak, 2007). Lubricant formulations for more environmentally benign are, therefore, being developed based on the benefits and limitations of vegetable oils.

In dry machining, selection of hard and high fracture strength tool coating is often used to reduce friction between the microcontact. In such instances, the mechanical properties of the coating control the frictional response. However, the high temperature involved during machining process has become the major problem of the use of various hard coatings due to formation of oxide layer on the surface due to oxidation phenomena which could modify its mechanical properties, hence limiting their performance.

Metal oxidation process is a chemical reaction involving oxygen and metal ions at the near-surface region, hence it occur in the presence of air or oxygen. Normally, oxide layer formed will act as protective role as it reduces metal loss rates by reducing and eliminating metal-to-metal contact. The oxide layer formed will also act as a diffusion barrier to resist further oxidation process. Extensive oxidation at elevated temperatures may embrittle the oxide layer, which increases the susceptibility to the cracking of the oxide layer. If this barrier fails to suppress further oxidation process, mass oxygen transportation to the inside of the film

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would occur that could cause detrimental effects to the subsurface structure, which leads to film breakdown (Barshilia et al., 2005).

Oxidation process is usually controlled by the rate of diffusion of these reactants across the oxide layer, and hence, is very dependent on surface temperature. The difference in oxidation kinetics results to much more rapid movement of oxygen or metal ions across the oxide film at high temperatures, thus increasing the oxidation rate. Hence, oxidation phenomena in sliding tribological conditions deserved further understanding, particularly in machining application whereby the temperature at the cutting edge of coated cutting tools may exceed 1000 °C (Gekonde and Subramaniam, 2002). The oxidation resistance behaviour of AlCrN is well known (Lin et al., 2008; Reiter et al., 2005; Kawate et al., 2003; Banakh et al., 2003) but the intrinsic characteristics of sliding wear behaviour of AlCrN is not well understood. Hence, it was determined to carry out tests in high vacuum under dry sliding conditions due to the great effects the atmospheric composition and pressure has on sliding wear.

1.3 Motivation and Contribution

A conventional machining process utilizes cutting fluids to provide the lubrication and cooling, as well as chip removal. With the increasing cost associated with the procurement and disposal of cutting fluids as well as the long-term effects of cutting fluids disposal into the environment are becoming increasingly evident and have raised much concern about the use of cutting fluids in manufacturing industry. Research has also corroborated the health hazards on manufacturing workers who come in contact with the cutting fluids (Shokrani et al., 2012; Kipling, 1977). There are three logical methods to tackle this issue, (i) reduce the consumption of cutting fluid, (ii) use of a more environmental friendly lubricant, in which vegetable-based oil is typically used, and (iii) to totally eliminate the use of cutting fluid through the deposition of advanced coating material on the cutting tool. With regards to the first and second methods, this thesis assesses viability of the use of palm-based oil as lubricant additive in machining, applied in mist form. As for the third method, this thesis explores the intrinsic characteristics of dry sliding wear of AlCrN, and provides important insight of the oxidation behaviour of the coating by doing comparative study in ambient air and in high vacuum. In addition, the effect of sliding parameters such as load, sliding velocity and ambient temperature in atmospheric condition on the tribo-oxidation behaviour of AlCrN was also examined. To the best of my knowledge, there was no published work related to the present study (i.e. utilizing POME for the use in machining application and tribological investigation of AlCrN in high vacuum environment) in the scientific world at the moment when this work was started.

1.4 Research Aim and Objectives

The aim of this work is divided into two major parts. Firstly, to experimentally investigate the effect of POME, a vegetable-based oil derived from palm oil, as lubricant additive in suppressing the wear of cutting tool in machining operation (i.e. low-speed milling). The experimental result obtained in milling test is to be correlated with the result obtained from a laboratory bench test via a four-ball tribotester, whereby the mechanism by which the tool wear reduction brought about by the presence of POME would be understood.

The second part is to experimentally examine the dry sliding friction behaviour of AlCrN by performing comparative test in atmospheric air and high vacuum using a ball-on-disk tribotester. The experimental result obtained in AlCrN is compared with TiN, a more conventional type of coating. Comparative study in air and in high vacuum environment was aimed to provide important insight on the effect of oxidation on the friction behaviour of AlCrN and TiN. Other important factors such as load, sliding velocity and temperature effects were also investigated using a reciprocating tribotester.

1.5 Scope of Thesis

Chapter 1 presents the introduction which covers backgrounds and motivations of the current study. It also reviews the aim and objectives of this work and outlines the details and the scope of the thesis.

Chapter 2 brings a theoretical foundation of the study and provides critical review of the important characteristics involved in the tribological aspects in dry

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and lubricated machining operation. This includes the use of coated cutting tools as well as the use of lubricant additives and the mechanism of which the friction reduction is involved in contacting metals, particularly at the microcontact between cutting tool and workpiece is reviewed. Previous research work and important factors those are relevant to the friction and wear reduction of metals are outlined in this chapter.

Chapter 3 describes the foundation theory, materials, experimental apparatus and methodologies used throughout this work.

Chapter 4 presents the experimental result from the four-ball wear and machining tests. Further discussions on the result obtained through comparisons between the lubrication provided by oil with the presence of POME with conventional lubricant samples were given.

Chapter 5 presents the experimental result from the ball-on-disk and reciprocating tests on AlCrN and TiN coatings under dry sliding conditions. The results pertaining to their dry sliding tribological behaviour is compared and factors affecting them are discussed.

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Chapter 6 summarises the work and conclusions drawn from the thesis, and suggestions provided for future studies.