UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF PRINTER NOZZLE FOR EXTRUDING SYNTHETIC BIOMATERIALS USING FUSED DEPOSITION MODELING PROCESS

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FK 2018 35

DEVELOPMENT OF PRINTER NOZZLE FOR EXTRUDING SYNTHETIC BIOMATERIALS USING FUSED DEPOSITION MODELING PROCESS

By

NOR AIMAN BIN SUKINDAR

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

January 2018

DEDICATION

This thesis is dedicated to my beloved wife, Nor Azira Binti Mohd Latif, and my parents, Norisah Binti Taib and Sukindar bin Kadiran.

Thank you for your love, patience and support during my journey to achieve this dream together with me

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Mohd Khairol Anuar B. Mohd Ariffin, PhD
Faculty : Engineering

This research focuses on the development of nozzle specifically for open-source 3D printing for extrusion of synthetic biomaterials. The factors that affect the stability, consistency and accuracy of the extrusion process were investigated by using finite element analysis (FEA) including nozzle die angle, nozzle diameter and liquefier design. From the simulations, it is seen that the die angle and nozzle diameter affect the pressure drop along the liquefier. The pressure drop variation has affected the road width of the printed parts, thus affecting the quality of the finished product. Based on the simulations, the convergent angle for extruding polylactic acid (PLA) and polymethylmethacrylate (PMMA) materials was found in this research at 130^{o} which provides stability and consistency of the extrusion process. For efficient printing process, nozzle diameter of 0.3 mm was found to be the optimum with respect to pressure drop and printing time. The liquefier design plays an important role in maintaining the liquefier chamber's temperature as constant as possible. The temperature variation has caused the changes in viscosity of the material, thus affecting the quality of the finished parts. Liquefier in cylindrical shape has been identified as the solution in minimizing the problems as it has been proven from the simulations that portray improved temperature distribution. The newly developed nozzle was compared with the original nozzle with respect to dimensional accuracy and mechanical properties and shows that the newly developed nozzle had a better performance in both criteria. By solving the issues related stability, consistency and accuracy of the extrusion process, the scaffold structure was successfully fabricated with compressive strength between 6 MPa to 7 MPa and porosities between 50% and 70% which is the range for trabecular bone. Furthermore, humerus bones was successfully fabricated with controlled porosity.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PEMBANGUNAN NOZEL PENCETAK 3D DENGAN MENGGUNAKAN FABRIKASI FILAMEN BAGI EXTRUSI BAHAN BIO SINTETIK

Oleh

NOR AIMAN BIN SUKINDAR

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Pengerusi : Mohd Khairol Anuar B. Mohd Ariffin, PhD
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Kajian ini memberi tumpuan kepada pembangunan nozel khusus untuk perisian terbuka pencetak 3D bagi extrusi bahan biosintetik. Faktor yang memberi kesan kepada kesetabilan, ketekalan dan ketepatan proses extrusi telah dikaji dengan menggunakan analisis unsur terhingga (FEA) seperti sudut nozel, diameter nozel dan reka bentuk pencair. Dari simulasi, ia menunjukkan bahawa sudut nozel dan diameter nozel mempengaruhi tekanan sepanjang ruang pencair. Keperluan mengkaji tekanan dengan teliti adalah penting kerana apabila tekanan berubah-rubah, lapisan-lapisan yang dicetak juga berbeza-beza dan dengan itu menjejaskan kualiti produk. Berdasarkan simulasi, sudut penumpuan yang sesuai untuk extrusi bahan polylactic acid (PLA) dan polymethylmethacrylate (PMMA) dalam kajian ini adalah 130^{o} darjah. Untuk proses pencetakan yang lebih efisyen, 0.3 mm diameter nozel didapati adalah yang paling optimum dari segi tekanan dan masa pencetakan. Reka bentuk pencair memainkan peranan penting dalam menjaga suhu di dalam ruang pencair. Kelikatan bahan akan berubah apabila suhu berubah. Keadaan ini akan memberi kesan kepada kualiti produk yang dihasilkan. Dengan menggunakan bentuk pencair silinder, masalah ini boleh dikurangkan dan hasil dari simulasi, taburan suhu adalah lebih baik. Nozel baru telah dibandingkan dengan nozel asal dan keputusan menunjukkan bahawa nozel baru memberikan ketepatan dimensi dan sifat-sifat mekanikal yang lebih baik kepada produk yang dihasilkan. Dengan menyelesaikan isu-isu yang berkaitan kesetabilan, ketekalan dan ketepatan dalam proses extrusi, struktur perancah berjaya difabrikasikan dengan tekanan mampatan antara 6 MPa hingga 7 MPa dan keliangan antara 50% sehingga 70%. Selain itu juga, tulang humerus telah berjaya difabrikasi dengan keliangan yang terkawal.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious and the Most Merciful.

Alhamdulillah, all praises be to Allah for giving His blessing in completing this thesis. I would like to express my appreciation to my supervisor Professor Ir. Dr. Mohd Khairol Anuar B. Mohd Ariffin from the Faculty of Engineering for the passionate participation, input and immense knowledge. His guidance has helped me in finding the right direction for completing this thesis. I would also like to thank the experts and the members of the Supervisory Committee including Associate Professor Ir. Dr. B.T. Hang Tuah Bin Baharudin, Dr. Che Nor Aiza Binti Jaafar and Dr. Mohd Idris Shah Bin Ismail, who have given me brilliant comments and ideas for the improvement of this thesis. Also, I would like to thanks to my beloved wife, Nor Azira Binti Mohd Latif, who has supported by giving encouragement, motivation and strength to complete this thesis. Last, but not the least, I would like to thank to my mother Norisah Binti Taib, my father Sukindar Bin Kadiran and family for giving full support and motivation directly and indirectly for this research.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile-Butadiene-Styrene
ADPS	Adaptable Filament Deposition System
AM	Additive Manufacturing
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CT	Computed Tomography
DOE	Design of Experiment
ECMs	Natural Extracellular Matrices
FDA	Food and Drug Administration
FDM	Fused Deposition Modeling
FEA	Finite Element Analysis
HIPS	High Impact Polystyrene
ISO	International Standards
LOM	Laminated Object Manufacturing
MRI	Magnetid Resonance Imaging
PCL	Poly(f-caprolactone)
PLA	Polylactic Acid
PMMA	Polymethylmethacrylate
PEEK	Polyether-Ether-Ketone
RP	Rapid Prototyping
SEM	Scanning Electron Microscope
SFF	Solid Freeform Fabrication
SLA	Stereolithography
STL	Standard Triangular Language

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Technology advancement has brought great implications to human beings in various ways. Rapid prototyping (RP) is one of the technologies that brings all the possibilities in fabricating 3D models especially in the biomedical field. It is synonym with solid freeform fabrication (SFF) which can create solid structure in layer by layer fashion upon creating design prototype by employing computer aided design (CAD) model data, computer tomography (CT) and magnetic resonance imaging (MRI) scans data, which then can be converted into standard triangular language (STL) format (Wohlers, 1998). Different forms of solid modeling can be fabricated from various materials making RP as one of the superior technologies in fabricating models within a short period of time.

The development of RP technology in the medical field brings major contribution in terms of product performance and cycle time reduction (Varatharaj et al., 2014). Nowadays the production of bone graft using RP technology has been widely applied. The production of scaffolds structure which requires high accuracy can simply be made by importing the required data from the computer (Zein et al., 2002).

The most commonly used RP technology in the field of manufacturing bone structure is fused deposition modeling (FDM) (Zein et al., 2002, Espalin et al., 2010). The flexibility of this technology in manufacturing scaffold design in which its parameters such as layer thickness and air gap can be manipulated, has been the reason for employing FDM technology in producing porous bone structure. Although the RP technology can easily create 3D model, it is very expensive with costs ranging from $100,000 to $500,000 (Turner et al., 2014). Since the expiration of FDM patent a few years ago (Crump, 1992), the technology of open-source 3D Printer has emerged with an affordable price (Jones et al., 2011). However, the accuracy of modeling parts requires further improvement. So far, limited research has been done pertaining to the open-source 3D Printer. Melenka et al. (2015) conducted a research using MakerBot Replicator 2 Desktop 3D Printer and the results demonstrates that printed parts show significant deviation from the nominal value (Melenka et al., 2015). The research suggested that careful selection of printing parameters can minimize these problems.

In order for the open-source 3D printer to have wide variety of applications in fabricating 3D model, particularly in medical field, the technology requires further analysis and development to fulfill the requirement in terms of accuracy, consistency and stability of the extruded parts. Recent researches only focus on the process parameters to improve the finish parts (Melenka et al., 2015, Galantucci et al., 2015). However, the hardware system is also an important element that contributes to the better extrusion process, hence providing good products. Thus, this brings in an opportunity to further improve on this technology. One of the most important parts is the 3D printer head, which comprises of nozzle, liquefier and heating element. It is the heart of the machine as the quality and compatibility of the material being extruded depends on the 3D printer head. In addition, the properties of material need to be investigated to allow smooth extrusion, consistent, accurate and not to clog the printer head during the extrusion process.

Hence, this study, intends to analyze and develop open-source 3D printer nozzle components. The reason for selecting the open-source 3D printer in this study is because of the cost of the technology which is affordable as well as the flexibility and accessibility of this technology. In this study, focuses is placed on several aspects such as nozzle die angle, nozzle diameter, and liquefier design which have significant impact on the extrusion process. The new open-source 3D printer nozzle will be used to fabricate porous bone structure using synthetic biomaterials.

1.2 Problem Statement

The demand in fabricating 3D model has increased over the years thus making the RP technology as one of the most chosen technologies. The industry has grown since 2010 with estimated around $1.325 billion for products and services and this number will increase by the year 2020 with estimated around $5 billion (Turner et al., 2014). Despite being the chosen technology in fabricating 3D models especially FDM, the price is still so much expensive and can hardly penetrate all levels of industry. It is started with Stratasys which was developed in the early of 90's and introduced a starting price ranging from with the price starts from above 15,000 euros and above (Minetola et al., 2016). They has developed a brand named Fortus of their FDM line which cost from $100,000-500,000 per unit (Turner et al., 2014). However, since the expiration of FDM pattern a few years ago, a low-cost 3D printing technology has been developed and introduced by Jones et al. in 2011 at an affordable price. A lot of manufacturers produced a low-cost 3D printer ranging from $1,500-5,000 (Turner et al., 2014). The main issue in term of cost can be seen as the major factor in choosing the technology. The comparison for both expensive and low-cost technology can be referred in the Appendices of A and B. If both technology has been compared in terms of overall manufacturing cost, the difference is very significant.

The comparison between the RepRap technology (open-source) which introduced by Jones (Jones et al., 2011) and Fortus 400mc from Stratasys shows the difference in term of price for more than $100,000. Basically, the main components for a low-cost 3D printer consists of controller, stepper motors, extruder, heated bead, and other parts that are available at any online stores with a low price. In addition, the particular software is available online and can be downloaded for free. The current product which will be used in this research cost approximately $625 (RM2500) (Appendix B) which is far cheaper compare to the expensive one available in the market.

The ability of FDM system in producing complex structure has been widely used in fabricating 3D model in medical field. Finding the best method in fabricating the numerous products such as tissue would be very crucial. It has been an alternative material for orthopedic surgeries such biodegradable material which matching with the new tissue (Park et al., 2007). Biodegradable material synonyms with synthetic biomaterial and possess some unique characteristics such as degrade over the period of time and possess adequate mechanical properties to sustain load during healing process (Park et al., 2007). Polylactic acid (PLA) and polymethylmethacrylate (PMMA) are the popular material used in biomedical fields. The challenge in extruding these materials using 3D printer is to understand the properties and the flow behavior along the liquefier. Since PLA and PMMA material possess quite low melting temperature, the temperature inside the liquefier must be kept as low as possible because if the material exposes to high temperature it will burn and contaminate the remaining material (Gibson et al., 2015). Furthermore, to maintain the properties of synthetic biomaterials being extrude, the temperature need to be carefully monitored and provide stable temperature within the system could be the key to have successful fabrication process. However, there are some issues related to the low-cost 3D printer. Research has been done to evaluate the dimensional accuracy using MarketBot 3D Printer where results demonstrated significant deviation from the nominal dimension (Melenka et al., 2015, Roberson et al., 2013). Other study has also measured the accuracy of 3D printer where differences of approximately 20% were observed between final product and CAD drawings (Roberson et al., 2013). Another research also shows that the low-cost 3D printer of 3D Touch^{TM} shows significant different in dimensional accuracy compare to the expensive of Dimension Elite^{TM} (Minetola et al., 2016).

The current issue with the open-source 3D printer is its performance to satisfy the industry’s requirement. These problems form a great opportunity to improvise the technology in various aspects particularly with low-cost 3D printer that can to penetrate the industry in high demand such as in the biomedical field for fabrication of human bone (Gibson et al., 2015). It is advantageous to have a low-cost machine that features similar quality as obtained from the high-end technology, which can fabricate complex parts such as porous human bone structure using synthetic biomaterials which is compatible to the human body. By improving the open-source 3D printer nozzle which comprises of nozzle parts, liquefier and insulator, the finish parts of the extruded materials can be improved and fabrication of complex structure such as porous structure can be achieved.

1.3 Research Objectives

The objectives of the research are as follows:

i. To analyze the factors affecting the accuracy, consistency and stability of extrusion process of synthetic biomaterials including, nozzle die angle, nozzle diameter and liquefier design.
ii. To develop the new nozzle based on the nozzle die angle, nozzle diameter and liquefier design.
iii. To compare the dimensional accuracy and mechanical properties of finish parts using the newly developed 3D printer nozzle to the original 3D printer nozzle.
iv. To fabricate the porous bone structure using the newly 3D printer nozzle of open-source 3D printer and synthetic biomaterials as the filament material.

1.4 Significance of Research

The significance of this study is the development of a new nozzle of open-source 3D printer for fabrication of porous bone structure. The rapid prototyping (RP) technology becomes rapidly developed over the years because of the ability to create a 3D model within short period of time. It saves millions of dollars on the production making this technology widely used in fabrication technology especially in the medical area. One of major concern here is the high cost of RP technology.

In order to make this technology economically feasible, the introduction of new technology of open-source 3D printer in the year of 2011 after the expiration of FDM patent brings a new era of fabricating 3D model in such affordable price. However, this open-source 3D printer has several drawbacks where the performance is still not proven. This research will focus on analyzing and developing the nozzle which concerns several aspects to improve the performance of open-source 3D printer in fabricating more complex models especially porous bone structure. Moreover, this research will bring a new idea and dimension on fabricating complex shape in medical area at an affordable price.

1.5 Scope of the Research

The scope of this research covers an analysis and development of open-source 3D printer nozzle which consists of liquefier, nozzle die angle and diameter, and insulator. The area of improvements is made on the 3D printer nozzle to achieve accuracy, stability and consistency in fabricating complex parts such as porous bone structure using synthetic biomaterials (PLA). The new nozzle was developed based on the analyzed factor. This research presents simulation and experimental studies to investigate the factor affecting accuracy, consistency and stability of the extrusion process. Secondly, the study compares the newly developed printer nozzle with the original ones, in terms of dimensional accuracy and mechanical properties. The mechanical properties include tensile test which follows Standard Test Method for Tensile Properties of Plastics ASTM D638-10 standard and compressive test which is done according to the Standard Test Method for Compressive Properties of Rigid Plastics ASTM D695 standard. Lastly, the newly developed 3D printer nozzle is used to fabricate scaffold design and porous bone structure by using synthetic biomaterials that is polylactic acid (PLA) and polymethylmethacrylate (PMMA) by following Standard Guide for Assessing Microstructure of Polymeric Scaffolds for Use in Tissue Engineered Medical Products ASTM F2450-04.

1.6 Organisation of the Thesis

The research consists of five chapters that covered all the project and the details of the thesis structure are presented as follows:

Chapter 1 – The problems of this research that contribute to the objectives as well as significance of this research. The scope is also presented in this chapter.

Chapter 2 – Comprehensive literature review related to this research and previous study that provides basic understanding throughout the research is presented in this chapter.

Chapter 3 – The methodology of the study is represented in this chapter. The analysis and development of the nozzle design are highlighted. The parameters setting also were investigated to find the best setting for the printing process. Later, the simulation until the design selection and the standard method to measure the dimensional accuracy, as well as mechanical properties are further elaborated. The scaffold design also is discussed in this chapter.

Chapter 4 – Chapter 4 concerns with the discussion on the results obtained from the simulation process and the final design. The fabrication of the new nozzle and together with the comparison results between the newly developed nozzle and the original nozzle in terms of dimensional accuracy and mechanical properties also are discussed. The fabrication of the scaffold structure is also presented.

Chapter 5 – The conclusions and the suggestion for the future research were presented in this section.

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Patent

1. Filament Nozzle Extruder For Ploylactic Acid (PLA) Material,Application No. **PI 2016703433**. Filing Date:21/09/2016. Applicant's file reference: *UPM/100-45/2 (A) KA1*

Award

1. Bronze Medal, Filament Nozzle Extruder for Synthetic Biomaterial, Exhibition of Inventions, Research and Innovation UPM (PRPi 2016), 15th – 16th November 2016.

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