



**Faculty of Mechanical Engineering**

**EXPERIMENTAL INVESTIGATION ON THE INFLUENCE OF DLC  
COATING ON THE WEAR BEHAVIOUR OF HELICAL GEAR**

**Abdul Hakim bin Abdul Hamid**

**Master of Science in Mechanical Engineering**

**2019**

**EXPERIMENTAL INVESTIGATION ON THE INFLUENCE OF DLC COATING  
ON THE WEAR BEHAVIOUR OF HELICAL GEAR**

**ABDUL HAKIM BIN ABDUL HAMID**

**A thesis submitted  
in fulfillment of the requirements for the degree of  
Master of Science in Mechanical Engineering**

**Faculty of Mechanical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2019**

## DECLARATION

I declare that this thesis entitled “Experimental Investigation on the Influence of DLC Coating on the Wear Behaviour of Helical Gear” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : .....

Name : Abdul Hakim bin Abdul Hamid

Date : .....

## **APPROVAL**

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : .....

Supervisor Name : Dr Reduan bin Mat Dan

Date : .....

## **DEDICATION**

To my loving parents and siblings

## ABSTRACT

The purpose of this research is to investigate the wear behaviour of amorphous hydrogenated carbon (a-C:H) coating deposited on the helical gears through wear debris analysis and oil analysis. The a-C:H coating were selected from various diamond-like carbon (DLC) coating variant using Pareto optimal analysis and weighted decision matrix, where it is deemed the most suitable for helical gear testing in this study. Helical gears were tested on a power recirculating test rig with constant loads of 100 Nm and speed of 1000 rpm. The tests were conducted for  $9 \times 10^6$  cycles or an initial pitting of 1% covering the surface of the teeth. Samplings were obtained for approximately 60 ml of the lubricant for every  $3.6 \times 10^5$  cycles which were then analysed through oil analysis which includes wear debris analysis as well as particle counting. The results revealed that the a-C:H coated gear reduces the particle generation by a factor of 3.11 as compared to the baseline testing. However, a-C:H does not improve the condition of the lubricant where in the uncoated gear, the lubricant oxidation increases per cycles while the coated gear is at a lower value while the viscosity of uncoated gear lubricant decreases per cycle as compared to the coated gear. Gear tooth image analysis reveals that the test reaches a micro-pitting stage with no visible pitting yet observed due to carburization of the base gear. However, a-C:H gears had a reduction in micro-pitting formation as compared to the uncoated gear yet peeling of the coating occurs. This suggest an extension of the life of the gear through the application of a-C:H coating is achievable.

## ABSTRAK

*Tujuan kajian ini adalah untuk menyiasat prestasi amorfus terhidrogen karbon (a-C:H) yang didepositkan di atas gear heliks dengan melalui analisis serpihan haus dan analisis minyak. Salutan a-C:H telah dipilih dari pelbagai variasi salutan karbon bersifat berlian (DLC) menggunakan analisis optimum Pareto dan matriks keputusan berat, di mana ia dianggap paling sesuai untuk ujian gear heliks dalam kajian ini. Gear heliks diuji pada rig ujian rim kuasa dengan beban berterusan sebanyak 100 Nm dan kelajuan 1000 rpm. Ujian ini dijalankan untuk  $9 \times 10^6$  kitaran atau pengesanan lubang pada permukaan gear di skala mikro dengan 1% meliputi permukaan gigi. Pensampelan diperolehi untuk kira-kira 60 ml pelincir untuk setiap kitaran  $3.6 \times 10^5$  yang kemudiannya dianalisis melalui analisis minyak yang termasuk analisis serpihan pakai serta pengiraan zarah. Hasilnya menunjukkan bahawa gear bersalut a-C:H mengurangkan penjanaan zarah dengan faktor 3.11 berbanding dengan gear tanpa salutan. Walau bagaimanapun, a-C:H tidak mempengaruhi keadaan pelincir di mana hasil kajian gear tanpa salutan menunjukkan pengoksidaan meningkat setiap kitaran manakala gear bersalut menunjukkan hasil yang sebaliknya, manakala kelikatan pelincir gear yang tidak bersalut berkurangan setiap kitaran berbanding dengan gear bersalut. Analisa imej gear gigi mendedahkan bahawa ujian itu mencapai peringkat pembentukan lubang pada skala mikro kerana karburisasi gear asas. Walau bagaimanapun, gear a-C: H mempunyai pengurangan pembentukan lubang pada skala mikro berbanding dengan gear yang tidak bersalut tetapi pengelupasan salutan berlaku. Ini menunjukkan bahawa pemanjangan jangka hayat gear melalui penggunaan salutan a-C:H dapat dicapai.*

## ACKNOWLEDGEMENTS

Advertently, I would like to express my sincerest gratitude to those whom are involved in the completion of this thesis, especially to my supervisor Dr. Reduan Mat Dan from the Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka (UTeM) who've given guidance as well as teaching me the value of being highly independent.

Additionally, I would also keen on extending my deepest gratitude to those involved in the technical aspects of the research, in particular towards Mrs. Hidayah, Mr. Azhar and Mr. Johardi, the Assistant Engineer from various laboratories of the Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka. An apology from the bottom of my heart is given to them for all the childish whims that they have to put up with throughout this journey.

A million of gratitudes are dedicated to those important to me, especially to Miss Fadrah Hanim whom have contributed towards the completion of this thesis individually and directly. Thine tiring aid and support shalt be remembered for eternity.

True acknowledgements are dedicated to my loving parents and siblings for the continuous support morally. Thank you for raising me to be a determined and stoical individual which is the ultimate criteria for the realization of this project.



## TABLE OF CONTENTS

	PAGE
<b>DECLARATION</b>	
<b>APPROVAL</b>	
<b>DEDICATION</b>	
<b>ABSTRACT</b>	i
<b>ABSTRAK</b>	ii
<b>ACKNOWLEDGEMENTS</b>	iii
<b>TABLE OF CONTENTS</b>	iv
<b>LIST OF TABLES</b>	viii
<b>LIST OF FIGURES</b>	viii
<b>LIST OF APPENDICES</b>	Error!
Bookmark not defined.	
<b>LIST OF ABBREVIATIONS</b>	xiv
<b>LIST OF SYMBOLS</b>	xiv
<b>LIST OF PUBLICATIONS</b>	xvi
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Research background	1
1.2 Problem statement	2
1.3 Research objectives	3
1.4 Research scopes	3
1.5 Thesis structure	4
<b>2. LITERATURE REVIEW</b>	<b>5</b>
2.1 Introduction	5
2.2 Surface technology	5
2.2.1 Diamond like carbon coating	6
2.2.2 DLC specification	8
2.3 Material selection	9
2.3.1 Pareto optimal analysis	10
2.3.2 Weighted decision matrix (WDM)	11
2.4 Gear wear	13
2.4.1 Gear wear mechanism	13
2.4.2 Gear flank stress influencing wear debris generation	15
2.4.3 Gear failure mode	17
2.4.4 Gear fatigue testing	18
2.5 Machine condition monitoring	21
2.5.1 Wear debris analysis and generation	21
2.5.2 Oil analysis	27
2.5.2.1 Viscosity	28
2.6 Wear debris classification	28
2.6.1 Particle morphology	29
2.6.1.1 Particle size	30
2.6.1.2 Shape	33

2.6.1.3	Colour	36
2.6.1.4	Surface texture	36
2.7	Research gap	37
2.8	Summary	43
<b>3.</b>	<b>METHODOLOGY</b>	<b>44</b>
3.1	Introduction	44
3.2	Research stages	44
3.3	DLC coating material selection	46
3.3.1	Pareto optimal analysis	46
3.3.2	Weighted decision matrix (WDM)	48
3.4	Selection of machine and experimental setup	52
3.4.1	Lubrication system	53
3.4.2	Gear installation	55
3.4.3	Gear selection and coating deposition	55
3.4.4	Loading setup	57
3.4.5	Experimental testing condition	58
3.4.6	Calculation of contact stress	58
3.5	Sampling and inspection procedures	59
3.6	Test and analysis	59
3.6.1	Oil analysis and particle count test	59
3.6.1.1	Off-line particle counting procedures	63
3.6.2	Surface roughness and profile	63
3.6.3	Analysis of data	63
3.6.3.1	Particle counting and wear rate	64
3.7	Summary	65
<b>4.</b>	<b>RESULT AND DISCUSSION</b>	<b>67</b>
4.1	Introduction	67
4.2	DLC material selection	67
4.3	Assumptions in analysis	71
4.4	Particle counting wear debris analysis	71
4.4.1	Preliminary test particle generation	72
4.4.2	Uncoated and a-c:h coated gear fatigue test	76
4.5	Analytical ferrography wear debris analysis	92
4.5.1	Uncoated gear	94
4.5.2	a-C:H coated gear	103
4.6	Lubricant condition	106
4.7	Surface failure analysis	108
4.7.1	Optical analysis of gear surface for fatigue failure damage	108
4.7.2	Gear surface roughness	111
4.8	Summary	112
<b>5.</b>	<b>CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORKS</b>	<b>114</b>
5.1	Conclusions	114
5.2	Recommendation for future works	116
	<b>REFERENCES</b>	<b>117</b>
	<b>APPENDICES</b>	<b>131</b>



## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	DLC variants specification	8
2.2	Evaluation scheme for design criteria (Dieter and Schmidt, 2009)	12
2.3	Failure patterns and their incidence in civil aircraft (Moubray, 1997)	22
2.4	Correlation between wear features and debris features (Hong et al., 2018)	29
2.5	Debris features of five typical wear types (Hong et al., 2018)	32
2.6	The size and appearance of platelets (Roylance and Hunt, 1999; Khan and Starr, 2006)	34
3.1	Gear lubricant properties (Pennzoil, 2019)	54
3.2	AISI 1020 physical-mechanical properties	56
3.3	Test gear parameters	56
3.4	Physical-mechanical properties of a-C:H	57
3.5	Experimental test parameters	58
4.1	Pareto optimal analysis parameters	68
4.2	Weighted decision matrix for a-C, a-C:H, a-C:H:W, a-C:H:Si, ta-C and ta-C:H	70
4.3	Particle group sizes for SD, MD and LD	72
4.4	Maximum particle count for each particle sizes	78

## LIST OF FIGURES

<b>FIGURE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Schematic of $sp^2$ and $sp^3$ hybridization (Robertson, 2002)	7
2.2	SEM micrograph cross section of hydrogenated DLC, non-hydrogenated DLC and doped DLC according to ionbond (Ionbond, 2017)	7
2.3	Schematic of pareto optimization with two-dimensional problem (Chauhan and Vaish, 2013)	10
2.4	Objective tree of a crane hook design (Dieter and Schmidt, 2009)	12
2.5	Wear mechanisms involved (a) abrasive wear, (b) fatigue wear and (c) adhesive wear (Hong et al., 2018)	14
2.6	Schematic diagram of flank load of two meshing gears (Dudley and Winter, 1965)	16
2.7	Gear surface failures (Snidle et al., 2003; Errichello, 2012; Kramer and Speer, 2014; Zhang, and Shaw, 2016)	17
2.8	FZG performance test result: (a) scuffing load test, (b) slow speed wear test, (c) micro-pitting and pitting test (Hoehn et al., 2008)	20
2.9	General trends for quantity features in machine component operation (Khan and Starr, 2006)	23

2.10	Debris monitoring for an F119 bearing through MetalSCAN sensor (Miller and Kitaljevich, 2000)	25
2.11	Debris mass monitoring for gears based on MetalSCAN (Dempsey, 2001)	26
2.12	Relationship between debris generation and wear process (Bhushan, 2000)	27
2.13	Typical debris types (a) rubbing, (b) cutting, (c) rolling fatigue, (d) severe sliding and (e) combined rolling and sliding (Khan, 2006)	31
2.14	Wear debris shape (Bowen, 1976; Anderson, 1991; Hunt, 1993)	36
2.15	Particle surface texture (a) micropitting, (b) striation, (c) crack and (d) smooth (Laghari, 2002)	37
2.16	Current research on DLC coated gear (Joachim et al., 2002; Kalin and Vižintin, 2006; Kržan et al., 2006; Fujii et al., 2010; Michalczewski et al., 2013; Tuszynski et al.; 2015)	42
3.1	Research flow chart	45
3.2	Coating requirements for helical gear	48
3.3	DLC coating objective tree with weight factor	51
3.4	Power recirculating gear test rig setup	52
3.5	Schematic diagram of the gear test rig with lubricant path	53
3.6	Torsional coupling	57
3.7	Front view of Spectro 5200 Trivector Analyzer (Emerson Process Manager, 2010)	60
3.8	Wear debris analysis: (a) weighing the sampling bottle, (b) predetermined testing oil sample mass transferred to the sampling	61

bottle, (c) dilution of oil sample with predetermined mass of paraffin oil, (d) mixture is shaken vigorously, (e) 30 ml of oil is taken into a syringe for particle count test, (f) minimum of 20 ml of oil is used for wear test, (g) degassing is conducted before particle count test, (h) filter patch are made from the wear test

3.9	Fluidscan Q1000 handheld infrared oil analyzer	62
4.1	Pareto optimal analysis of DLC variants	69
4.2	Preliminary result for particle generation at 0.551 GPa: (a) raw data, (b) normalization	73
4.3	Preliminary result for particle generation at 0.808 GPa: (a) raw data, (b) normalization	75
4.4	Particle generation: (a) AISI 1018 carburized, (b) a-C:H coated AISI 1018 carburized	77
4.5	Normalized SD particle generation: (a) AISI 1018 carburized, (b) a-C:H coated AISI aisi 1018	79
4.6	Normalized MD particle generation: (a) AISI 1018 carburized, (b) a-C:H coated AISI 1018 carburized	82
4.7	Normalized LD particle generation: (a) AISI 1018 carburized, (b) a- C:H coated AISI 1018 carburized	84
4.8	Normalized particle generation categorized by diameter size: (a) AISI 1018 carburized, (b) a-C:H coated AISI 1018 carburized	86
4.9	Cumulative particle count of a-C:H coated vs uncoated gear	87
4.10	Particle mass: (a) uncoated gear, (b) a-C:H coated gear	89

4.11	Raw data wear rate: (a) AISI 1018 carburized, (b) a-C:H coated AISI 1018 carburized	90
4.12	Cumulative wear rate of a-C:H coated vs uncoated gear	92
4.13	Common WPA particle shape sample (a) chunks, (b) needle, (c) platelets, (d) ribbons and (e) spherical (Anderson et al., 1991), indicated by the arrow	93
4.14	Wear debris at $1.8 \times 10^5$ cycles: (a) platelets (b) needle (c) platelets with striation, indicated by arrows	95
4.15	Wear debris at $1.08 \times 10^6$ cycles: (a) chunks, (b) needle, (c) spherical, (d) ribbon, indicated by arrows and (e) particle distribution at 5x magnification	96
4.16	Wear debris at $1.98 \times 10^6$ cycles: (a) chunks, (b) chunks, (c) ribbon, (d) platelets and (e) needles, indicated by arrows	98
4.17	Wear debris at $2.88 \times 10^6$ cycles: (a) platelets, (b) platelets and (c) 50x sphere, indicated by arrows	99
4.18	Wear debris at $3.9 \times 10^6$ cycles: (a) chunks, (b) chunks and (c) needles, indicated by arrows	100
4.19	Wear debris at $5.04 \times 10^6$ cycles: (a) chunks, (b) platelets and (c) platelets, indicated by arrows	101
4.20	Wear debris at $7.26 \times 10^6$ cycles: (a) ribbon and (b) chunks, indicated by arrows	102
4.21	Wear debris at $7.26 \times 10^6$ cycles: (a) ribbons (b) chunks	103
4.22	Wear debris distribution: (a) particle distribution at $8.4 \times 10^5$ cycles, (b) black platelets at $8.4 \times 10^5$ cycles, indicated by arrow, (c) particle	104



	distribution at $4.2 \times 10^6$ cycles and (d) particle distribution at $5.16 \times 10^6$ cycles	
4.23	Wear debris distribution: (a) particle distribution at $5.52 \times 10^6$ , (b) metallic platelets at $5.52 \times 10^6$ , indicated by arrow, (c) particle distribution at $5.76 \times 10^6$ and (d) black metallic chunks at $5.76 \times 10^6$ , indicated by arrow	105
4.24	Wear debris distribution: (a) particle distribution at $6.66 \times 10^6$ and (b) chunks, indicated by arrow	106
4.25	Oxidation for uncoated and coated gear	107
4.26	Viscosity comparison for uncoated and coated gear	108
4.27	Optical stereo images of uncoated gear surface at the end of the test with peak contact stress of 1.231 GPa: (a) tooth root, (b) contact pitch line, (c) tooth tip	109
4.28	a-C:H coated gear surface: (a) tooth root, (b) contact pitch line, (c) tooth tip	110
4.29	Surface profile of: uncoated gear surface: (a) before test and (b) after test, coated gear surface: (c) before test and (d) after test	111
4.30	Surface roughness of the gears at the contact pitch line	112

## LIST OF APPENDICES

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	DLC specification	131
B	Hertzian contact stress calculation	132
C	Particle count data obtained from gear testing	140
D	Gear surface image	151
E	Wear debris particle atlas comparison	156
F	Particle count volume data and calculation	159
G	Oil analysis data for uncoated and coated gear	163

## LIST OF SYMBOLS

$E$	-	Elastic modulus
$H$	-	Hardness
$H/E$	-	Deformation relative to yielding
$H^3/E^2$	-	Resistance to plastic indentation
$P_c$	-	Critical pressure for plastic deformation
$R_s$	-	Recovery resistance
$V$	-	Wear volume
$W_i$	-	Weighing factor

## LIST OF ABBREVIATIONS

a-C	-	Amorphous Carbon
a-C:H	-	Hydrogenated Amorphous Carbon
a-C:H:Si	-	Silicon Doped DLC
a-C:H:W	-	Tungsten Doped DLC
DLC	-	Diamond-like Carbon
FZG	-	Forschungsstelle fur Zahnrad und Getriebebau
Me-DLC	-	Metal Doped DLC
PACVD	-	Plasma Assisted Chemical Vapor Deposition
PVD	-	Physical Vapor Deposition
ta-C	-	Tetrahedral Amorphous Carbon
ta-C:H	-	Tetrahedral Hydrogenated Amorphous Carbon
X-DLC	-	Non-metal Doped DLC

## LIST OF PUBLICATIONS

### JOURNAL:

1. Abdul Hakim Abdul Hamid, Reduan Mat Dan, Azma Putra, Mohd Nizam Sudin and Rozdman Khaidir Mazlan, 2019. Wear Behaviour of a-C:H Helical Gear Through Particle Generation. *Defence S and T Technical Bulletin*, 12 (1), pp. 151-165.

### PROCEEDING/CONFERENCE:

2. A.H.A., Hamid, R.M., Dan., N.I., Zulkafli, A., Putra, R.K., Mazlan, 2017. Investigation of the Wear Characteristics of Helical Gear Using Wear Debris Analysis. *Proceeding of Mechanical Engineering Research Day 2017*.

# CHAPTER 1

## INTRODUCTION

### 1.1 Research background

Gears are one of the main mechanisms for power transmissions in almost all machines. The primary purpose of gear system is to implement motion transmission as well as increasing or decreasing the speed of shafts carrying rollers or load. Recent development on design and manufacturing of gearboxes strives for a more compact yet yields a larger capacity. Due to the nature of the power transmissions which involves variable speed of rotary mechanism and heavy load, gear tends to experience failures at various cycle of the machine operation.

Thus, surface technology is a feasible solution towards improving the service life and is extensively developed which includes various methods such as surface hardening, shot penning and nitriding. Surface coating are a promising method to improve the surface performance where the current generations of hard coatings are the “diamond like carbon” (DLC). Various researches (Krantz et al., 2004; Fujii et al., 2010) are conducted on the influence of DLC coatings towards the improvement of the common failure mode resistance mainly the contact fatigue and scuffing resistance. Krantz et al. (2004) demonstrated an extension of the life of the tungsten DLC coated gear by a factor of 6 through accelerated fatigue testing. However, it is discovered that the performance of DLC coated gear changes with the load condition applied, under low load condition the gear exhibits a longer fatigue life while in a high load condition the fatigue life is comparatively shorter or equal to the non-coated gear (Fujii et al., 2010). Although DLC coating provides an advantage towards

maximizing resistance towards gear failures, the complex interactions towards various parameters such as the elastohydrodynamic lubrication (EHL), temperature and contact pressures leads to a varied result of enhancements as well as deterioration.

## **1.2 Problem statement**

Helical gears are employed for high speed and high load applications which subjects the gears to a high wear condition. This high wear conditions includes the two types of wear mainly but not specifically exclusive to gears which are scuffing and contact fatigue failure. Additionally, meshing gears results in various surface complications with every advancement in the material and design of the gear thus different demands deems a distinctive problems and solution. In order to alleviate the problems, a universal development is advocated through improvements on lubrications, gear material and surface to enhance the life of the gear or reducing the friction and wear. Application of coating proves to be sufficient in this matter compared to the method of altering the substrate or base material via case hardening or shot peening. This is due to a distinction between the mechanical properties of the coating and the substrate causing the tribological behaviour and subsurface stress field deviation as compared to the uncoated surface, which would either result in an enhancement or detrimental.

Diamond like carbon coatings are yet to be fully utilized in any industry that involves power transmission, thus an understanding to its wear behaviour in a specific condition are not yet well established. The primary purpose of this research intends to give an insight into the wear behaviour primarily involving scuffing and contact fatigue performance of the DLC coated helical gear under dynamic loading similar to those used in automotive applications with condition monitoring approach. This work focuses on the influence of the

DLC coating on the wear debris generation of the helical gear which is a part of the condition monitoring technique.

### **1.3 Research objectives**

The primary objectives of the research are:

- a. To select the most suitable DLC coating for helical gear mechanism usage.
- b. To quantify and characterise the wear behaviour of DLC coated helical gear tested under dynamic loading with uncoated gear as a baseline.

### **1.4 Research scopes**

The research investigates the correlation the wear behaviour of DLC coating under different dynamic loading characterisation. This research scopes are limited towards the following as well as covers:

- a. Power recirculating gear test rig which is generally a four-square principle of load application for dynamic testing were set up to perform the experimentations.
- b. The dynamic loadings are varied through varying the face width of the gear mesh which results in a varied Hertzian contact stress.
- c. The wear behaviour of the DLC coating are limited towards a casehardened gear under spraying and reservoir lubrication condition. Other operating conditions may result in a profound variation with the data discussed in this research.
- d. DLC coatings are limited to one variant which undergoes material selection to determine the most suitable variant for the experiment. This is due to time and resource constraint on the research.