UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

VACUUM SYSTEM ASSISTED FUSED DEPOSITION MODELING TO IMPROVE PARTS TENSILE STRENGTH

John Wong Huang Ung

Master of Science in Manufacturing Engineering

2017

VACUUM SYSTEM ASSISTED FUSED DEPOSITION MODELING TO IMPROVE PARTS TENSILE STRENGTH

JOHN WONG HUANG UNG

**A thesis submitted
in the fulfilment of the requirements for the degree of Master of Science
in Manufacturing Engineering**

Faculty of Manufacturing Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

I declare that this thesis entitled "Vacuum System Assisted Fused Deposition Modeling to Improve Parts Tensile Strength" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : …………………………………..

Name : …………………………………..

Date : …………………………………..

APPROVAL

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

Signature   :   ………………………………..

Supervisor Name   :   ………………………………..

Date   :   ………………………………..

DEDICATION

Dedicated to my mother and father

Cherished siblings

Honourable supervisors and lecturers

Faithful friends

ABSTRACT

Additive manufacturing (AM) has come a long way since the days of rapid prototyping began with the capability to produce a complex solid part rapidly. AM has begun to be acknowledged and accepted in numerous industries such as aerospace, automotive, medical, and even art. Fused deposition modeling (FDM), one of the AM technologies, is a popular and most used technology based on polymer extrusion method. FDM generally works by depositing a molten thin polymer filament from the nozzle onto the build platform repeatedly layer by layer up to create a solid part. Despite having the advantages to produce part without any complexity restrictions, the known poor mechanical strength for a functional part produced is the limitation. Literature has found out that one of the main reasons anisotropic behaviour which was the insufficient bonding between layers was found weakest at the z-axis. The layer by layer bonding occurred too fast and was not fully fused together causing weak structural strength and easily shattered through pulling force. It was found that vacuum technology could improve the layer bonding by reducing the convective heat transfer. In a vacuum environment, the reduced amount of air molecules hindered the heat energy to be released from the deposited filament. Simulations were successfully created a vacuum chamber to sustain the vacuum pressure and confirmed the thermal behaviour of heat transfer in the vacuum was similar to the literature study. The pilot test confirmed that the different level of vacuum pressure does affect the tensile strength of the printed parts. Then, a total 20 experiment runs with 60 printed specimens were conducted with two parameters namely layer thickness and vacuum pressure. Results have found out that the highest percentage improvement (16.77 %) were 18.0846 N/mm^2 produced by 0.20 mm/21 inHg, while the highest strength measured at 0.25 mm/21 inHg, giving 19.7202 N/mm^2. The z-axis produced in vacuum environment was now at 77.67 % of strength produced by x-y axes signifying reduced anisotropic behaviour. It was found out that under scanning electron microscope (SEM), the specimens produced under vacuum pressure had a better bonding formation compared to normal atmospheric ones. Lastly, the ANOVA method had validated the significance of the set of parameters and the optimised parameter was 0.25 mm/21 inHG for recommended tensile strength while 0.22 mm/21 inHg for recommended tensile strain. The vacuum assisted FDM was proven to be feasible and this study had increased the understanding of vacuum technology and FDM to improve the tensile strength of the printed part. Further improvements of vacuum assisted FDM will allow the creation of mechanically stronger complex parts in a wide range of applications.

i

ABSTRAK

Pembuatan tambahan (AM) telah berkembang dari proses pembuatan pantas bermula dengan keupayaan untuk menghasilkan rekabentuk yang kompleks dengan pantas. AM telah mula diakui dan diterima di banyak industri seperti aeroangkasa, automotif, perubatan, dan juga seni. Pemendapan pemodenan terlakur (FDM), salah satu teknologi AM yang popular and paling banyak digunakan berdasarkan kaedah penyemperitan polimer. FDM biasanya berfungsi dengan mendepositkan filamen polimer lebur dari muncung ke platform binaan berulang kali lapisan sehingga menghasilkan sesuatu produk. Walaupun mempunyai kelebihan untuk menghasilkan produk kompleks tetapi kekurangan kekuatan mekanikal untuk produk berfungsi telah menjadikannya had batasan. Kajian literasi telah menemui bahawa salah satu sebab utama kelakuan anisotropik yang merupakan ikatan yang lemah antara lapisan didapati paling kurang pada paksi z. Perlekatan lapisan demi lapisan berlaku terlalu cepat dan tidak menyatu sepenuhnya menyebabkan kekuatan struktur mekanikal yang lemah dan mudah pecah melalui daya tarik. Didapati bahawa teknologi vakum boleh meningkatkan ikatan lapisan dengan mengurangkan pemindahan haba konveksi. Dalam persekitaran vakum, jumlah molekul udara yang dikurangkan menghalang tenaga haba untuk dilepaskan dari lapisan filamen. Simulasi berjaya mencipta ruang vakum untuk mengekalkan tekanan vakum dan mengesahkan kelakuan haba pemindahan haba dalam vakum adalah sama dengan kajian kesusasteraan. Ujian rintis mengesahkan bahawa tekanan tekanan vakum berbeza mempengaruhi kekuatan tarik bahagian-bahagian yang dicetak. Kemudian, sebanyak 20 esperimen yang dijalankan dengan 60 spesimen telah dijalankan dengan dua parameter iaitu ketebalan lapisan dan tekanan vakum. Keputusan mendapati bahawa peningkatan peratusan tertinggi (16.77%) adalah 18.0846 N / mm2 yang dihasilkan oleh 0.20 mm / 21 inHg, manakala kekuatan tertinggi diukur pada 0.25 mm / 21 inHg, memberikan 19.7202 N / mm2. Paksi z yang dihasilkan dalam persekitaran vakum kini berada pada 77.67% kekuatan yang dihasilkan oleh paksi x-y yang menandakan kelakuan anisotropik yang berkurangkan. Keputusan kajian dari imbasan mikroskop electron (SEM) menunjukkan bahawa spesimen yang dihasilkan di bawah tekanan vakum mempunyai pembentukan ikatan yang lebih baik berbanding dengan yang biasa di atmosfera. Akhir sekali, kaedah ANOVA telah mengesahkan kepentingan set parameter dan parameter yang dioptimumkan ialah 0.25 mm / 21 inHG untuk kekuatan tegangan yang disyorkan manakala 0.22 mm / 21 inHg untuk tegangan yang disyorkan. FDM yang dibantu vakum terbukti boleh dilaksanakan dan kajian ini telah meningkatkan pemahaman teknologi vakum dan FDM untuk meningkatkan kekuatan tegangan bahagian yang dicetak. Penambahbaikan selanjutnya bagi FDM dengan vakum akan membolehkan penciptaan rekabentuk produk yang kompleks serta baik dari aspek mekanikal untuk pelbagai aplikasi.

ACKNOWLEDGEMENTS

My deep gratitude to my supervisor, Associate Professor Dr. Shajahan Bin Maidin, from the Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka (UTeM), who passionately guided and supported me towards the completion of this thesis. His unwavering enthusiasm kept me constantly involved with my research. I am equally thankful to my co-supervisor, Dr. Suriati Binti Akmal from the Faculty of Manufacturing Engineering, for her mentoring and encouragement. Special thanks to UTeM for providing a high-quality learning platform. Above ground, I am thankful for my family, relatives and friends with their moral support. Lastly, thank you to all who kept me going and this completion of thesis would not have been possible without them all.

TABLE OF CONTENTS

LIST OF TABLES

with others

LIST OF FIGURES

thickness

LIST OF APPENDICES

LIST OF ABBREVIATIONS

3D	-	3 Dimensional
ABS	-	Acrylonitrile Butadiene Styrene
AES	-	Auger electron spectroscopy
AFM	-	Atomic Force Microscope
AM	-	Additive manufacturing
ANOVA	-	Analysis of variance
ASTM	-	American Society for Testing and Materials
CAD	-	Computer aided design
CAE	-	Computer aided engineering
CAM	-	Computer aided manufacturing
CNC	-	Computer numerical control
CO2	-	Carbon dioxide
DED	-	Direct energy deposition
DOE	-	Design of experiment
DOF	-	Degree of freedom
EBM	-	Electron beam melting
ESCA/XPS	-	Electron Spectroscopy for Chemical Analysis
EUV	-	Extreme ultraviolet lithography
FEA	-	Finite element analysis
FDM	-	Fused deposition modeling

GMDH	-	Group method of data handling
inHg	-	Inch mercury
Kn	-	Knudsen number
LAN	-	Local area network
LEED	-	Low-energy electron diffraction
LOM	-	Laminated sheet manufacturing
Nu	-	Nusselt number
PEEK	-	Polyether-ether-ketone
PET	-	Polyethylene terephthalate
PLA	-	PolyLactic Acid
PLC	-	Programmable logic controller
PMMA	-	Poly(methyl methacrylate)
Ra	-	Rayleigh number
SEM	-	Scanning electron microscope
SIMS	-	Secondary ion mass spectrometry
SLA	-	Stereolithography
SLM	-	Selective laser melting
SLS	-	Selective laser sintering
STL	-	Stereolithography
STM	-	Scanning tunneling microscope
TEM	-	Transmission Electron Microscopy
UAM	-	Ultrasonic additive manufacturing
UPS	-	Ultraviolet photoelectron spectroscopy
UTM	-	Universal testing machine
VE	-	Virtual environment

LIST OF PUBLICATIONS

Journal

Maidin, S., Wong, J. H. U., Mohamed, A. S., Mohamed, S. B., 2017. Effect of Vacuum Assisted Fused Deposition Modeling on 3D Printed ABS Microstructure. *International Journal of Applied Engineering Research*, *12*(15), pp.4877-4881.

Conference proceeding

Maidin, S., Wong, J. H. U., Mohamed, A. S., Romlee, W. F. A., Akmal, S., 2017. Investigation of heat transfer for vacuum system assisted fused deposition modeling: A finite element analysis. *Proceedings of Innovative Research and Industrial Dialogue 2016*, *1*, pp.7-8.

CHAPTER 1

INTRODUCTION

1.1   Background

Additive manufacturing (AM) technology has been around for decades, with the advances in technology powering each segment's growth. The term additive manufacturing is defined as "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (ISO/ASTM52900-15, 2015). AM has successfully used in various industries such as automotive, aerospace, medical and even art. In early the years, the exposure to AM was little and hard to revolutionize in any industry simply because of expensive technology and slow process. However, as the more researchers and inventors developed new kind of AM technology, the competitiveness arises. The prices drop and manufacturing industries began to adapt the AM technology. AM is different compared to subtractive manufacturing such as CNC machining, lathe and milling, which they remove a block a material to form the desired shape, whereas AM builds through layer by layer to form highly complex shape.

The technology AM possesses capable of producing complex geometries with little post-processing and low material waste while broadly applicable to a variety of materials including metals and polymers. Thus, with design freedom offered by AM, it would be the best alternative to allow engineers and designers to create any products economically for prototyping and manufacturing purpose in a small volume (Bikas et al., 2015). AM

1

effortlessly generates 3D prototypes from concepts and ease manufacturing processes including assembly jobs. This kind of flexibility makes AM an advantageous leap in manufacturing technology (Croccolo et al., 2013).

Fused deposition modeling (FDM) is one of the AM technologies that is capable of producing complex geometry of polymer parts. FDM technology's main principle is to use three-dimensional CAD data and converted it to STL files. After proper setup, tool paths will be generated and transferred to the FDM machine for fabrication (Hossain et al., 2013). In FDM machine, a coil of plastic filament supplied to the extrusion nozzle, heated and deposits a thread of molten polymer to form required geometry (Jain and Kuthe, 2013). A functional application from FDM parts requires dimensional accuracy, surface finish and mechanical strength of the parts which is important to optimise parameters to achieve desired quality build of parts manufactured (Nidagundi et al., 2015; Kumar et al., 2014). In reality, FDM part strength is still below the satisfactory level. Although FDM is capable to produce complex parts, it is still unable to provide a satisfactory mechanical strength of the printed parts. FDM printed parts possess anisotropic behaviour where the strength has a different value at different axes (Torrado and Roberson, 2016).

On the other hand, vacuum technology has become a valuable industrial tool. Vacuum is used to create a space without matter or no particles. The use of vacuum will create a pressure is much less than the atmospheric pressure. At normal atmospheric pressure (1 atm), the surrounding contains air molecules that are constantly colliding with one another. Therefore, lowering the pressure lower than one atmospheric requires air molecules to be reduced by suctioning them out. Vacuum ranges from low to extremely high vacuum and each level are used for vast applications in studies and industries to perform tasks under low pressure such as instrumentation, coating, refrigeration, light bulb, leak detection and more. Lowering the pressure will reduce the number of air particles

© Universiti Teknikal Malaysia Melaka

which will limits the energy transfer such as heat energy (Wang et al., 2007). This particular vacuum's characteristic could be the potential solution to the poor mechanical strength of FDM parts by stimulating neck growth between layer bonding and directly improving the mechanical strength.

In this research, the novelty of using vacuum technology was tested to determine its influence and effect on the mechanical properties of the FDM printed parts. An open-sourced FDM machine was used to build the specimens under a vacuum environment by conducting different operating parameters (vacuum pressure and layer thickness) to obtain the optimum results. The results from various parameters were analysed on the specimen mechanical properties.

1.2 Problem Statement

Additive manufacturing (AM) technologies have been around for the past few decades with dramatic improvements on the quality build. However one of the great restrictions to further implementation of 3D printed parts is the weak strength of the printed parts (Bikas et al., 2015; Gao et al., 2015; Nelaturi and Shapiro, 2015; Martínez et al., 2013). The 3D printed parts easily damaged upon force and thus hindered them to be used as a functional product. The strength and stiffness of the parts built is not relatively high and hard to be defined as they possess strong anisotropy (Croccolo et al., 2013; Ahn et al., 2002; Hildebrand et al., 2013). Under additive manufacturing processes, selective laser sintering (SLS) with metal processes compatibility are better in mechanical strength compared to other processes such as fused deposition modeling (FDM) and stereolithography (SLA). The available materials for FDM are limited to ABS, PLA, Nylon, and Polycarbonate which produced lower strength in printed parts (Belter and Dollar, 2015).

3

The current techniques and published information related to AM parts mechanical properties improvement focusing on additional processing such as chemical treatment (Galantucci et al., 2010), fill compositing method (Belter and Dollar, 2015), parameter optimization (Onwubolu and Rayegani, 2014), computer assisted automatic detection and correction system (Stava et al., 2012), composites (Nikzad et al., 2011) and slicing method (Hildebrand et al., 2013). All the processing mentioned requires the aid of additional equipment, hazardous control, consistent efficiency and labour which involves time and cost.

Therefore, novel studies of integrating two different technologies, FDM and vacuum system has been explored to understand the properties of the mechanical properties of the 3D printed parts. Currently, there is no information published on the vacuum assisted FDM in studying its feasibility to improve the mechanical properties of printed parts. Therefore, to fill this knowledge gap, a fundamental knowledge focuses on the study of vacuum assisted FDM and their relationships with the parameters involved were explored.

1.3   Objectives

The aim of this this research is to improve the tensile properties of printed parts through vacuum assisted FDM machine by identifying the optimum process parameters. In order to fulfil the aim, the objectives are:

  i.   To explore the feasibility study of using vacuum technology to increase the tensile strength of FDM printed parts.

 ii.   To conduct finite element analysis on the vacuum chamber and thermal behaviour of FDM process in a different level of vacuum pressure.

© Universiti Teknikal Malaysia Melaka