Faculty of Manufacturing Engineering

OPTIMISATION OF MILLING PARAMETER AND ANNEALING CONDITION FOR MACHINING POLYETHERETHERKETONES (PEEK) BIOMATERIALS IMPLANT

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OPTIMISATION OF MILLING PARAMETER AND ANNEALING CONDITION FOR MACHINING POLYETHERETHERKETONE (PEEK) BIOMATERIALS IMPLANT

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APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Master of Science in Manufacturing Engineering..

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DECLARATION

I declare that this thesis entitled “Optimisation of Milling Parameter and Annealing Condition for Machining Polyetheretherketones Biomaterials Implant.” 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	:	....
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Date	:	....

DEDICATION

Special dedicate to all persons that help me in completing my Master research especially to my project supervisor Dr. Raja Izamshah bin Raja Abdullah and co-supervisor Dr. Mohd Amran bin Mohd Ali.

To my beloved parents, my sweet family, thank you for your comfort and supported me...

And not forgotten, thanks to technicians and friends…
This report I'm fully dedicate to all of you…

ABSTRACT

Polyetheretherketones (PEEK) which has been widely used in many applications is now commercialized as implant components because of its biodegradability and non-allergic reactions compared to the metal implants. Generally, implants are fabricated by extrusion and injection molding for a larger scale. However, often for prototype designs or patient specific implant designs, it is not economically viable to manufacture by an injection molding. Under such circumstances, it is common to employ a machining process on the PEEK materials to form the components. However, milling parameters are the factors that have to be considered in the machining process to reduce the defects to the minimum and increase its durability. Apart from milling parameters, annealing also plays important roles in reducing residual stress and improving surface finishes. Thus, this research aims to develop exact milling parameters prior to the annealing process for machining PEEK material in order to enhance the machining performance and productivity. To achieve the objective, both statistical and experimental techniques were employed for the methodology. Response surface methods (RSM) were used to get the mathematical models and ANOVA analysis while milling parameters (feed rate, depth of cut and cutting speed) were used in order to get the machining performance on surface roughness, machining force, dimensional accuracy and material removal rate. Through experiments, the optimised parameters have improved the machining performance and qualities prior to the annaeling. The conclusions provide a theoretical basis for the annealing technique where the increased of the percentage crystalline, it helps improving the properties and the materials structure which leads to improve the machinability of the materials. Milling parameters (feed rate, depth of cut and cutting speed) are important factors in machining process and significantly affect the machining performances. To obtain 0.87µm surface finish, unannealed PEEK with 25.3 percentages crystalline will be using cutting speed 150.8 mm/min, feed rate of 0.035mm/tooth and 2mm depth of cut. PEEK annealed with 200°C increase crystalline to 30.3 percentages using high cutting speed (150.8 mm/min), low feed rate (0.033mm/tooth) and low depth of cut (2mm) can produce 0.4µm surface finish. PEEK annealed with 250°C has 30.9 percentages crystalline and 0.39µm surface finish can be obtained by using high cutting speed (150.8 mm/min), low feed rate (0.034mm/tooth) and low depth of cut (2mm). Therefore, milling machining is recommended to be further used in fabricating PEEK biomedical implants.

ABSTRAK

Polyetheretherketones (PEEK) telah digunakan secara meluas dalam banyak aplikasi yang sekarang dikomersialkan sebagai komponen implan kerana biodegradability dan tiada tindak balas alergi berbanding implan logam. Secara umumnya, implan adalah dimesin oleh penyemperitan dan acuan suntikan pada skala yang lebih besar. Walau bagaimanapun, untuk reka bentuk prototaip atau reka bentuk khas pesakit, ia tidak praktikal dari segi ekonomi untuk dibentuk oleh acuan suntikan. Oleh itu, ia adalah perkara biasa untuk menggunakan proses pemesinan pada PEEK untuk membentuk implan. Walaubagaimanapun, parameter pengilangan adalah faktor-faktor yang perlu dipertimbangkan dalam proses pemesinan untuk mengurangkan kecacatan kepada minimum dan meningkatkan ketahanannya. Selain daripada pengilangan parameter, penyepuhlindapan juga memainkan peranan penting dalam mengurangkan tegasan baki dan meningkatkan kemasan permukaan. Oleh itu, kajian ini bertujuan untuk membangunkan parameter pengilangan tepat sebelum proses penyepuhlindapan untuk pemesinan bahan PEEK untuk meningkatkan prestasi pemesinan dan produktiviti. Untuk mencapai matlamat tersebut, kedua-dua teknik statistik dan eksperimen telah digunakan untuk metodologi. Kaedah gerak balas permukaan (RSM) telah digunakan untuk mendapatkan model matematik dan analisis ANOVA manakala parameter pengilangan (kadar suapan, kedalaman pemotongan dan kelajuan pemotongan) telah digunakan untuk mendapatkan prestasi pemesinan pada kekasaran permukaan, kuasa pemesinan, ketepatan dimensi dan bahan kadar penyingkiran. Parameter yang optimum meningkatkan prestasi pemesinan dan kualiti bersesuaian dengan penyepuhlindapan. Kesimpulan menyediakan asas teori untuk teknik penyepuhlindapan dimana peningkatan peratusan kristal membantu meningkatkan sifat-sifat dan struktur bahan-bahan dimana ia meningkatkan kebolehupayaan memesin bahan. Parameter pengilangan (kadar suapan, kedalaman pemotongan dan kelajuan pemotongan) adalah faktor penting dalam proses pemesinan dan ketara memberi kesan kepada persembahan pemesinan. Untuk kemasan permukaan 0.87µm, PEEK tanpa penyepuhlindapan dengan 25.3 peratus kristal akan menggunakan pemotongan kelajuan 150.8 mm/min, kadar suapan daripada 0.035mm / gigi dan 2mm kedalaman pemotongan. PEEK dipenyepuhlindapan pada 200°C peningkatan kristal kepada 30.3 peratus menggunakan kelajuan pemotongan tinggi (150.8 mm/min), kadar suapan rendah (0.033mm / gigi) dan kedalaman pemotongan rendah (2mm) boleh menghasilkan kemasan permukaan 0.4µm. PEEK dipenyepuhlindapan pada 250°C dengan 30.9 peratus kristal dan 0.39µm kemasan permukaan boleh diperolehi dengan menggunakan kelajuan pemotongan tinggi (150.8 mm/min), kadar suapan rendah (0.034mm / gigi) dan kedalaman pemotongan rendah (2mm). Oleh itu, pemesinan pengilangan adalah disyorkan untuk terus digunakan dalam reka PEEK implan bioperubatan.

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LIST OF ABBREVIATIONS

PEEK - Polyetheretherketone

PEEK CF30 - Carbon reinforced of PEEK

PEEK GF30 - Graphite reinforced of PEEK

PSI - Patient Specific Implants

CT - Computer Tomography

CAD - Computer Aided Design

CAM - Computer Aided Manufacturing

CNC - Computer Numerical Control

MRI - Magnetic Resonance Imaging

UL - Underwriters Laboratories

LOI - Limiting Oxygen Index

HSS - High Speed Steel

3D - Three Dimensional

DSC - Differential Scanning Calorimetry

MRR - Material Removal Rate

RSM - Response Surface Methodology

DOE - Design of Experiments

ANOVA - Analysis of Variance

CMM - Coordinate Measuring Machine

PCD - Polycrystalline Diamond

MMCS - Metal Matrix Composite

LIST OF SYMBOLS

μm - micro meter

°, ° C - degree, degree Celcius

Pa, Mpa, Gpa - pascal, mega pascal, giga pascal

J/g - joule/gram

g/ $cm3$ - gram per centimetre cube

kg / $m3$ - kilogram per meter cube

mm/ tooth - millimetre per tooth

mm/min - millimetre per min

mm/rev - millimetre per revolution

rpm - revolution per minute

% - percent

R_a - Roughness average

R_q - Root Mean Square Roughness

R_y - Maximum Peak-Valley Roughness

n - number of samples

y, ȳ - measured data, average measured data

N - spindle speed

V_c - cutting speed

D - the cutter diameter

V_f - feed rate

f_z - feed per tooth

N - spindle speed

N - number of tooth

F_s - shear force

N_s - normal shear force

R - resultant force

F - friction force

F_t - tangential force

F_c - cutting force or radial force

ΔHm - melting enthalpy of sample

ΔHm^0 - melting enthalpy of 100%

LIST OF PUBLICATIONS

1. R. I. Raja Abdullah, A. Yu Lung, M. A. Mohd Amran, M. S. Kasim, A. B. Mohd Hadzley, S. Subramonian, "Optimisation of Machining Parameters for Milling Polyetheretherketones (PEEK) Biomaterial", Applied Mechanics and Materials, Vol. 699, pp. 198-203, Nov. 2014

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"Optimization of Milling Parameter for Untreated and Heat Treated Polyetheretherketones (PEEK) Biomaterials", Applied Mechanics and Materials, Vol. 761, pp. 293-297, May. 2015.

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CHAPTER 1

INTRODUCTION

This chapter describes the introduction of the research and briefly explains the problem statements and objectives in the research. The scope and the outline of the research are fully described in this chapter.

1.1 Background

Polyetheretherketones also known as PEEK materials are semi-crystalline thermoplastics, aromatic ring structure bridging with repeating monomers of two ether groups and a keytone group linkages. PEEK is a rigid opaque material characterised by good mechanical properties maintained in high temperatures with a unique combination of properties, which include exceptional chemical, wear and electrical resistance.

Due to its biocompatibility, demands on PEEK start to increase especially on medical application. Proven by Davim et. al. (2003), PEEK is also well known for its high specific strength, high performance thermoplastic polymer and directional properties. PEEK has emerged as a leading biomaterial and most widely used for short and long terms implantable plastics in medical application like orthopaedics and traumatology. According to Green S. (2001), PEEK can be interesting material to replace titanium or other implantable materials because of their biocompatibility and high performance.

Marcus (2006) states that PEEK is attractive for both their mechanical properties and associated processing technologies, which enable medical device manufacturers to tailor their characteristics to meet certain needs. The ability to tailor the characteristics provides higher design freedom means that the device designers can consider factors other than the structural substitution of the natural tissue and ultimately lead to improved applications. Mechanical properties such as the strength, wear resistance and impact performance of PEEK can be comparable to metals and offer additional benefits.

Processing for some plastics can be easily scaled up to meet the increasing demand for product parts using injection moulding and extrusion. It is economic for large scale production, while complex shapes or small scale production can be formed as required using fabrication processes. In medical applications, it is common used as a machining process on the PEEK polymer materials to form the Patient Specific Implants (PSI).

Surface roughness is a vital factor for medical implants since the cells of the surrounding tissue interact with the underlying substrate on the micro and nanometer scales (Jasmine et. al. 2012). For some applications, such as self-mating articulation cervical disc implants smooth surface finish is critical so as to minimize the contact friction and wear. Nevertheless, the bone-cell adhesion is directly related to the surface integrity of the implant.

One of the major concerns in machining PEEK is to attain a good surface roughness and dimensional precision (Petropoulos G. et. al. 2008). The complex interaction between the matrix and reinforcement structure yield the gaps different between thermal and mechanical phase of PEEK. However, the machining knowledge acquired from metal cutting cannot be directly applied to the polymeric material without taking into account of the peculiar material response towards machining (Rahman M. et. al. 1999).

The milling process to fabricate implants is studied in this thesis. From the previous research on milling parameters, cutting speed has the greatest influence on the machining force and by reducing feed rate; the cutting pressure will also be reduced. Davim J. P. (2003) and Rahman M. (1999) both agreed that when the cutting speed increases, the quality of the surface finish will increase until a critical cutting speed is reached. As for the surface roughness, feed rate exerts the biggest effect to while cutting speed as second factor and the effects from depth of cut are the chip formation and cutting force have proven by Mata F. (2010). PEEK reinforced with carbon or glass fibre is highly recommended to use Diamond coated tools and unfilled PEEK are recommended to use carbide as the milling cutting tool.

Figure 1.1: Example of a PEEK implant fabricated using milling process

1.2 Implant Fabrication Techniques

In large scale production of conventional medical implants, injection molding and extrusion are used in the fabrications. However, the main downside of these processes is that, it only produces standard size implant. Therefore, the reconstruction method during surgery needs to be carried out to fit the standard- implant to human bones anatomy depending on the size and contour of the patients (Mahoney et. al. 2010).

Through the helps from the Computer Aided Design (CAD) technology, patients' specific implant design technique was introduced as an alternative technique to solve the problem. Patient specific implants are designed to customize a particular orthopedic patient. The production of patient specific implants started with the Computer Tomography (CT) scan data containing of implant prescription by the surgeon. The CT scan data will then be reconstructed by the manufacturer into a CAD model and creates the Computer Aided Manufacturing (CAM) code for machining purposes (Fadda et. al. 1998).

1.3 Problem Statement

To remain competitive, manufacturer is always seeking for product improvement and qualities by producing 'right first time' machined component. Machining processes are needed when there is a demand for prototype or custom made or complex shapes for the implants. However, the excellent physical properties and wear characteristics of these materials can pose a challenging machining process.

Apart from that, traditional manufacturing methods associated with metallic implants are generally not satisfactory for polymeric materials. Polymers are relatively soft when compared with implant alloys and this can create manufacturing problems related to machining, deburring, and cleaning operations. Extra knowledge is needed in order to produce high qualities PEEK biomaterials implants.

In fabricating PEEK implants, annealing plays important roles in reducing residual stress and improving surface finishes. Annealing is a heat treatment that alters the microstructure of a material causing changes in properties such as strength, hardness, and ductility. With the changes in properties, the machining parameters need to be changed according to the heat treatment. Due to the customers' high quality requirements and the high price of the materials, particular care and precision are required during machining.

1.4 Objective and Scope of Research

Both the difficulties and conventional cutting strategies for machining the PEEK materials cause to initiate this research. The objectives of this research are;

a) To investigate the correlation between the milling parameters (cutting speed, feed rate and depth of cut) and machining performances (surface roughness, machining force, accuracy and material removal rate).
b) To compare the milling parameter for effectively machining PEEK material prior to heat treatment.
c) To optimise and validate the parameters based on machining performance.

1.5 Research Phases

The proposed research is based on optimizing the milling parameter and annealing technique for effectively machining PEEK material. A systematic design of experiment principle will be used with the aim to investigate the correlation between the investigated parameters and machining performance such as component accuracy, surface integrity and machining force. The objective of this research will be achieved as follows;

a) Phase 1: Conceptual and Planning

Firstly, all of the fundamental knowledge on the concept/ theories/ practice on annealing and machining Polyetheretherketones (PEEK) material will be identified. Factors such as machining parameter, material properties, annealing procedures and performance measurement will be identified and studied. Based on the surveys of literature, preliminary proposed technical solutions on the design criteria will be made. Then, project planning will be carried out so as to minimize the risks and failure of the project.