DELAMINATION-FRETTING WEAR FAILURE EVALUATION AT HAP-TI-6AL-4V INTERFACE OF ARTIFICIAL HIP IMPLANT

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UNIVERSITI TUN HUSSEIN ONN MALAYSIA

STATUS CONFIRMATION FOR THESIS
DOCTOR OF PHILOSOPHY

DELAMINATION-FRETTING WEAR FAILURE EVALUATION AT HAP-TI-6AL-4V INTERFACE OF ARTIFICIAL HIP IMPLANT

ACADEMIC SESSION: 2020/2021

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NAGENTRAU S/O MUNIANDY

A thesis submitted in
fulfilment of the requirement for the award of the
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MARCH 2021

I hereby declare that the work in this project report is my own except for quotations
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"IT'S NOT THE LOAD THAT BREAKS YOU DOWN, IT'S THE WAY YOU CARRY IT"

To my beloved mother and father,

Mr. Muniandy & Mdm. Nookkaretnam

For being the backbone of my life by supporting me from the very beginning

To my supervisor and mentors,

Assoc. Prof. Ts. Dr. Saifulnizan Jamian

Dr. Abdul Latif Mohd. Tobi

Prof. Dr.Yuichi Otsuka

Ts. Dr. Rosniza Binti Hussin@Isa

For their consistent encouragement, guidance and support throughout the research journey

To my siblings, family and friends

Ms. Kumari Achana

Ms. Shangkari Muniandy

Mr. Prathabrao Muniandy

Close family members & true friends

For their trust, cooperation and motivation during this project

To supporting company/organisation

UOW Malaysia KDU University College

iCEE international Sdn. Bhd.

SHM Future Resources

For their direct and indirect support in completing various stages of this research

ACKNOWLEDGEMENT

First and foremost, I praise the almighty God for blessing me strength and capability to complete my doctorate research successfully. This thesis dissertation owes its presence to the inspiration, encouragement and assistance from several good souls. My sincere gratitude is extended to my parents, siblings, close family members and friends for their unconditional and genuine love through my thick and thin.

My greatest appreciation goes to my supervisor, Dr. Abdul Latif Bin Mohd Tobi who has been constant source of guidance and motivational factor to take up this PhD challenge. I would like to express my deepest appreciation to my present supervisor, Assoc. Prof. Ts. Dr. Saifulnizan Bin Jamian for his consistent encouragement, flexible discussion time and most importantly his trust on me which boosted my effort in completing this research. I greatly appreciate Ts. Dr. Rosniza Binti Hussin@Isa, Ts. Dr. Nurasyikin Binti Misdan, Dr.Aimi Syamimi Binti Ab Ghafar and Ts. Dr. Azrin Hani Binti Abdul Rashid for their assistance and support from Faculty of Engineering Technology (FTK). A special appreciation goes to my mentor Ir. Dr. Thirumalaichelvam for keep inspiring me to achieve more. I am indebted to Prof. Dr.Yuichi Otsuka from Nagaoka University of Technology (NUT), Japan whose deepest knowledge in biomechanics field enhanced present work's quality.

I am grateful for financial assistance from The Ministry of Education Malaysia and Faculty of Engineering Technology (FTK), Universiti Tun Hussein Onn Malaysia (UTHM) during my research years. In addition, I am indebted to supportive companies/organisations such as UOW Malaysia KDU University College, iCEE international Sdn. Bhd. and SHM Future Resources for their unflagging support and unconditional love throughout my doctorate journey. I would never forget all the good-hearted personalities that have been an indispensable impetus who contributed directly nor indirectly throughout this research. Last but not least, I wholeheartedly dedicate this thesis dissertation to individuals who constantly striving for excellence in life.

ABSTRACT

Osteoarthritis due to rapid aging population in Malaysia and developed countries leads to an extensive application of titanium artificial hip implants. However, titanium alloys (Ti-6Al-4V) cannot directly adhere with human bone due to bio-compatibility issue. Thus, Hydroxyapatite (HAp:$Ca_{10}(PO_4)(OH)_2$) coating which consists of main composition of human bone is plasma sprayed on titanium implants to maintain fixations during bone in-growth process. HAp coatings are susceptible to fail due to brittle fractures (coating through thickness crack) to initiate delamination which promotes fretting wear behaviour. Fretting wear particles are concerned for activating inflammations at surrounding organs, which lead to loosening of implants or subsequent failures. Present research aims to develop a finite element model to examine delamination-fretting wear behaviours that can suitably mimic actual loading conditions at HAp-Ti-6Al-4V interface of hip implant femoral stem component to formulate maximum wear depth predictive equation as a novel and fast failure prediction tool. Three simple finite element contact configuration models subjected to different mechanical and tribological properties consist of contact pad (bone), HAp coating and Ti-6Al-4V substrate are developed using contact modelling, cohesive zone modelling (CZM) and adaptive wear modelling (UMESHMOTION) approaches to be examined under static simulation. The developed finite element models are validated and verified with modified Hertzian theoretical solution and reported literatures. The findings revealed that significant delamination-fretting wear is recorded at contact edge (leading edge) as a result of substantial contact pressure and contact slip driven by stress singularity effect. Tensile-compressive condition ($R = -1$) experiences most significant delamination-fretting wear behaviour (8 times higher) compared to stress ratio $R = 0.1$ and $R = 10$. Finally, maximum delamination-fretting wear depth predictive equations are successfully formulated with significant goodness of fit and reliability as a fast failure prediction tool.

ABSTRAK

Osteoarthiritis disebabkan populasi penuaan yang pantas di Malaysia dan negara maju yang lain membawa kepada penggunaan prostesis pinggul aloi titanium secara meluas. Namun, aloi titanium tidak dapat dicantum secara langsung pada tulang manusia disebabkan masalah ketakserasian bio. Oleh itu, lapisan Hidroksiapatit (HAp:$Ca_{10}(PO_4)(OH)_2$) disalutkan pada prostesis pinggul untuk mengekalkan penetapan semasa proses pertumbuhan tulang. Lapisan HAp terdedah kepada keretakan ketebalan menyeluruh sampai antara muka HAp-Ti-6Al-4V dan menyebabkan delaminasi lapisan serta mempercepatkan proses haus penggeselsuaian. Partikel-partikel haus penggeselsuaian boleh mengaktifkan keradangan pada organ sekitarnya sehingga boleh melonggarkan prostesis pinggul serta kegagalan berikutnya. Penyelidikan ini bertujuan membangunkan model kaedah unsur terhingga (FEM) untuk menganalisis haus penggeselsuaian-delaminasi pada antara muka HAp-Ti-6Al-4V yang tertakluk kepada keadaan beban yang sebenar dan merumuskan persamaan ramalan kedalaman maksimum haus penggeselsuaian-delaminasi sebagai alat ramalan kegagalan yang pantas. Tiga model FEM yang terdiri daripada pad kontak, lapisan HAp dan substrat Ti-6Al-4V tertakluk kepada sifat mekanikal dan tribologikal yang berbeza dibangunkan menggunakan pendekatan *contact modelling, cohesive zone modelling (CZM) dan adaptive wear modelling (UMESHMOTION)* untuk dikaji di bawah simulasi statik. Model FEM disahkan dengan teori Hertzian yang diubahsuai dan kajian sebelumnya. Hasil kajian menunjukkan bahawa haus penggeselsuaian-delaminasi yang ketara direkodkan pada pinggiran kontak disebabkan singulariti tegasan didorong oleh tekanan sentuh dan slip sentuh. Nisbah tegasan (R = -1) menunjukkan haus penggeselsuaian-delaminasi yang 8 kali lebih tinggi berbanding dengan nisbah tegasan R = 0.1 and R = 10. Akhirnya, persamaan ramalan kedalaman maksimum haus penggeselsuaian-delaminasi berjaya dirumuskan dengan ketepatan dan reliabiliti yang tinggi untuk digunakan sebagai alat ramalan kegagalan yang pantas dan tepat.

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LIST OF SYMBOLS AND ABBREVIATIONS

E_d	-	Accumulated dissipated energy
Δ	-	Opening displacement
Δh	-	Wear depth
μ	-	Friction coefficient
μm	-	Micrometre
a	-	Half-width length
b	-	Coefficient
E	-	Elastic modulus
E^*	-	Combined elastic modulus
E_{bone}	-	Bone elastic modulus
F	-	Normal load
G_N^c	-	Normal energy release rate
G_T^c	-	Shear energy release rate
H	-	Hardness
k	-	Coefficient of wear
K	-	Dimensionless wear coefficient
K_c	-	Stress intensity factor
K_N	-	Normal interfacial stiffness
K_T	-	Shear interfacial stiffness
N	-	Newton
N	-	Number of cycles
$p(x)$	-	Contact pressure distribution
P_0	-	Maximum contact pressure
P_m	-	Flow pressure
P_N	-	Normal load
R	-	Curvature radius
R^*	-	Combined radius

rpm	-	Rotation per minute
S	-	Sliding distance
t	-	Specific time
$t_N{}^0$	-	Normal interfacial strength
$t_T{}^0$	-	Shear interfacial strength
U2	-	Spatial displacement of nodes in vertical direction
v	-	Poisson's ratio
V	-	Wear volume
W	-	Total work done
x	-	Horizontal length
x	-	Independent variable
y	-	Dependent variable
α	-	Dundur's first parameter
δ	-	Amplitude of displacement
ΔK	-	Kinetic energy
ΔN	-	Cycle jump
ΔU	-	Potential energy
π	-	Phi
σ	-	Interface traction
$\sigma_{fatigue}$	-	Fatigue load
R	-	Stress ratio
2D	-	Two-dimensional
3D	-	Three-dimensional
ALE	-	Arbitrary Lagrangian-Eulerian
CNC	-	Computer numerical control
CoC	-	Ceramic-on-ceramic
COF	-	Coefficient of friction
CoP	-	Ceramic-on-plastic
CPRESS	-	Contact pressure
CSLIP	-	Contact slip
CZM	-	Cohesive zone modelling
Del	-	Delamination
ETP	-	Economic Transformation Programme
FE	-	Finite element

FEM	-	Finite element method
GPa	-	Gigapascal
GTP	-	Government Transformation Programme
HAp	-	Hydroxyapatite
HXLPE	-	Highly cross-linked polyethylene
LEFM	-	Linear elastic fracture mechanics
mm	-	Millimetre
MoM	-	Metal-on-metal
MoP	-	Metal-on-plastic
MPa	-	Megapascal
NEM	-	National New Economic Model
NKEA	-	National Key Economic Area
NUT	-	Nagaoka University of Technology
ODB	-	Output database
PP	-	Polypropylene
PU	-	Polyurethane
SBF	-	Simulated body fluid
SDEG	-	Stiffness degradation
SEM	-	Scanning electron microscope
SRI	-	Strategic Reform Initiatives
THR	-	Total hip replacement
Ti	-	Titanium
Ti-6Al-4V	-	Titanium alloy
TSL	-	Traction-separation law
TTS	-	Tribologically transformed structure
UHMWPE	-	Ultra-high-molecular-weight polyethylene
UTHM	-	Universiti Tun Hussein Onn Malaysia
VCCT	-	Virtual crack closure technique
XFEM	-	Extended finite element method

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1   Background of study

Hip joint is one of the important synovial ball and socket joints which connecting femur with pelvis in human body (Abd-elsayed, 2019). Basically, hip joint is made up of femoral head (ball) and acetabulum (socket) as shown in Figure 1.1. The hip joint transmits load from lower limb through the pelvis to the axial skeleton. However, hip diseases are prone to occur due to injuries, infections, chronic conditions and developmental conditions. Osteoarthritis, inflammatory arthritis, bone fracture, slipped capital femoral epiphysis, abnormal developmental conditions, soft tissue pain and perthes disease are among the common hip disorders (Fallahnezhad, 2018).

Osteoarthritis is the most common form of hip disorders that affecting millions of people around the globe. Osteoarthritis is a condition where the protective cartilage that cushions at hip ball and socket joint is worn out over time as illustrated in Figure 1.2. The deterioration of protective cartilage will cause bone rubbing on bone and worsening of connective tissues/muscles at hip joint. Osteoarthritis is one of the critical hip disorders, especially in developed countries due to rapid aging population (Otsuka *et al*., 2016). In fact, osteoarthritis is a degenerative disorder that worsens over time and can lead to several complications such as chronic joint pain, immobility and disability. Thus, total hip replacement (THR) surgery is required to replace damaged or worn out hip joints. Damaged protective cartilage and femoral head of hip joint are removed and replaced with hip prosthetic components (artificial hip implants) which made up of acetabular cup, plastic inner, femoral head and stem which connecting pelvis with femur as shown in Figure 1.2.
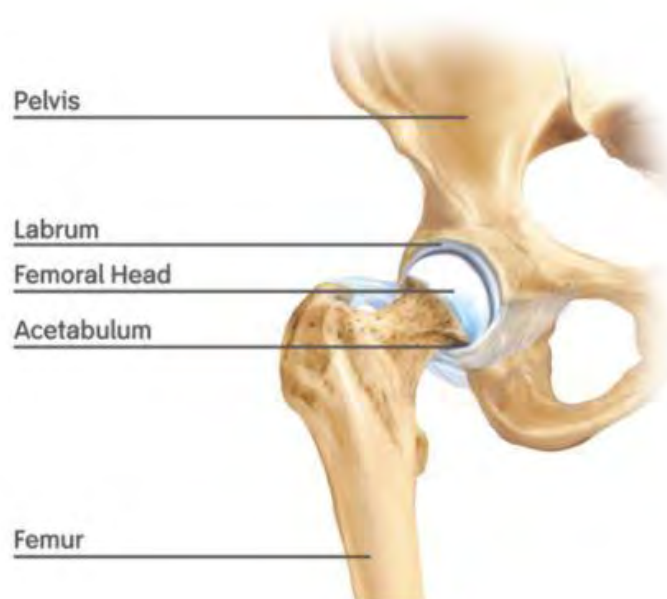
Figure 1.1: Hip joint anatomy (Fallahnezhad, 2018)
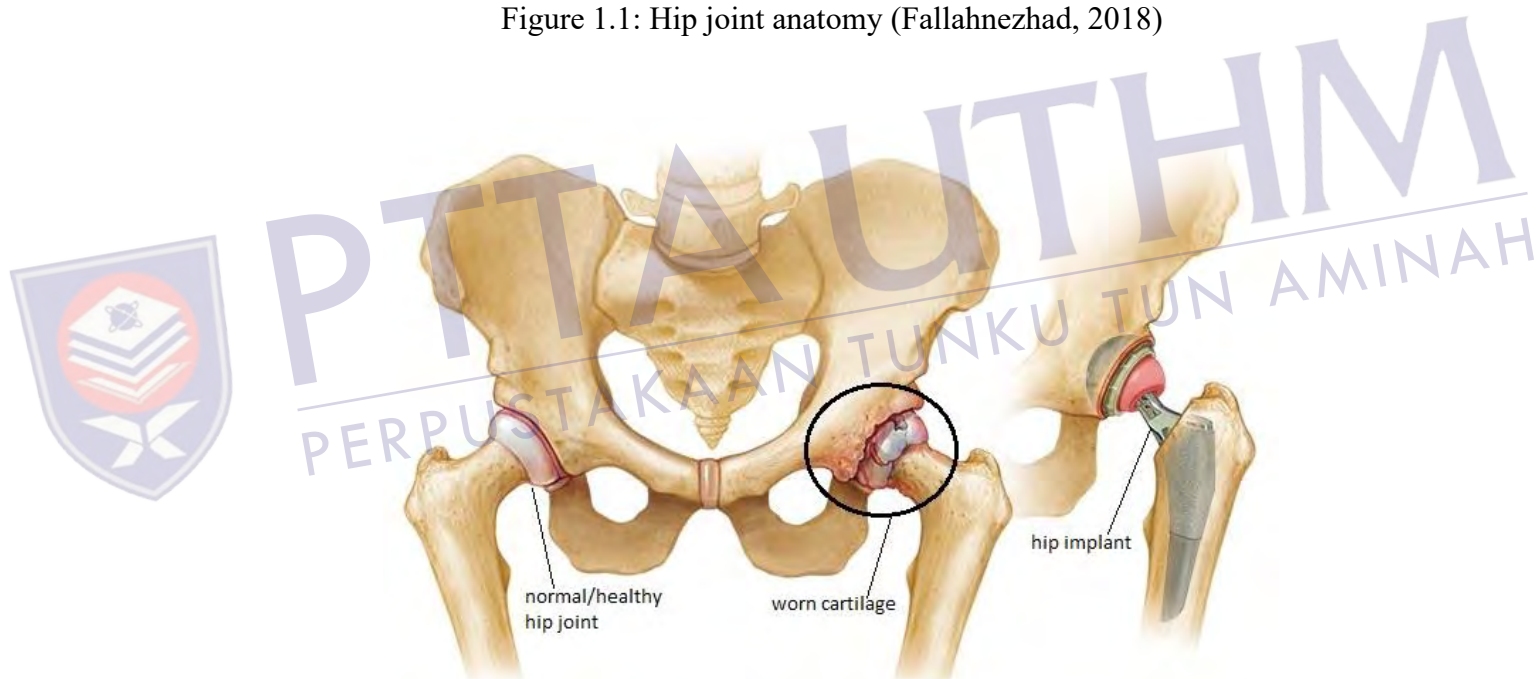
Figure 1.2: Osteoarthritis and total hip replacement (THR) surgery (Fallahnezhad, 2018)

The Australian Orthopaedic Association National Joint Replacement Registry (Graves *et al*., 2004; System, 2019) has reported that 88.8 % of total hip replacement (THR) surgery is attributable to osteoarthritis condition.

Artificial hip implants utilised in total hip replacement (THR) surgery is normally made of titanium alloys (Ti-6Al-4V). The extensive application of titanium

alloys (Ti-6Al-4V) in biomechanics field mainly as artificial hip implant is predominant due to its low weight, high strength and corrosion resistance characteristics (Nagentrau *et al.*, 2019). However, titanium alloys (Ti-6Al-4V) cannot directly adhere to human bone due to biocompatibility issue (Nagentrau *et al.*, 2020). Thus, bonds/coating that having similar properties of bone minerals is necessary to increase bone bonding ability with titanium (Ti-6Al-4V) artificial hip implants. Hydroxyapatite (HAp:$Ca_{10}(PO_4)(OH)_2$), a bio-ceramics material which contains main composition of human bone is broadly used to promote bonds between bone and titanium (Ti-6Al-4V) artificial hip implants (Otsuka *et al.*, 2016).

Hydroxyapatite (HAp) coating is deposited on Ti-6Al-4V artificial hip implant femoral stem by plasma spraying technique. Practically, Hydroxyapatite (HAp) coated Ti-6Al-4V artificial hip implant femoral stem can achieve good fixation with human bone upon completion of subsequent adhesion due to bone ingrowth process. On the other hand, Hydroxyapatite (HAp) coating is susceptible to fail due to fatigue cracks, brittle fracture, delamination and fretting wear (Otsuka *et al.*, 2016). Consequently, the effectiveness of Hydroxyapatite (HAp) coating is greatly challenged in long term usage more than 10 years. Hydroxyapatite (HAp) coating can experience coating through thickness crack (vertical crack) due to fretting fatigue as results of gait cycle.

Hydroxyapatite (HAp) coating interfacial delamination is initiated as coating through thickness crack (vertical crack) reached until the interfaces of HAp-Ti-6Al-4V and HAp-human bone respectively. The coating delamination condition can lead to relative contact slip which accelerating fretting wear behaviour at interfaces. Figure 1.3 presents the delamination-fretting wear mechanism at hip implants. Wear particles are formed from delamination-fretting wear mechanism able to activate inflammations at surrounding organs, which causes implant loosening and subsequent failures (Nagentrau *et al.*, 2019). Thus, such a condition can increase the risk of artificial hip implant revision surgery.
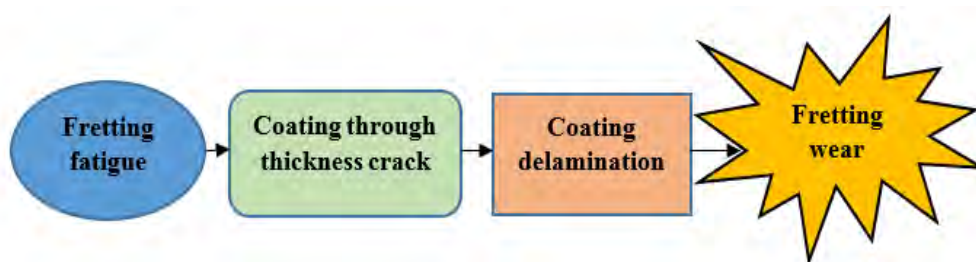
Figure 1.3: Delamination-fretting wear failure mechanism (Nagentrau *et al*., 2019)

However, to the best of authors knowledge, far too little attention has been paid to combined delamination and fretting wear behaviours at artificial hip implant femoral stem part that can suitably mimic actual loading conditions. In fact, most of the open literatures are focussing on failure behaviour at acetabular cup (ball-socket interface) and very limited studies are considering artificial hip implant femoral stem part (English *et al*., 2015; Fallahnezhad *et al*., 2017; Otsuka *et al*., 2016). Therefore, this research aims to develop a delamination-fretting wear finite element model to formulate maximum wear depth predictive equation as a novel and fast failure prediction tool. In addition, present research addresses contact pressure, contact slip, interface damage, delamination initiation and delamination-fretting wear behaviours at HAp-Ti-6Al-4V interface of artificial hip implant femoral stem component by adopting finite element approach using contact modelling, cohesive zone modelling (CZM) and adaptive wear modelling (UMESHMOTION subroutine) respectively. The influence of delamination length, loading condition, bone elastic modulus, stress ratio, number of cycles along with interfacial properties are among the focus of present study.

1.2 Problem statement

Artificial hip implant failure is commonly occurring at acetabular cup (ball-socket interface) and femoral stem region. Research on delamination and fretting wear in artificial hip implant has been carried out for many years. However, far too little attention has been paid to femoral stem region and in-depth research are required to investigate delamination and fretting wear failure behaviour at that region. Previous researchers have explored cyclic delamination of plasma sprayed Hydroxyapatite

(HAp) coating and its effect on fretting wear behaviour. However, no study has been examined combined delamination-fretting wear behaviour at artificial hip implant femoral stem component. Delamination of Hydroxyapatite (HAp) coating due to coating through thickness crack (vertical crack) initiated by fretting fatigue can promote fretting wear behaviour in femoral stem region of artificial hip implant (Nagentrau *et al.*, 2019; Otsuka *et al.*, 2016). In fact, there is absence of combined delamination-fretting failure prediction model that could suitably mimic actual loading conditions at HAp-Ti-6Al-4V interface accurately. This clearly shows that limited attempt has been done to explore the potential of developing a reliable combined delamination-fretting wear failure prediction model. It appears from the reported literatures that most attention has been paid to experimental work and it is essential to develop a finite element model to perform detailed parametric studies at HAp-Ti-6Al-4V interface. Combined delamination-fretting wear failure prediction model is very crucial for better design process of Hydroxyapatite (HAp) coated Ti-6Al-4V implants to minimize artificial hip implant in service failure. Besides that, research studies focussing the effect of mechanical and tribological properties of HAp-Ti-6Al-4V interface on delamination-fretting wear are still lacking in biomechanics field.

In fact, delamination-fretting wear possibly can occur at two artificial hip stem interfaces such as HAp-Ti-6Al-4V and HAp-human bone respectively (Otsuka *et al.*, 2016). HAp-Ti-6Al-4V interface solely focussed in present study rather than in HAp-human bone interface as Hydroxyapatite (HAp) coating able to achieve good fixation and subsequent adhesion with human bone once bone ingrowth. Thus, fretting wear particles generated in HAp-human bone interface will be suppressed. However, HAp-Ti-6Al-4V is considered as critical interface as fretting wear particles will be ejected and transported along the surrounding region as shown in Figure 1.4. Present study is designed to shed a light to explore the combined delamination-fretting wear behaviour at HAp-Ti-6Al-4V interface since no attempt has been done previously by other researchers.

In addition, the lack of new findings and advancement in fundamental knowledge about delamination-fretting wear failure behaviour using finite element methodology requires in-depth exploration. It should be noted that no attempt is done previously to develop a delamination-fretting wear model using finite element methodology to formulate maximum wear depth predictive equation as a novel and fast failure prediction tool which able to assist in reducing the amount of testing

required and better design process of Hydroxyapatite (HAp) coated artificial hip implant femoral stem component. Besides that, there have been no controlled studies which compare the influence delamination length, loading condition, bone elastic modulus, stress ratio, number of cycles along with interfacial properties on delamination-fretting wear behaviour to minimise associated failure because such a flaw is life threatening and also costly.
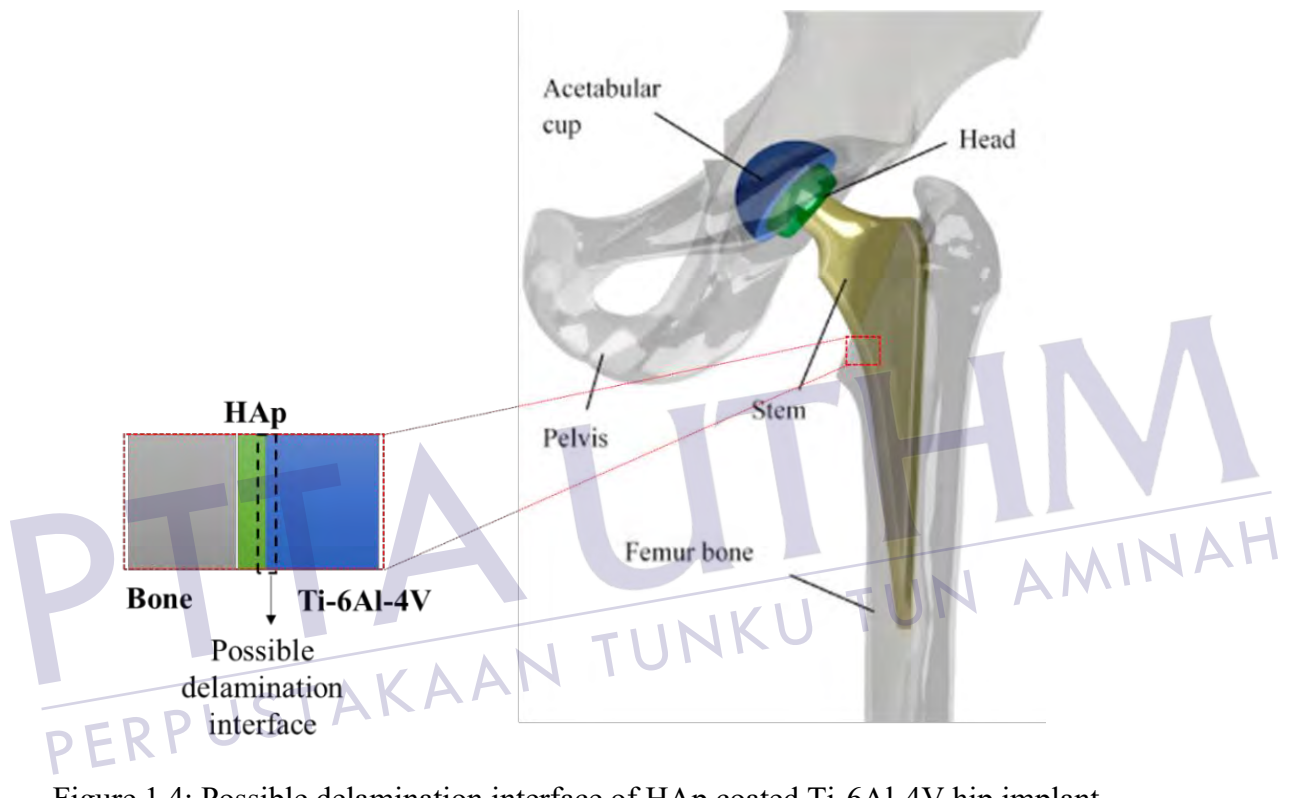
Figure 1.4: Possible delamination interface of HAp coated Ti-6Al-4V hip implant
(English *et al.*, 2015)

1.3 Research questions

This research will contribute in enhancing knowledge about delamination-fretting wear behaviour at HAp-Ti-6Al-4V interface of hip implant femoral stem by imposing following research question:

i. How does the different mechanical and tribological properties affect contact pressure and contact slip distribution at HAp-Ti-6Al-4V interface of artificial femoral stem component?

ii. How does the different mechanical, tribological and interfacial properties such as interfacial stiffness, strength and energy release rate affect interface damage along with coating delamination at HAp-Ti-6Al-4V interface of artificial femoral stem component?

iii. How does the finite element methodology can be implemented to perform detailed parametric studies and develop delamination-fretting wear model subjected to different mechanical and tribological properties to formulate maximum wear depth predictive equation using multiple linear regression as a novel and fast failure prediction tool at HAp-Ti-6Al-4V interface?

1.4 Research objectives

The objectives of present research work are presented as follows:

i. To develop finite element contact model of HAp-Ti-6Al-4V interface subjected to different mechanical and tribological properties to predict contact pressure and contact slip distribution.

ii. To analyse HAp-Ti-6Al-4V interface damage and coating delamination initiation behaviour under different mechanical, tribological and interfacial properties using cohesive zone modelling (CZM).

iii. To evaluate proposed delamination-fretting wear finite element model subjected to different mechanical and tribological properties to formulate maximum wear depth predictive equation as a novel and fast failure prediction tool.

1.5   Research scopes and limitations

The scopes and limitations of the present research are established in order to achieve focused goals in line with research questions and aims. Hence, the scopes and limitations of this research are drawn as following:

i.   Modelling ¼ symmetric two-dimensional (2D) plane strain case HAp coated Ti-6Al-4V based on fretting fatigue specimen to represent artificial hip implant femoral stem using ABAQUS commercial finite element software (version 6.13).

ii.   Modelling HAp coated Ti-6Al-4V substrate contact configuration subjected to normal and fatigue loading condition.

iii.   Ti-6Al-4V substrate and HAp coating are modelled as fully elastic bodies with elastic modulus of 110 GPa and 70 GPa respectively.

iv.   HAp coating thickness is modelled as 150 μm representing plasma sprayed coating deposition.

v.   PU foam contact pad with elastic modulus of 0.1 - 1.0 GPa and 2.0 - 20.0 GPa are modelled to represent porous (cancellous) and cortical bones respectively.

vi.   Friction and wear coefficients at HAp-Ti-6Al-4V interface are modelled as 0.7 and 2.0×10^{-8} $(mm^3/N.mm)$ respectively.

vii.   HAp coating vertical crack is applied by ¼ symmetric modelling approach to represent coating through thickness crack until the interface to initiate delamination.

viii.   Evaluating concerned variables of fatigue loading (250 - 350 MPa), normal loading (20 - 30 MPa), delamination length (0.25 - 1.0 mm), stress ratio (0.1, 10, -1) and bone elastic modulus (0.1 - 20 GPa) at HAp-Ti-6Al-4V interface.

ix.   Only HAp-Ti-6Al-4V interface of artificial hip implant femoral stem component is focussed.

x.   Delamination length is controlled by implementing tie constraint technique during finite element contact and wear modelling.

xi.   Cycle jump technique with $\Delta N = 1 \times 10^4$ is implemented during finite element wear modelling.

xii.   The developed delamination-fretting wear model can be utilised for delamination length ranging from 0.25 mm - 1.0 mm, normal loading of

20 MPa - 30 MPa with fatigue loading of 250 MPa - 350 MPa subjected to stress ratio, R = 0.1, R = 10 and R = -1 and number of cycle up to 1,000,000.

1.6   Research novelty

It appears from the aforementioned investigations that most attention has been paid to artificial acetabular cup (ball-socket interface) and very few studies examined artificial hip implant femoral stem component. Thus, present research is mainly focussing on the combined delamination-fretting wear behaviour at artificial hip implant femoral stem. Besides that, delamination-fretting wear behaviour at HAp-Ti-6Al-4V interface has not been considered before. Nevertheless, limited attempt has been done to explore the potential of developing a delamination-fretting wear behaviour model using finite element methodology to formulate maximum wear depth predictive equation as a novel and fast failure prediction tool. In addition, present research is hoped to shed some light in evaluating different mechanical and tribological properties such as delamination length, loading condition, bone elastic modulus, cycle number and stress ratio at HAp-Ti-6Al-4V interface and its response on contact pressure, contact slip, interface damage, delamination initiation and delamination-fretting wear behaviour.

1.7   Research significance

The contribution of present research is obvious as resulting outcomes can be capitalised as guideline to evaluate artificial hip implant femoral stem failure associated with delamination and fretting wear through implementation of finite element methodology. In addition, the proposed finite element model can be easily accommodating different mechanical, tribological and interfacial properties of artificial femoral stem component HAp-Ti-6Al-4V interface to perform detailed parametric studies with minimal costly experimental works. The uniqueness of this research will be an advancement in fundamental understanding of delamination-fretting wear behaviour at HAp- Ti-6Al-4V interface.

The outcome of this research is a novel and fast failure prediction tool which can be used to better assist in maximum delamination-fretting wear depth prediction at artificial hip implant femoral stem component. The maximum delamination-fretting wear depth prediction tool will assist in reducing the amount of testing required and better design process of HAp coated hip implants. Besides that, accurate prediction and speedy assessment of delamination-fretting wear could contribute in improving service life of implants. Present research also relevant and inline to with Malaysian Sustainable Development Goals (SDG) focussing on Goal No. 3 and Goal No.4 which are Good Health and Well-being and Quality Education respectively. Besides that, present research also can be related to Science, Technology, Innovation & Commercialisation from Economic Empowerment pillar and Health & Education from Social Re-engineering pillar under Twelfth Malaysian Plan (RMK-12).

1.8 Thesis organisation

The outline of the thesis is presented as below:

Chapter 1: Presents research background, problem statement, research questions, objectives, scopes and limitation. In addition, novelty and significance of research also highlighted.

Chapter 2: Presents extensive literature review on anatomy of hip, artificial hip implant, contact mechanics of HAp coated Ti-6Al-4V addressing delamination and fretting wear failure, finite element contact modelling, cohesive zone modelling and wear modelling. The research gap is identified towards the end of literature review.

Chapter 3: Outlines whole methodology including contact modelling, cohesive zone modelling (CZM) and wear modelling using finite element methodology to develop novel and fast failure prediction tool.

Chapter 4: Evaluates influence of different mechanical and tribological properties such as delamination length, loading condition, bone elastic modulus, cycle number

and stress ratio on contact pressure, contact slip, interface damage, delamination initiation and delamination-fretting wear behaviour at HAp-Ti-6Al-4V interface of artificial hip implant femoral stem.

Chapter 5: Draws conclusion and knowledge contribution of present work with . recommendation for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the overview of total hip replacement (THR) using artificial hip implant is highlighted to firmly understand contact mechanics associated failures. In addition, HAp coated artificial femoral stem failure due to fretting condition is discussed in detail. HAp-Ti-6Al-4V interface delamination and fretting wear experimental studies are focussed. Apart from that, cohesive zone modelling and fretting wear modelling approaches to predict delamination and fretting wear behaviour are reviewed comprehensively. Based on the literature review, several research gaps are identified to be addressed in present study.

2.2 Anatomy of hip joint

Hip joint is basically ball and socket connection which made up of femoral head (ball) and acetabulum (socket) (Hongyu & Blunt, 2009). Although, hip joint is stable to bear more weight but only can carry less range of motion compared to other ball-socket joints in human body such as shoulder joint (English *et al.*, 2015). Human hip joint comprises several parts i.e. femur bone head, acetabulum, joint capsule/ligaments, cartilage and tendons as illustrated in Figure 2.1. In fact, the human hip joint is supported with tendons, ligaments and muscles.

The human hip joint is enclosed by ligaments (joint capsule) which assists in stabilising hip motion during human activities. This thick ligament (joint capsule) contains pubofemoral, ischiofemoral and ilofemoral ligaments which located near ligmentum teres and labrum as shown in Figure 2.1. In addition, these ligaments cover femur head cartilages along with acetabulum. The thigh bone or femur is the heaviest, longest and strongest bone in human body (English *et al*., 2015). The main function of femur is to transmit and support body weight during various human activities. It is noteworthy to mention that femur is always exposed to extreme force and can be stabilised with attached muscles strength. Meanwhile, acetabulum is a cup dented in the pelvis (concave surface). The hip joint is formed when pelvis and femur head is connected at this concave surface.
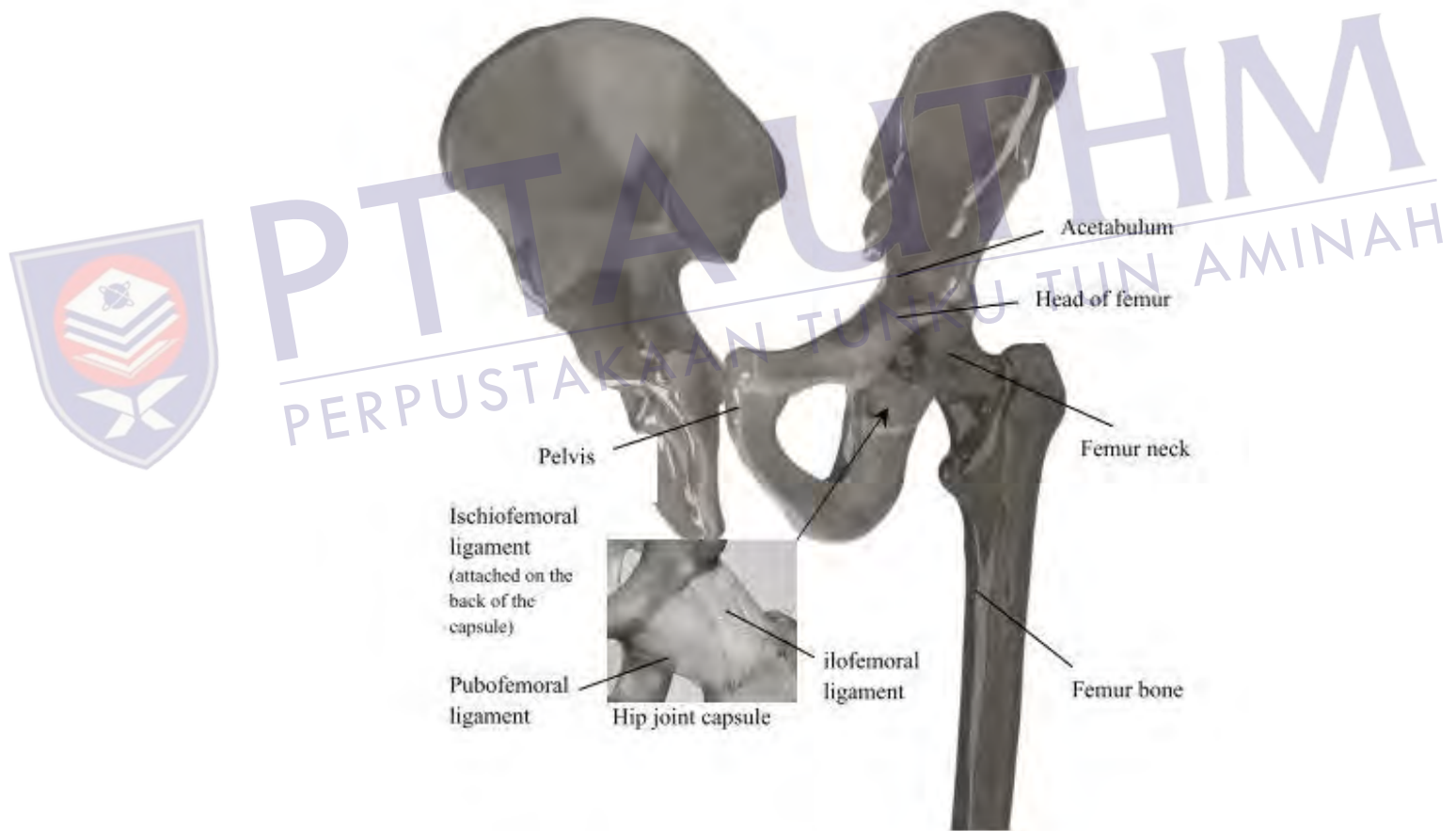
Figure 2.1: Human hip joint anatomy (English *et al*., 2015)

Cartilage on femur head and acetabulum is responsible to lubricate the joint by providing smooth surface with the purpose of facilitate smooth or nearly frictionless motion. From a mechanical perspective it acts in similar manner as lubricant in

machineries. The human hip joint performance can be affected if damaged due to bone disease, overweight, overuse and others. Furthermore, the damaged or worn out cartilage can lead to articulation of high friction as hard bone surfaces such as femur head and acetabulum contact upon each other (English *et al*., 2016). This condition will be causing high stresses and results in making the hip joint stiffer and painful.

2.3   Hip joint disorders

Human hip joint can transmit significant dynamic loads and extensive range of movement during human activities. The ability of hip joint in carrying and transmitting loads to provide mobility is remarkable. However, it is susceptible to deterioration and functional loss due to certain types of hip joint disorders. Hip joint can experience osteoarthritis, rheumatoid arthritis, avascular necrosis, trauma and bone fracture (English *et al*., 2016). Osteoarthritis is a common and high-risk hip disorder due to worn cartilages which causing femur head and acetubulum bone contact each other and results in stiffness, immobility and chronic pain (Loeser, 2006).

Rheumatoid arthritis is a disorder where human suffer because of hip joint ligaments damage and bone erosion. Meanwhile, a condition of limited blood supply at joint tissue which leads to organ cells death in femur bone top region is known as avascular necrosis. This hip disorder can change bone shape, joint stiffness, loss of movement range and pain (English *et al*., 2015). Besides that, trauma and bone fracture can be arisen due to sudden impact or fall and medical complication such as stress injuries, cancer and osteoporosis which weaken the bone and susceptible to fracture.

Physiotherapy and drugs can aid in reducing pain for patients experiencing hip joint disorders. However, effective treatment such as affected hip joint replacement is required to eliminate chronic pain in severe hip joint disorder cases. Total hip replacement (THR) is key solution to restore mobility and normal lifestyle of hip disorder patients as shown in Figure 2.2. Among all the hip disorders, Osteoarthritis is the principal cause for total hip replacement surgery as reported in The Australian Orthopaedic Association National Joint Replacement Registry (Graves *et al*., 2004).
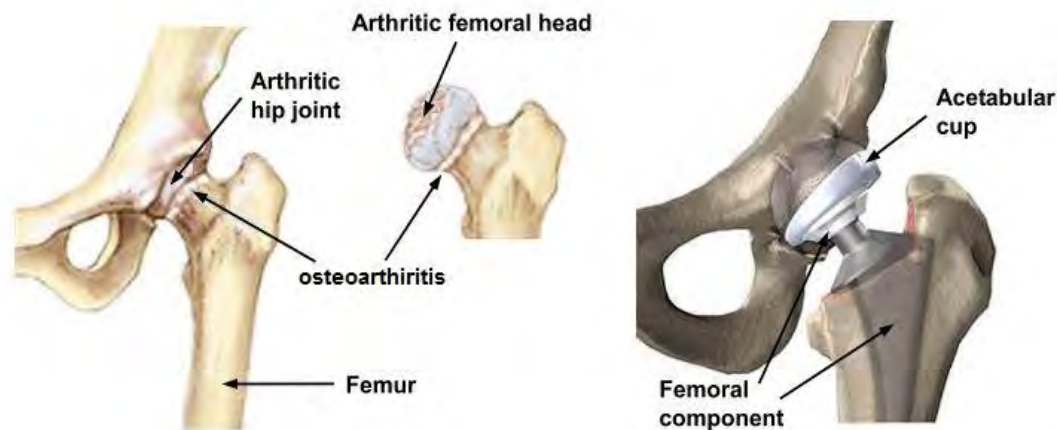
Figure 2.2: Osteoarthritis and total hip replacement (THR) surgery (Hongyu &
Blunt, 2009)

2.4   Total hip replacement (THR) using artificial hip implant

Total hip replacement surgery is most effective orthopaedic surgery performed
worldwide with the aim of dramatically enhance mobility and life of patients suffering
from hip related disorders such as osteoarthritis (Hongyu & Blunt, 2009). Total hip
replacement (THR) surgery is commonly carried out using metallic artificial implant.
Such a metallic artificial implants normally made up of Titanium alloys (Ti-6Al-4V)
due to its interesting properties (Nagentrau *et al*., 2019; Otsuka *et al*., 2016). Titanium
alloys (Ti-6Al-4V) is a high interest material in engineering application due to their
low weight, excellent corrosion resistance, high ductility and fatigue resistance
characteristics (Nagentrau *et al*., 2016; Nagentrau *et al*., 2015; Siswanto *et al*., 2016;
Siswanto *et al*., 2015).

Total hip replacement surgery can bring immediate relief to patients who
experiencing unremitting pain. In fact, this surgical procedure performed as a last
attempt to relief pain and improve mobility of hip disorder patients. The very first total
hip replacement is performed by Sir John Charnley (1911-1982) in November 1962
by replacing entire hip joint with metallic artificial implant and established surgical
approach of implantation. The implantation foundation proposed by Charnley leads to
advancement in surgical technique to facilitate active lifestyle of patients in present
day. Artificial hip implant is a ball and socket joint which comprising femoral head,
acetabular cup and femoral stem as shown in Figure 2.3.
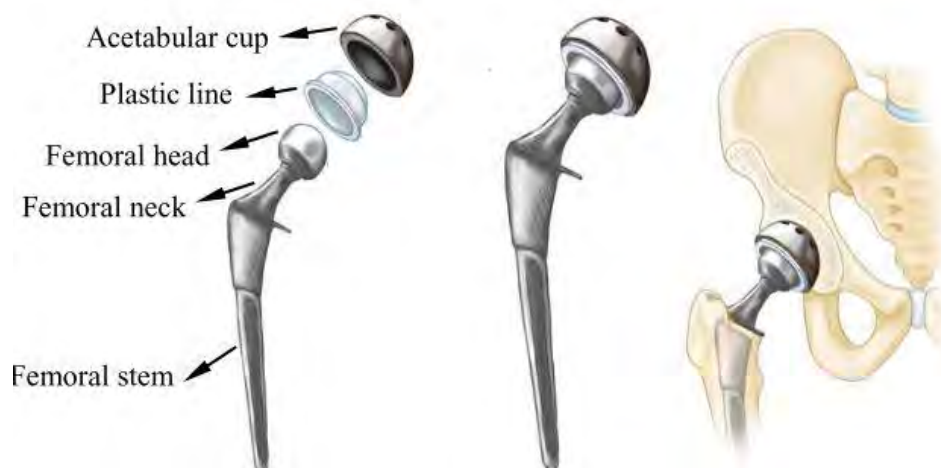
Figure 2.3: Artificial hip implant parts (English *et al*., 2015)

There are two types of hip implant fixation approach as illustrated in Figure 2.4 to secure metallic femoral stem into femur such as cemented and uncemented total hip replacement respectively. Acrylic bone cement is utilised during metallic implant fixation to act as an intermediary agent stabilising femoral stem and transferring loading in cemented total hip replacement. Meanwhile a porous bio ceramic coating is applied on artificial femoral stem surface to enhance bone ingrowth in uncemented total hip replacement. Generally, bonds between metallic titanium alloy and bone are required as both cannot adhere directly (Laonapakul *et al*., 2012).

Acetabular cup is fixed into artificial femoral stem in similar way under both uncemented and cemented total hip replacement (THR) techniques. The acetabular cup is held by fit tightness or with screws in uncemented THR, whereas bone cement is utilised to stabilise acetabular cup in cemented THR. The fixation method of THR using cemented or uncemented is highly personal and different according to counties and surgeons. For instance, national variations across the Europe ranges from 91% cemented THR in United Kingdom to 10% in Austria (Graves *et al*., 2004). The combination of uncemented acetabular cup and cemented femoral stem is known as Hybrid THR which becoming popular in treating elderly patients (50 - 60 years old) in present day. However, the present research is focuses on uncemented THR where Hydroxyapatite (HAp) coating is plasma sprayed on metallic femoral stem.
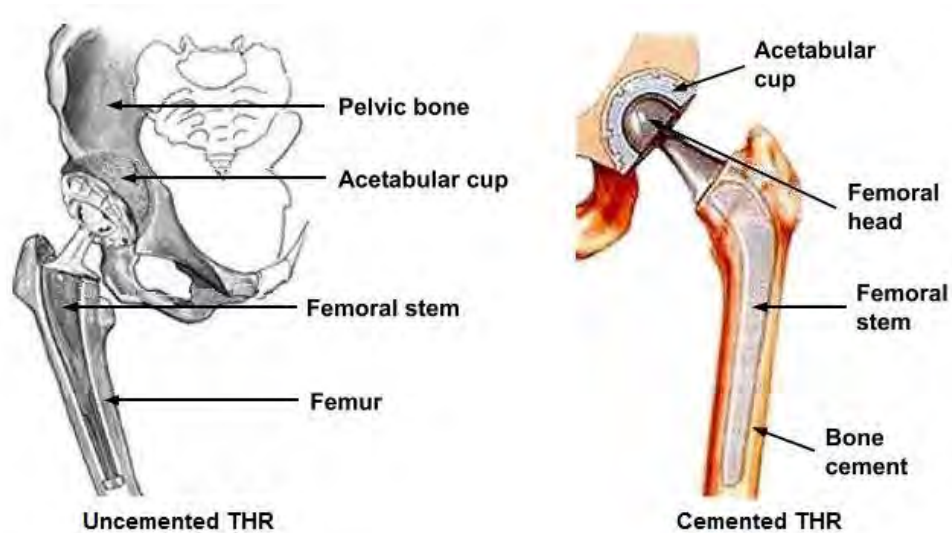
Figure 2.4: Uncemented and cemented total hip replacement (THR) (Hongyu & Blunt, 2009)

2.5 Hydroxyapatite (HAp) coated uncemented THR

Despite prior evidence, debates still ongoing concerning the ideal choice of total hip replacement (THR) fixation methods i.e. cemented THR and uncemented THR. The primary goal of uncemented THR is to enhance long term success in younger patients (Hongyu & Blunt, 2009). Ideally, Hydroxyapatite (HAp) coating is applied on Ti-6Al-4V metallic femoral stem in order to achieve osseointegration by promoting bone ingrowth. Potential benefits of HAp coated femoral stem fixation are capability of remodel activity and self-restoration over time.

Hydroxyapatite (HAp) ($Ca_5(PO_4)_3(OH)$) is broadly used as bio ceramic material because of its exceptional compatibility with bone (Lindahl, 2012). HAp coating is having similar properties with bone minerals. Several researchers have revealed that HAp coating is utilised as autogenous free bone grafting substance for past 30 years. In fact, it is most promising bioactive ceramics that widely used in orthopaedic, alveolar ridge, dental implants and scaffolds for bone growth during surgery (Haibo Wang, 2004). Plasma sprayed HAp coating on femoral stem surface forming textured or irregular surface for better mechanical interlock is fixed as shown in Figure 2.5.
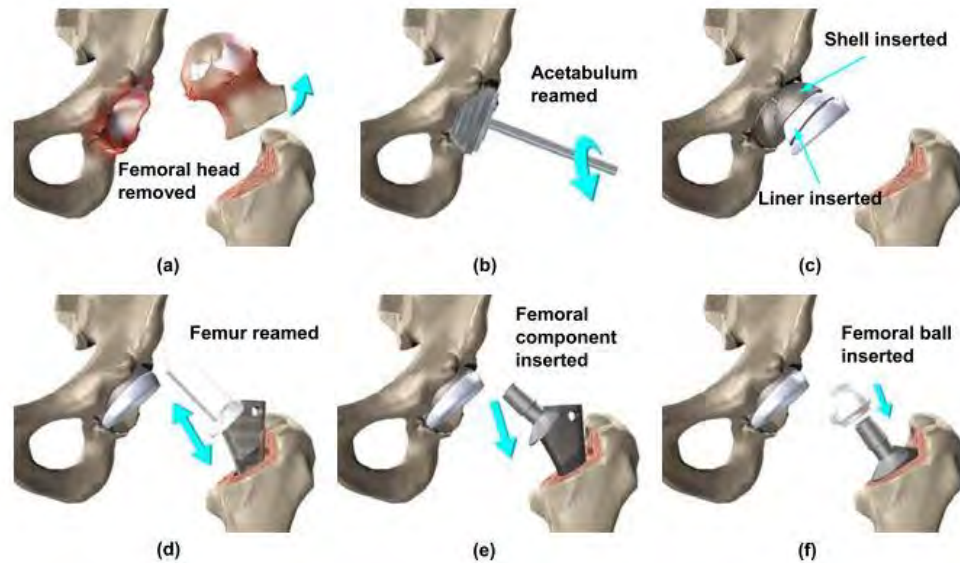
Figure 2.5: Typical procedures of HAp coated uncemented THR (Hongyu & Blunt, 2009)

2.6 Material of artificial hip implant

The material utilised to manufacture artificial hip implants should be biocompatible to reduce rejection risk and minimise toxicity. The increase in number of young patients using artificial hip implant has maximise application of bearing materials. The material characteristics of artificial hip implant components play a vital role in improving durability as human body environment is highly corrosive (English *et al*., 2015). The components material of artificial hip implant in total hip replacement (THR) surgery is as below:

Acetabular cup: The acetabular cup which held into pelvis or bearing surface is typically fabricated from Ultra-High-Molecular-Weight Polyethylene (UHMWPE). UHMWPE is an appealing material due to its low wear rate, low friction, good impact resistance, high toughness and good biocompatibility characteristics. Besides that, Highly Cross-linked Polyethylene (HXLPE), alumina ceramics, zirconia ceramics and cobalt-chrome alloy are also common materials to manufacture acetabular cup (English *et al*., 2016).

Femoral head: Artificial hip implant femoral head are commonly manufactured using cobalt-chrome alloys, stainless steel (high grade) and ceramic. Cobalt-chrome alloys usually compatible with UHMWPE acetabular cup besides displaying superior corrosion resistance, reduced inflammation, high wear resistance, high hardness and excellent biocompatibility characteristics. Thus, it enables comparatively successful performance to be utilised in orthopaedic application (Brown & Lemons, 1996; Kohn, 1998). In addition, ceramic material also suitable for femoral head due to its low friction which can reduce wear rate and wear debris.

Modular stem: Artificial hip modular stem which fixed into femur bone medullary cavity is made up of titanium alloys (Ti-6Al-4V). Ti-6Al-4V is low weight high strength material compared to other orthopaedic alloys *(*Apostu *et al.,* 2018*;* Fokter *et al*., 2017*)*. In addition, Ti-6Al-4V alloy exhibiting good tissue tolerance, high wear and corrosion resistance. Cobalt-chrome alloy or stainless steel also used to fabricate modular stem but very seldom (Malahias *et al*., 2020).

Different materials are combined to manufacture artificial hip implant components to achieve different interfacial properties. Material combination term is basically referring to bearing material combination in acetabular cup and femoral head. There are numerous material combinations for surface articulation in manufacturing artificial hip implants i.e. Ceramic-on-plastic (CoP), Metal-on-Plastic (MoP), Metal-on-Metal (MoM) and Ceramic-on-Ceramic (CoC).

CoP and MoP: High cross-linked Polyethylene and UHMWPE are common plastics employed in CoP and MoP application due to high wear resistance compared to other types of plastics. However, it exhibits high wear rate if compared with ceramic and metal materials (English *et al*., 2015). UHMWPE plastic permits the usage of larger femoral head and perform well as good shock absorber to allow greater mobility during human activities.

CoC: This category of artificial hip implant protects the surface by minimising scratch possibilities and ensure couples experience limited deterioration due to wear. In fact, CoC displaying 10% of less wear compared to MoM type artificial hip implant. The application of thinner acetabular cup is possible using CoC type due its strength. Thus, larger femoral head can be fitted into smaller acetabular shell. Besides that, it offers

wider motion range, good bearing and higher stability in young patients. However, CoC artificial hip implants are expensive, squeaking, brittle and unpleasant to patients (Wu *et al*., 2016).

MoM: The key advantage of MoM type artificial hip implant is hardness differences. The MoM type artificial hip implants are manufactured from various metallic alloys i.e. cobalt-chromium alloys. MoM type implants are hard and not brittle compared to ceramic types. Meanwhile, MoM hip implants displaying higher scratch and wear resistance when compared with plastic type. MoM type also permits larger femoral head diameter for constant acetabular shell size which able to provide wider hip motion range along with lower bone resorption, less wear, lower dislocation risk, minimised offset problems and easier revision surgery. The MoM coupling is susceptible to metallosis and infection which leads to increased failure rate (Milošev *et al*., 2000). Thus, there is great necessity for smooth articulating bearing surface in femoral head and acetabular cup to minimise wear accompanied by allowing required hip movement. It has been suggested that UHMWPE acetabular cup with cobalt-chrome femoral head offer excellent bearing surfaces combination. Besides that, the combination of cobalt-chrome femoral head and titanium modular stem extensively used in hip related orthopaedic devices (English *et al*., 2015).

2.7 Metallic artificial femoral stem

The artificial femoral stem design transformed in many ways in term of design since the introduction of Charnley femoral stem in 1960's. As a result, more diverse types of artificial stems are manufactured as shown in Figure 2.6. Artificial hip implant technology continuously evolving as new methodologies and designs have been introduced. There are 62 types of artificial hip implant manufactured by 19 different companies (Hongyu & Blunt, 2009).

Figure 2.6: Different artificial femoral stem designs (Hongyu & Blunt, 2009)

The metallic artificial femoral stem offers geometry and cost flexibilities without any doubt. However, difficulty arises in choosing optimal artificial femoral stem for patients by considering long term follow up requirement in order to evaluate new femoral stem performance (Salentiny *et al*., 2018). It is reported that several new designs cause patient's discomfort and premature failure which requires revision surgery in less than 5 years. Thus, new femoral should be tested in term of sustainability before market release. Continuous development should be given an insight to improve longevity of total hip replacement surgery (THR) (Johanson, 2017). In recent time, Charnley, Stanmore, Exeter and Müller artificial femoral stems are used as benchmark compared to other stem designs due to better evaluation and long term durability (Hongyu & Blunt, 2009).

There are two major design categories such as modular and monoblock artificial femoral stems as shown in Figure 2.7. Femoral stem and head are fabricated as a single component in modular stem design which able to solve complications of monoblock design femoral stem application in special hip joint anatomy patients (Hongyu & Blunt, 2009). In addition, modular design femoral stem provides flexibility of femoral head size, neck length and combination material variation. For example, combination of material improves the wear resistance in femoral head (cobalt chrome alloy) and excellent mechanical properties is achieved by femoral stems when

manufactured by titanium alloys or stainless steel. Femoral head polished smoothly prior to fixation with femoral stem to facilitate less friction rotation in prosthetic socket.
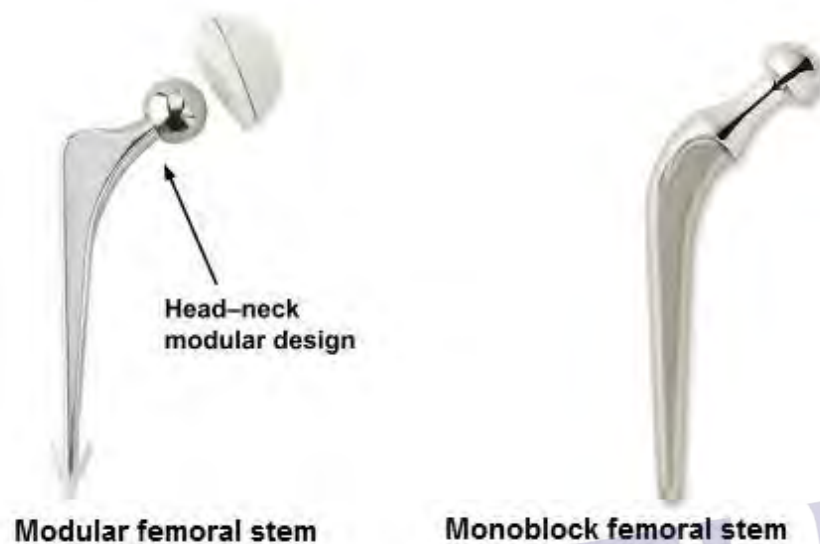
Figure 2.7: Different designs of artificial femoral stems (Hongyu & Blunt, 2009)

2.7.1 Stem material

In artificial femoral stem designing process many variables such as material, geometry and surface finish should be considered. Optimal tribological and mechanical characteristics, biocompatibility, human body physical environment and loading regime in femoral stem significantly influences material selection (Hongyu & Blunt, 2009).

The material of artificial femoral stem should withstand active individual's physical loading according to their activities and day-to-day utilisation. The material's strength in term of yielding and fatigue no longer a critical issue as most of the materials used to fabricate femoral stems are stronger. However, stress shielding should be given an attention as one of the material selection design constraint. Reduction in bone density as stiffer implant transmits much load and initiating high

stress gradient between femur lower section and cancellous bone is known as stress shielding (Hongyu & Blunt, 2009).

Stress shielding can cause discomfort and pain to patients. Therefore, material selection should be performed considering similar stiffness, strength, mechanical properties and density to minimise stress shielding effect. Lately, titanium alloys, cobalt chrome alloys and stainless steels are most common materials to manufacture artificial femoral stem because of their excellent biocompatibility, tribological and mechanical characteristics (Nagentrau *et al*., 2019).

Unfortunately, these materials are much stiffer with higher yield strength than bone which might results in stress shielding. Besides that, artificial femoral stem made from titanium alloys susceptible to fail earlier compared to cobalt chromium and stainless-steel materials as occurrence of crevice corrosion due to gap generation between stem-bone/cement or head-taper. Present study focussing on artificial hip stem manufactured from titanium alloy.

2.7.2   Stem geometry

Stem geometry is an important variable in artificial femoral design as it can affect directly in-vivo behaviour and subsequent failure mechanism of total hip replacement (THR) (Fokter *et al*., 2017). In fact, certain artificial femoral stems have been removed from market due to their poor short-term survival rate which is highly design dependent. The optimal design of femoral stem should be able to transfer load in axial and torsional direction without stress singularity and excessive micromotion between cement-implant (cemented THR) and HAp-implant (uncemented THR) interfaces as shown in Figure 2.8.

Artificial femoral stem geometry encompasses overall shape (anatomical/symmetrical), cross-section (square/oval), flange and collar presence, stem tip shape and stem length. Besides that, double/triple taper design and greater/lesser degree of rounded edges are influencing stem geometry (Hongyu & Blunt, 2009). Femoral stems with symmetrical geometry design exhibiting excellent clinical performance. The number of artificial femoral hip stem geometry designs rapidly increasing in market. Thus, effective clinical assessment in term of performance and durability should be performed on new design femoral stem.
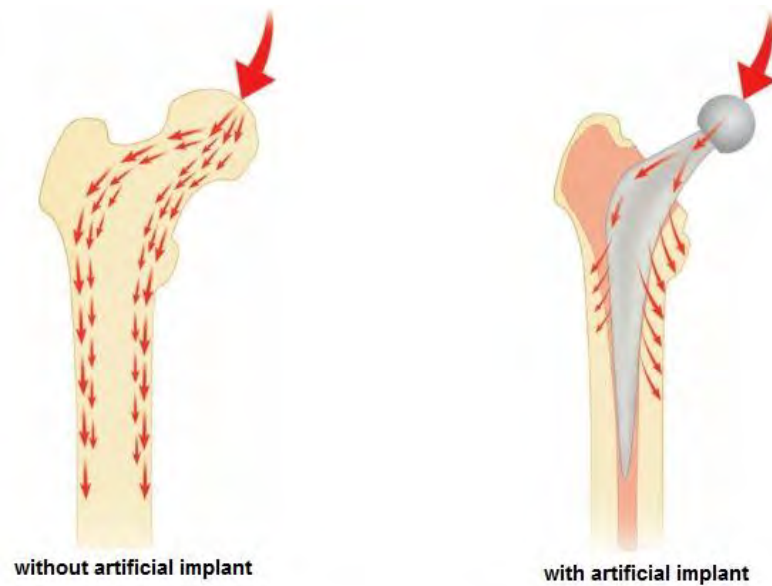
Figure 2.8: Load transfer patter with and without artificial hip implant (Hongyu & Blunt, 2009)

2.7.3 Stem surface finish

Artificial femoral stem surface finish is another vital design property which vary among different type of femoral stems. The effect of stem surface finish on total hip replacement (THR) performance have been disputed for long time as no specific standard available regarding this variable (Hongyu & Blunt, 2009). Certainly, the texture of femoral stem surface having direct influence on bonding strength at stem-HAp coating/stem-cement interfaces. Matte femoral stems could promote bond strength at interface compared to polished femoral stems which as HAp coating or bone cement attachment will be enhanced.

Matte and polished femoral stems often known as closed design and force closed design which depend on stem mechanical taper locking to accomplish self-tightening properties. Although matt surface finished stem can promote bonding at interface but inclined to generate more debris and sourcing severe interfacial damage once delamination/debonding occurs. This indicates thick and good quality with strong interface are required to minimise delamination failure. From clinical point of view, stem surface finish is a complex matter and still under investigation since there is not

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