MICRO-CRACK CHARACTERIZATION FOR METAL-ON-METAL HIP IMPLANT OF TEXTURED SURFACE USING ELECTRICAL DISCHARGE MACHINING

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DEDICATION

Special dedicated to:

My beloved husband, Muhammad Nabil bin Mohd Warid

My beloved daughter, Nuraa Maisara binti Muhammad Nabil

My dear father, Hashim bin Ibrahim

My dear mother, Halimah binti Abu Nasir

My dear father-in-law, Mohd Warid bin Hussin

My dear mother-in-law, Wan Kamaliah binti Wan Ahmad

And all my dear family members.

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ABSTRACT

In hip implant, it has been proven that surface texturing which is also known as dimples can improve the lubrication performance and reduce friction. However, little attention is paid to the effect of textured surface by assessing the crack formation on the dimple areas. This research focuses on the formation of cracks on dimple edges during manufacturing process using electrical discharge machining (EDM) as higher stress is produced in this area. The crack formation then was observed during operational use of metal-on-metal (MoM) hip implant in the case that the dimples parameters are not fully optimized. For dimple manufacturing on a S45C mild steel material, machining angles was varied at 50°, 70° and 90° using developed workpiece positioning system in this research. The pulse currents were set at 1 A, 2 A and 3 A. Cracks formed on the dimple edge after the machining were observed using Scanning Electron Microscope (SEM) and measured in terms of its length. Then, nine dimples were machined on the samples of acetabular cup part using the chosen EDM parameters. Friction screening on the hip implant samples with femoral head of 28 mm diameter and radial clearance of 30 µm was carried out using four-ball bearing machine. The loads varied up to 250 N, 500 N and 1000 N representing the loading gait in the hip joint. The formation of cracks on the dimple edges for each load was then observed. The experimental results showed that when lowest current 1A was applied, the micro-cracks total length appeared during EDM process increased substantially. For MoM hip implant, it was found that the optimal setting for the EDM machining was 3 A at 90° machining angle, taking into account the curved hip implant surface. However, more than 50% of the cracks formed during machining were removed after loading due to surface grooving. It is suggested that it is suitable to machine the dimples on the hip implant surface using EDM in terms of crack formation. While new cracks formed after the loading were found to be far more dominant than the original cracks due to EDM machining. The cracks were found to be much wider and longer especially with the imposition of the maximum load of 1000 N. The contribution of this study is on the effect of crack formation on hip implant improvement, as well as providing basic data of textured surface in hip implant. This is because the crack formed can cause wear and friction which can lead to wear fatigue in hip implant thus shorten lifespand its lifespan.

ABSTRAK

Dalam bidang implant pinggul, telah dibuktikan bahawa tekstur permukaan yang juga dikenali sebagai lubang dapat meningkatkan sifat-sifat tribologi dan mengurangkan geseran. Namun begitu, terlalu sedikir perhatian diberikan kepada kesan tekstur permukaan ini dengan melihat kepada penghasilan retak. Penyelidikan ini fokus kepada penghasilan retak pada kawasan di pinggir lubang semasa proses pemesinan menggunakan mesin EDM kerana kawasan ini merupakan kawasan yang mempunyai tekanan yang tinggi. Penghasilan retak mikro juga diperhatikan semasa penggunaan operasi implan pinggul *Metal-on-Metal*, MoM sekiranya parameter lubang tidak optimum sepenuhnya. Bagi menghasilkan lubang, sudut pemesinan diubah kepada 50°, 70° dan 90° menggunakan sistem kedudukan EDM yang telah dibina. Arus yang digunakan diubah dari 1 A, 2 A dan 3 A. Retak yang terbentuk selepas pemesinan diperhatikan menggunakan Mikroskop Pengimbasan Elektron (SEM) dan dianalisis dari segi panjangnya. Kemudian, sembilan lubang kecil dimesin pada beberapa sampel bahagian acetabular implan pinggul menggunakan parameter EDM yang menghasilkan parameter EDM yang terpilih. Pemeriksaan geseran juga dilakukan pada sampel implan pinggul dengan diameter kepala femoral sebesar 28mm dan pelepasan jejarian 30 μm menggunakan penguji galas bebola. Beban yang digunakan diubah sehingga 250 N, 500 N dan 1000 N mewakili beban yang ditanggung oleh pinggul. Pembentukan keretakan di permukaan dan pinggir lubang bagi setiap beban diperhatikan. Daripada kajian ini, didapati kejadian retak menjadi bertambah teruk dari segi jumlah dan panjang retak apabila arus paling rendah iaitu 1 A digunakan. Untuk aplikasi implant pinggul, didapati tetapan yang optimum untuk pemesinan EDM adalah menggunakan 3 A dan sudut 90 ° dengan mengambil kira permukaan melengkung pada permukaan implan. Walau bagaimanapun, lebih daripada 50% retak yang dibentuk semasa pemesinan terhakis dan tidak kelihatan lagi selepas ujian pemeriksaan geseran. Ini menunjukkan bahawa pemesinan EDM sesuai digunakan untuk memesin lubang pada permukaan implan pinggul. Manakala retak baru yang didapati wujud selepas beban dikenakan adalah lebih dominan berbanding retak asal disebabkan oleh pemesinan EDM. Retak yang terhasil lebih panjang dan lebar apabila berat 1000 N dikenakan. Penyelidkan ini menyumbang kepada pengetahuan dan memberikan data asas penghasilan retak dalam bidang tekstur permukaan untuk penambahbaikan yang selanjutnya. Ini kerana retak yang terhasil menyebabkan permukaan implan semakin haus seterusnya memendekkan lagi jangka hayat implan.

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LIST OF ABBREVIATIONS

EDM	-	Electrical Discharge Machining
SCD	-	Surface Crack Density
ECD	-	Edge Crack Density
MoM	-	Metal-on-Metal
VP- SEM	-	Variable-Pressure Scanning Electron Microscopy
WLT	-	White Layer Thickness
SR	-	Surface Roughness
ROI	-	Region of Interest

LIST OF SYMBOLS

V_w	-	Wear volume
W_y	-	Normal load
x	-	Sliding distance
R_1	-	Radius of femoral head
R_2	-	Radius of acetabular cup
c	-	Radius clearance
a	-	Contact radius
η	-	Lubricant viscosity
Vm	-	Volume of material removed
m	-	Weight of material removed
ρ	-	Density of workpiece
E	-	Young modulus
v	-	Poisson's ratio
Qu	-	Energy surface flux density
V	-	Voltage
I_p	-	Pulse current
T_{on}	-	Pulse on-time
T_{off}	-	Pulse-off-time
L_c	-	Crack length
L_{cu}	-	Crack length for upper side of dimple
L_{cl}	-	Crack length for lower side of dimple
$\sum L_c$	-	Total crack length for each dimple
C_H	-	Horizontal crack
C_V	-	Vertical crack
C_R	-	Crack along recast layer
C_N	-	Network crack

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Human hip joint is a ball and socket joint, consisting of a femoral head and acetabular cup that connects the lower limb to the pelvic girdle. It is designed to accommodate a wide range of movements while transmitting large dynamic loads involved in many daily human activities. Therefore, hip joint is expected to function well throughout human life. It has the risk of diseases such as osteoarthritis, rheumatoid arthritis, and trauma, for which certain conditions may require these natural bearings to be replaced with artificial ones which are also called hip implants [1]. Implant replacement surgery of hip joint consists of joint substitution with an implant that can recreate the articulatory function [2].

Although hip replacement has been recognized as the most successful treatment for hip joint diseases, it still shows some drawbacks. It is shown statistically that not all implant devices can survive in the long run in which they need to be revised [3]. The most common causes of revision are repetitive dislocation, mechanical failure such as wear and tear, loosening and also infection. Over the years, many research have been conducted to investigate and improve the performance of the implant devices and prolong its lifespan, especially in improving the tribology performance in terms of material and bearing design [4,5]. Tribology is a study of wear, friction and lubrication of a joint. In order to reduce wear and friction that occur in hip implant, lubrication activities must be presented. However, there was no enough room or space for lubricant to be sustained into the space between the acetabular cup and femoral head of the implant devices [6]. Therefore, many previous researchers hve shown their interest in studying the effect sof textured surface machining on hip implant joints to improve lubrication in the implant devices [7,8].

Surface texturing is a well-defined identical feature of discrete dimples or grooves on a surface. With a lot of research that have focused on reducing wear on hip implants by improving the bearing design and bearing materials, some studies investigate the effects of performance using surface texturing approach [2,9–11]. Surface texturing, which is also known as a hole, oil-pocket, dimple, or cavity, is a feasible method for contact performance enhancement in terms of load-carrying capacity, film thickness, friction, and wear. Various simulation models have been developed to explain the phenomena of tribology for a textured surface. There are several benefits of surface texturing on lubrication performance [12]. The hydrodynamic effect in which the flow approaching the dimple can increase the pressure, thus generating an additional load-carrying capacity [13]. Surface texturing also has the secondary lubrication effect which acts as the regime of mixed lubrication [14]. In this case, the textured surface acts like a reservoir where fluid is trapped in the textured region. It can be considered as a secondary source of lubricant in reducing friction. The trapped fluid can prevent direct contact between surfaces, hence reducing the risk of wear. Finally, the textured features can capture any wear debris formed, which can reduce abrasive wear between the contact surfaces [15].

To fabricate textured surfaces, there are many machining techniques that can be used such as laser surface texturing (LST), computer numerical control (CNC) micro drilling, CNC ultrasonic, chemical etching, electrochemical machining (ECM) and electrical discharge machining (EDM). However, due to the limitations of certain machining techniques such as surface defects that offer direct contact machining with CNC drilling, poor fatigue properties after ECM machining in which some of them require high cost for complex machining. It can be seen that EDM is of great interest in the current research scenarios for surface modifications of metallic biomedical applications [16,17]. Therefore, this research will utilize electrical discharge machining (EDM) technique. EDM is a non-traditional precision machining process that removes electrically conductive materials into the desired shape in terms of spark energy. It is a non-contact process in which there is no physical contact between the electrode and the workpiece. This can help eliminate mechanical stresses, chatter, and minimize vibration during the machining process, producing better surface finish and accuracy.

Recently, many studies have been conducted to investigate the improvement of EDM performance. EDM process involves many parameters. They can be divided into two categories, namely electrical parameters, such as pulse on time, pulse of time and supply voltage and the non-electrical parameters, such as dielectric type, tool material, and flushing type. The performance parameters typically measured in EDM are material removal rate (MRR), tool wear rate (TWR), machining time, and surface quality [18,19]. Surface quality is determined by the surface roughness of the machined materials, the formation of white layer thickness, and also the formation of crack. Most cracks caused by EDM are in micro-crack scale. Micro-crack is one of the common problems occurred during the machining process and is discussed among researchers [20, 23].

In addition to the formation of cracks due to the manufacturing, cracks can also occur due to the use of device in operation under certain loads and conditions. Crack is an unwanted feature that commonly occurs in engineered parts. It significantly reduces the material's ability to withstand loads. It usually starts small and continues to grow during operational use. During sliding between two metal surfaces, the forced contact between them can produce deformation and extension of microscopic cracks. The crack growth due to cyclic loading is called fatigue crack growth. When the crack grows until it reaches a critical size, failure will occur. Repeated cyclic loading cause crack to propagate, leading to the formation of particles. Some of them removed from the surface as wear particles. They are one of the main causes of most implant failure, which must be avoided or at least reduced [24, 25].

1.2 Problem Statement

Surface engineering is a field that deals with the surface of solid matter to achieve superior performance and durability. This includes surface texturing, a proven approach that can improve the tribological properties of mechanical components. It can also reduce friction by providing micro-hydrodynamic bearings, enhancing load support and acting as a reservoir for lubricant [12;[26][27]. Textured surface studies on hip implant have been extensively researched by many researchers [8]. Most of the studies focus on experimental works to investigate the mechanism of surface texturing in improving lubrication performance by reducing wear and friction [28]. Studies using computational modelling have also been conducted to determine the optimum parameters of surface texturing that can increase film thickness and hydrodynamic pressure on the contacted surfaces on hip implants [29][30]. From previous studies, it can be concluded that it is difficult to determine an optimal texture design for hip implant since it is highly dependent on the type of contact and operating conditions. Besides that, the manufacturing and fabrication processes of the dimple are among the factors that can determine the role of surface texturing approach.

Electrical Discharge Machining (EDM) method to fabricate surface texture will be applied in this research as it has more advantages in micro-machining compared to other conventional machining methods. This is due to the ability of EDM to improve the surface properties of implants, whose healing time is shortened, and bone formation increases. This has been proven in many research that EDM can provide better potential surface for osteoblastic cell attachment [16]. However, the use of EDM for surface modification of biomaterials is limited due to fatigue performance which can still result in high surface roughness and one of the drawbacks in EDM is that the machined area is exposed to crack formation during the machining process which can decrease the fatigue performance of the biomedical implant devices [31].

During machining, a white layer (also known as recast layer) filled with carbon will form from the molten material that is not removed. The layer is heated to the point of the molten state but not hot enough to be forced into the gap through flushing. A rapid heating and cooling in EDM machining will produce considerable stress in the recast layer and once the magnitude of this stress exceeds the yield stress of the recast layer, micro-cracks will form [32]. The presence of micro-cracks in EDM is usually in the size of a white layer and extends perpendicular to the analysed surface, rarely penetrating the recast layer. Some research indicate that the micro-crack formation in EDM machining is best presented and measured in terms of average crack length and surface crack density (SCD) [33].

Previous studies in EDM investigated the effects of related parameters on the crack formation, such as pulse current, electrode material, and dielectric type and flushing system. They conclude that pulse on time and peak current lead to an increase in heat conditions causing the length of the crack to expand. In this study, the effect of machining angle on crack formation is investigated because of the curved nature of hip implant surface. This is because to date, no research on the effects of machining angles on the formation of cracks in EDM is conducted. In hip implant applications, to produce a consistent depth and diameter, the dimples will be machined perpendicular to the acetabular cup surface to standardize the position of the micro pit [34]. Therefore, the EDM in this study will be equipped with a jig as the workpiece positioning system. The jig will allow the EDM to machine the dimples from various angles, including perpendicular to the curved surface of the hip implant.

In terms of the use of hip implant in operational conditions, the performance of dimples should also be accessed. This is because the crack formation and the repeated cyclic loading can cause small particles to be generated between the sliding contacts, which can lead to secondary wear [24] that may shorten the lifespan of the hip implant devices. As mentioned before, there are many studies conducted in tribology performance of the textured surface of hip implant, which include the film thickness, hydrodynamic pressure, and friction coefficient. However, little attention is paid to the effects of textured surface on the devices by evaluating the crack formation of the textured curved surface of the hip implant. This is because not all surface texturing will give the desired effect. Some may improve, but others may worsen the surface contact performance. Hence, in this research study, performance tribology test will be conducted to investigate the effects of dimple machining to the friction coefficient, as well as the formation of cracks on metal-on-metal (MoM) hip implant. It is expected that cracks will be formed at positions with higher stress. Based on a finite element analysis (FEA) study, high stress position is located at the dimple edges [35].

Crack studies are important as cracks on the dimple edges can be the main source of the formation of wear particles and can cause fatigue and implant failure. This research will provide fundamental data in the field to improve the study of hip implants. This is to ensure that the future research can focus more on the manufacturing of the dimples. This research is expected to provide clearer idea on the factors contributing to the crack formation on a textured surface of MoM hip implant and which type of crack is more pronounced, either due to EDM or operational use of the hip implant itself.

Overall, this research will cover the following research questions:

(a) Can the applied pulse current used in EDM and machining angle of the dimple affect the crack formation on a workpiece?

(b) How to machine a standard-sized dimple on a curved surface of the acetabular cup?

(c) Can dimple machining improve the friction coefficient of the articulating surface?

(d) What is the effect of dimple machining on crack formation?

1.3 Objectives

This research aims to investigate the behaviour of cracks caused by EDM and to identify whether high load conditions will result in significant micro-crack growth or crack formation on the EDMed textured surface of MoM hip implant. This aim will be achieved through the following objectives:

(a) To investigate the effects of different machining angles and EDM pulse currents on the crack formation on dimple edges using a customized jig as workpiece positioning system.

(b) To evaluate the effects of applied load with reference to the crack formation on the EDMed dimples.

(c) To classify the types of new cracks formed on the EDMed dimples edge after loading.

1.4 Hypothesis

There are three hypotheses made for this research which are as follows:

(a) Different angles of machining by EDM will have different effects on crack formation.

(b) A new crack will form after several loading cycles applied to the bearing devices on the dimple edges, the location with the highest stress point.

(c) Surface texturing will reduce friction coefficient, but cracks can still form on the dimple edges.

1.5 Scope and Limitation

The scopes of this research are as follows:

(a) This research is conducted on metal-on-metal (MoM) hip implant application, using S45C mild steel material head of 28 µm in diameter and 30 µm of clearance.

(b) The parameters that are varied during machining using developed EDM available are pulse current (1 A, 2 A, and 3 A) and machining angles (50°, 70°, and 90°).

(c) The crack analysis is performed on the original EDMed dimple surfaces, which does not undergo any treatment process such as polishing or coating, after machining.

(d) The observation of the cracks using SEM is conducted only on the dimple edge of the contacted surface between femoral head and acetabular cup by measuring crack length in image j software and measured using edge crack density (ECD).

1.6 Significances and Original Contributions of This Study

It is known that surface texturing can enhance tribology performance in sliding contact by reducing its friction and wear. However, in the manufacturing aspect, it is still not clear whether dimple formation on implant devices will be beneficial or cause a contradicting effect on the devices in the long term. It seems that crack formation also needs to be taken into consideration in texture surface for hip implant but studies on it are still found to be few. Therefore, this research will investigate the effects of dimple machining and the effects of operational use of the MoM hip implant on the crack formation. The findings in this research will provide significant findings on crack formation for future work such as for simulation to estimate the life of hip with surface texturing and to determine the best method for machining of dimples on the hip implant surface. This is because, to date, research is still of interest among researchers and still being conducted to find the best method or strategy to prlong the life of implants.

1.7 Thesis Structure and Organization

This thesis consists of 5 chapters. Chapter 1 presents the introduction of this research, which includes the research background and highlights the research gap. This chapter consists of background of the study, statement of problem, objectives of the study, scope of the study, and significance of the study. Chapter 2 reviews previous literature on human hip, hip implant, EDM, surface texturing and tribology experiment in a hip implant. Chapter 3 on the other hand provides a detail explanation of the overall methodology used in this research study. Chapter 4 discusses the findings found from the experimental works conducted in this study. Findings of the crack formation, as well as the analysis, are further discussed in this chapter. Last but not least, the conclusion of the findings is presented in Chapter 5. The limitations and recommendations for future work are also highlighted in this chapter.

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