UNIVERSITI PUTRA MALAYSIA

MECHANICAL CHARACTERIZATION OF POLYMER PARTS PRODUCED VIA MULTI-JET PRINTING AND FUSED DEPOSITION MODELLING

ZALIHA BINTI WAHID

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By

ZALIHA BINTI WAHID

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November 2021

Chair : Mohd Khairol Anuar bin Mohd Ariffin, PhD
Faculty : Engineering

Layer by layer additive manufacturing techniques have inherently low strength in z-orientation. Mechanical properties of the final products are influenced by both materials and processing method utilized. The multijet 3D printing technique is not new in Additive Manufacturing. Studies on the processing and product optimization are still ongoing. However, studies on the characterization of fabricated products using this technique has not yet been fully explored. Additionally, the said attributes might be distinctive depending on machine brand and manufacturer. Therefore, the main objective of this study is to investigate the effects of orientation by conducting mechanical and structural testing involving tensile strength, compression, flexural strength, and surface roughness at various orientations. Specimens of liquid resin VisiJet M3 Black materials were printed using ProJet 3510 HD by 3D Systems. For each test, specimens were prepared in three different orientations which were x-orientation, y-orientation, and z-orientation. To support the findings and to rule out material influences, tensile testing was performed using comparable materials but with a different printing technique, Fused Deposition Modelling (FDM). As an end use product, it is necessary to characterize fatigue behaviour and effect of orientation to structural integrity. In the fatigue test, specimens of each orientation underwent dynamic loading for fatigue life and fatigue properties. Another objective of this study is to characterize interconnecting layers and to relate how printing orientation may influence product performance. To achieve the objectives, a literature review on jetting and ultraviolet curing methods was carried out. Finally, the objective is to analyse the correct parameters reflected to product quality printed using ProJet 3510 HD. It was found that printing using ProJet 3510 HD had a significant effect to the mechanical strength at the x-orientation. From tensile testing, as compared to the x-orientation, the strength of the y-orientation was higher by 22%. While the strength showed only 6% difference as compared to the low strength z-orientation. These results was supported by the flexural test where the ultimate flexural stress at the y-orientation was almost four times higher than that of the x-orientation. Fracture surface microstructure

observations explained interconnection layers, failure characteristics, and effects of orientation. From this study, fatigue life data for specific materials, machine, and orientation has been discovered for future reference.

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

PENCIRIAN MEKANIKAL BAHAN POLIMER YANG TERHASIL MELALUI PERCETAKAN JET BERBILANG DAN PERMODELAN PEMENDAPAN BERCANTUM

Oleh

ZALIHA BINTI WAHID

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Pengerusi : Mohd Khairol Anuar bin Mohd Ariffin, PhD
Fakulti : Kejuruteraan

Kaedah lapisan demi lapisan dalam teknik Pembuatan Tambahan mempunyai kekuatan yang rendah pada orientasi-z. Ciri mekanikal pada produk akhir dipengaruhi oleh bahan yang digunakan dan kaedah pemprosesan yang dilalui semasa pembuatannya. Teknik percetakan 3D jet berbilang bukanlah satu kaedah yang asing dalam Pembuatan Tambahan. Kajian berkaitan pengoptimuman proses dan produk masih berlangsung. Namun, pencirian terhadap proses serta hasil produk yang difabrikasi melalui teknik ini masih belum diteroka sepenuhnya. Lebih-lebih lagi, ciri proses dan produk akhir mungkin berbeza dari satu jenama pengeluar mesin pencetak 3D ke satu jenama yang lain. Oleh itu, objektif utama kajian ini adalah untuk Kajian ini mengkaji kesan perubahan orientasi dengan menjalankan ujian-ujian mekanikal dan struktur melibatkan kekuatan tegangan, mampatan, lenturan dan kekasaran permukaan pada pelbagai orientasi. Spesimen dari bahan cecair jenis VisiJet M3 Black dicetak menggunakan mesin pencetak 3D jenis jet berbilang ProJet 3510 HD dari 3D Systems. Bagi setiap ujian yang perlu dijalankan, spesimen dicetak dalam tiga orientasi berlainan iaitu orientasi-x, orientasi-y dan orientasi-z. Untuk menyokong keputusan dan untuk membuktikan bahawa pengaruh bahan tidak signifikan, ujian tegangan dilakukan ke atas bahan yang hampir sama tetapi menggunakan teknik percetakan yang berbeza iaitu Permodelan Pemendapan Tergabung (FDM). Sebagai produk yang sedia digunakan, adalah penting untuk mencirikan sifat lesu dan kesan orientasi terhadap integriti struktur. Di dalam ujian lesu, spesimen diuji dengan ujian pembebanan dinamik bagi mendapatkan sifat serta hayat lesu setiap orientasi. Seterusnya, objektif kajian adalah untuk mencirikan hubungan antara lapisan-lapisan pembuatan tambahan dan menghubungkaitkan bagaimana orientasi percetakan yang berbeza boleh mempengaruhi prestasi produk. Untuk mencapai objektif ini, kajian literatur tentang mekanisme semburan serta pemejalan bahan cecair dengan sinaran ultra ungu dijalankan. Akhir sekali, objektif kajian adalah untuk menganalisis parameter yang menentukan kualiti produk yang dihasilkan menggunakan ProJet 3510 HD. Dari kajian ini, didapati percetakan dengan teknologi dan jenis mesin ProJet 3510 HD memberi kesan signifikan terhadap kekuatan mekanik bagi orientasi-x. Melalui ujian tegangan, secara perbandingan dengan orientasi-x sebagai rujukan, orientasi-y melebihi sebanyak 22% sementara perbezaan dengan orientasi-z adalah 6% sahaja. Keputusan disokong dengan ujian lenturan di mana terikan lenturan orientasi-y adalah hamper empat kali ganda lebih tinggi berbanding pada orientasi-x. Hasil pemerhatian mikrostruktur permukaan patah menjelaskan ikatan antara lapisan, pencirian kegagalan dan pengaruh orientasi. Daripada kajian ini, hayat lesu bagi bahan, mesin dan orientasi yang spesifik diperolehi dan dapat digunakan sebagai rujukan bagi kajian akan datang.

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To quote a Sufism philosopher Rumi once said "*It is your road, and yours alone. Others may walk it with you, but no one can walk it for you*".
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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. The members of the Supervisory Committee were as follows:

Mohd Khairol Anuar bin Mohd Ariffin, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

B.T. Hang Tuah bin Baharudin, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Idris Shah bin Ismail, PhD
Associated Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Faizal bin Mustapha, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 July 2022

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research and the writing of this thesis were done under our supervision;
- supervisory responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2015-2016) are adhered to.

Signature:	
Name of Chairman of Supervisory Committee:	Prof. Ir. Dr. Mohd Khairol Anuar Mohd Ariffin
Signature:	
Name of Member of Supervisory Committee:	Prof. Ir. Dr. B.T. Hang Tuah Baharudin
Signature:	
Name of Member of Supervisory Committee:	Assoc. Prof. Dr. Mohd Idris Shah Ismail
Signature:	
Name of Member of Supervisory Committee:	Prof. Ir. Dr. Faizal Mustapha

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LIST OF ABBREVIATIONS

3D	Three Dimension
3DP	Three Dimension Printing
ABS	Acrylonitrile butadiene styrene
AFO	Ankle foot orthosis
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CSL	Ceramic stereolitography
DOE	Design of experiments
FDM	Fused Deposition Modelling
FEA	Finite element analysis
FFF	Fused Filament Fabrication
FMEA	Failure mode and effects analysis
HCF	High cycle fatigue
HD	High definition
HDPE	High Density Polyethylene
Hz	Hertz
ISO	International Organization for Standardization
MJP	Multi jet printing
MPa	Mega Pascal
MSDS	Material safety data sheet
NASA	National Aeronautics and Space Administration
PA-12	Polyamide 12
PCL	Polycaprolactone

PEEK	Polyether ether ketone
PEG	Polyethylene glycol
PLA	Polylactic acid
PLLA	Poly (l-lactic acid)
PP	Polypropylene
PPF	Poly propylene fumarate
R_a	Average roughness
RM	Rapid Manufacturingfvc
RP	Rapid Prototyping
RT	Rapid Tooling
SD	Standard definition
SEM	Scanning Electron Microscopy
SL	Stereo Lithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TE	Tissue Engineering
UHD	Ultra-high definition
UTS	Ultimate tensile strength
UV	Ultraviolet

CHAPTER 1

INTRODUCTION

1.1 Additive Manufacturing

Additive Manufacturing (AM), as officially defined according to industry-standard term (ASTM F2792) is a joining process to make objects from 3D model data by adding materials layer-upon-layer. AM is a disruptive (Griffiths et al., 2016) and emerging (Babu et al., 2015) technology in product manufacturing and is opposed to traditional subtractive methodologies such as machining process which fabricating is by subtracting materials from the block to get the final product. Besides the capability of freeform fabrication with a high degree of freedom in design (Klahn et al., 2014), Tang, Mak, & Zhao, (2015) in their study found that AM is providing huge potential to reduce the environmental impact as compared to conventional manufacturing processes. The AM process can be divided into various methods based on the raw material form, whether liquid, solid, or powder.

Since the emergence of this new technology, some commonly used terms have been used when describing the process in the engineering community all over the world. ‘3D Printing’ is the most popular term though rapid developments of AM have found ways of making parts layer by layer and not necessarily by depositing material from the nozzle as is simply comprehended by the terms of ‘printing’. Referring to the process chain, some enthusiasts call the process as layering manufacturing, direct CAD manufacturing, and rapid prototyping.

The term ‘prototype’ is used for components intended for presentation purposes or testing at a smaller scale which usually require non-performing properties. However, for end-user products, individual parts, as well as series products, higher durability and long term stability are required (Klahn et al., 2014). Though the use of “Rapid Prototyping” is nowadays considered outdated (Chua & Leong, 2015), its terms are still valid when a physical model is created rapidly. Goodridge, Tuck, & Hague (2012) claimed that AM is the evolution of additive techniques from its origin, Rapid Prototyping. The process of Rapid Prototyping is still prevalent as it offers a better way of designing before mass manufacturing. Predominantly, various AM technologies available these days have been primarily aimed at producing prototyping models (Campbell et al., 2012). By Rapid Prototyping, rework of the process can be repeated when necessary until an acceptable prototype is obtained.

Basically, the concept of Rapid Manufacturing (RM) is the production of end-use parts from additive manufacturing systems (Griffiths et al., 2016; Vayre et al., 2013). Rapid manufacturing is also an additive manufacturing of individual parts or small lot sizes for industrial applications (Klahn et al., 2014). Based on this definition, products to be used as real products (end products) should meet the various basic requirements for such production parts. Rapid Tooling (RT) may be considered in this context as a sub-category of RM, i.e., production of functional tool components produced by layered manufacturing (Kruth et al., 2007).

1.2 Research Background

Additive manufacturing technology emerged in the late 1980s. Since then, various AM technologies have been born and classified according to their method of material deposition. Due to the printing method, anisotropy or the dependence of properties according to their printing orientation has been a topic of great debate in AM. Research and investigations have been done to determine, lessen, avoid, and ensure usage of non-critical orientation. For jetting AM, historically, the technology was first brought to market by 3DSystems in 1996, then similar technology was founded in 1999 by Objet which was later patented by Stratasys.

Two well-known brands for AM are 3D Systems and Stratasys. The key players, from their published works, mainly used PolyJet and ProJet printers. Preliminary work regarding jetting was published back in 2011, still focusing on process capability (Singh, 2011). Not long after, investigations on fatigue properties was conducted using elastomer and PolyJet printing (2012), and later the fatigue of multiple materials that was only possible with PolyJet at the time (Moore & Williams, 2012; Moore & Williams, 2015).

As early as 2012, variability of PolyJet printing was investigated based on the cause and effect Ishikawa diagram presented, and found that orientation was a very determining factor of tensile strength (Barclift & Williams, 2012). Research conducted by a group from Zurich, Switzerland, carried out a very specific and quite systematic analysis on jetting process orientation effects (Mueller et al., 2015). Later studies better highlighted the effects of orientation though the studies were more focused on multi material interface issues as PolyJet was able to dispense multiple types of materials (Das et al., 2018; Lumpe et al., 2019). Among the key players of material jetting printing, ProJet has rarely been employed in research, and even for literature that is available on them, the research was not mainly on orientation (Ibrahim & Hafsa, 2014; Kasparova et al., 2013; Limmahakhun et al., 2017).

1.3 Problem Statement

The Rapid Manufacturing (RM) process has evolved from rapid prototyping, and this promotes product evolution from prototyping to the production of functional end-use parts. These end-use parts are fully functional and no more a prototype

(Yuan et al., 2021), therefore long term time-dependent properties must be taken into account. Fatigue properties is one attribute that once seemed not associated to and unnecessary with rapid prototyping (RP) but nowadays is very important for RM. AM-part properties depend on structural and process parameters rather than purely on material properties (Mueller et al., 2015); therefore, each printing orientation or process condition should have their fatigue study conducted before the part is fabricated. Hence, it is essential to predict the lifetime of products manufactured by AM/RM because most of them were initially only prototypes where fatigue life was not a concern. Particularly for the AM jetting type, until 2018, it was reported that there are still very few studies regarding fatigue behaviour (Dizon et al., 2018). Therefore, new research data on this will be very useful for the researchers to understand the in use behaviour of jetting manufactured product.

Anisotropic is one characteristic inherent to additive manufacturing. Because of the printing mechanism where layers of material are added upon the previous one, all AM technology products are anisotropic. The mechanical characteristic depends on the printing orientation and is different in each direction, the weakest in the z-direction. As the issue is caused by the printing mechanism, each technology will give different levels of distinction when tested from different directions. Jetting type of AM is one technology yielding differences in X and Y-directions (Das et al., 2018) caused by the printing mechanism (Lumpe et al., 2019). However, no specific research has studied on the magnitude of the x and y differences. Z-orientation mechanical properties, on the other hand, has usually been assumed to be the worst disadvantage of 3D printing and therefore has been ignored because of challenges to print in a standing upright position (Miller et al., 2017).

AM is formed from a layer-by-layer basis of molten or fused materials. Numerous research has determined that mechanical failure originates from within. For example, porosity concentrated in the interlayer planes and unfused powder particles can initiate cracks in Selective Laser Sintering (SLS) type of AM (Safai et al., 2019). As for Fused Deposition Modeling (FDM), abundant voids, air pores, and interlayer gaps were among interconnection issues commonly initiating failure when tested. As for jetting AM, the manufacturing process the parts had gone through may trigger/initiate failure. The mechanism of layers bonded to other layers fused by high temperature or UV light curing would not make the part as perfect and strong as one solid built material. There are combinations of bindings, and beneath the interlayers, there are sources of mechanical failure that also need attention and investigating. Jetting also have issues of marking formations on its product surface (Mueller et al., 2015) but the effect of these markings on mechanical performance has never been explored before.

1.4 Objectives

The aim of this research is to perform a series of works to characterize products from specific materials and processing methods. The objectives of the study are as follows;

1) To investigate mechanical performance, failure mode, and fatigue properties of 3D printed end-use parts.

2) To determine the effect of anisotropic features on the strength of additively manufactured parts.

3) To characterize the interconnection in between layers of functional end-use parts fabricated by 3D printing.

4) To analyse the correct parameters reflected to quality of the product produced using 3D printing.

1.5 Scopes and limits of study

The study was conducted within the scope as follows:

1) The selected material in this study was VisiJet M3 Black, claimed by 3D Systems as Polypropylene-like. Reference properties for VisiJet M3 was as in the MSDS provided by the supplier. As it was not stated anywhere, the mechanical properties might not be from testing on 3D printed samples.

2) For printing, the machine, ProJet 3510 HD, was used only in HD mode, with other parameters at default settings.

3) Characterisation was unrestricted to any specific future application. Mechanical testing was to characterize common properties only. While in dynamic loading there were various ranges of loading types and frequencies, the study focused on the most popular, tension-tension fatigue test with trial-and-error approach to select for the most suitable frequency.

This research study was also with some limitations.

1) Materials employed in this research was subjected to availability. VisiJet M3 Black was one of the materials that came as a package with the ProJet 3510 HD 3D Printer. Therefore, the material was selected to be characterised throughout this research study mainly because of availability. In fact, other materials printable with the machine were more commonly studied by researchers with more desirable properties and wider potential applications.
2) Other limitations included of the machine itself. The printer was subjected to scheduled routine maintenance. Thus, fabricated samples might be from several different batches.

3) Despite some studies reporting on the effects of batching and time gaps between tests, these effects were neglected in this study. In fatigue characterisation, whole batches for one orientation did not show perfect tests as it was first intended and as per standard. However, because of time constraints to repeat the tests, it was decided to just accept the condition and justify the findings through discussion.

1.6 Thesis Structure

Chapter 1 INTRODUCTON: The overview of AM in general was briefly introduced. This chapter also has highlighted research background and problem statements involving issues concerning knowledge gaps in the AM field. This chapter states the objectives, scope and limits of the study, and finally why this research work is important has been explained as the novelty of research.

Chapter 2 LITERATURE REVIEW: This chapter describes the history of AM, as understood by the researchers and the need of the technology as end use product fabricating technique. This chapter also explains and distinguishes different types of 3D printing techniques, printing orientation overview and issues, also the past research on several types of characterizations and finally some popular applications of AM products.

Chapter 3 METHODOLOGY: This chapter explains in detail of parameter selection for printing, orientation, mechanical experimental tests, dynamic loading, SEM investigation and simulation works. This chapter also describes procedures taken to conduct all the experimental works and justification of selecting all related instruments employed to achieve the objectives of this study.

Chapter 4 RESULTS AND DISCUSSION: This chapter presents and discusses all the results from the experimental test. The findings from the SEM analysis were discussed and synthesized with the theoretical data from literature study. Finally, this chapter discusses issues in jetting, the effect of orientation and potential source of failure from the study.

Chapter 5 CONCLUSION AND RECOMMENDATIONS: This chapter concludes how the whole research achieved the objectives, highlights research findings and presents recommendations for future work.

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