MECHANICAL AND PHYSICAL PROPERTIES OF POLYLACTIC ACID BASED COMPOSITE FILAMENT USING STATISTICAL ANALYSIS IN FUSED DEPOSITION MODELLING

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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

Faculty of Mechanical Technology and Engineering

UNIVERSITI MALAYSIA TEKNIKAL MALAYSIA MELAKA

2025

DECLARATION

I declare that this thesis entitled "Mechanical and Physical Properties of Polylactic Acid Based Composite Filament Using Statistical Analysis in Fused Deposition Modelling" 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 : Nurul Nadia Mohamad

Date : 16th September 2025

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 Mechanical Engineering.

Signature : ………………..

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DEDICATION

To my beloved mother and family.

ABSTRACT

Fused Deposition Modelling (FDM) three-dimensional (3D) printing is one of the most broadly employed technique of small additive manufacturing (AM). FDM gained their popularity rather than other AM processes due to its affordable cost and the simple working principle. FDM can employ various of polymers including polylactic acid (PLA). Nowadays, natural fibre (NF) had been chosen as enhancements in FDM filaments as it exhibit excellent specific properties, low cost, and higher availability. However, the addition of NF modified the properties of polymer, thus the printing process parameter need to be reset. FDM had various of printing process parameter that impacted on the properties of the FDM printed part. This study analyses the effect of printing process parameter setup on the mechanical and physical properties of natural fibre reinforced polymer composite (NFRPC) which are sugar palm fibre (SPF)/PLA and pineapple leaf fibre (PALF)/PLA. The optimum printing process parameter for both SPF/PLA and PALF/PLA composites is determine based on the results on the mechanical and physical properties. The correlation between the printing process parameter with the mechanical and physical properties of the SPF/PLA and PALF/PLA composites was also determine in this study. The fabrication of the composites filament preparation started with the cutting, grinding, and sieving the fibres. Then, the process continues with the mixing the fibres with the PLA. Finally, the composites were crushed and extrude into the composite's filament before the printing process of the samples for the analysation of mechanical and physical properties. The design of experiment utilised in this study was Taguchi method with three levels of printing process parameter which are layer thickness, printing speed and infill density. The total samples printed for each composites filament are 90 samples. The results shown that for SPF/PLA composites, the optimum printing process parameter are 0.1 mm layer thickness, 25 mm/s printing speed and 100% infill density for the good mechanical and physical qualities. From all the parameters, infill density has a positive linear correlation with all properties and layer thickness has a negative linear correlation with all the properties. Thus, infill density concluded to have the greater impact on the tensile properties than the other parameters with *r* between 0.703 and 0.773. As for PALF/PLA composites, the optimum printing process parameter are 0.1 mm layer thickness, 25 mm/s printing speed and 100% infill density for the good mechanical and physical attributes. From all the parameters, infill density also had a strong positive linear correlation with tensile properties with value of *r* between 0.931 and 0.951 and layer thickness had a positive linear correlation with the surface roughness with *r* value of 0.628. Other parameters had a various correlation with the properties. Therefore, infill density is concluded to have the greater impact on the mechanical properties and layer thickness have the higher impact on the surface roughness properties. In conclusion, both SPF/PLA and PALF/PLA had the same optimum printing process parameter for the good mechanical and physical characteristics. In fact, each of the properties for both materials has a different correlation with printing process parameters.

KEBOLEHCETAKAN FILAMEN KOMPOSIT ASID POLIKAKTIK DALAM PEMODELAN PEMEMPATAN BERFUS MENGGUNAKAN ANALISIS STATISTIK

ABSTRAK

Percetakan tiga-dimensional (3D) Fused Deposition Modeling (FDM) ialah salah satu teknik yang paling banyak digunakan dalam pembuatan bahan tambahan kecil (AM). FDM meraih popularitinya berbanding proses AM lain kerana kos kemampuannya dan prinsip kerja yang lebih mudah. FDM boleh menggunakan pelbagai polimer termasuk asid polilaktik (PLA). Kini, gentian asli (NF) telah dipilih sebagai penambahbaikan dalam filamen FDM kerana ia mempamerkan sifat khusus yang sangat baik, kos rendah dan ketersediaan yang lebih tinggi. Walau bagaimanapun, penambahan NF telah mengubahsuai sifat polimer, oleh itu parameter proses pencetakan perlu ditetapkan semula. FDM juga mempunyai pelbagai parameter proses pencetakan yang memberi kesan kepada sifat bahagian cetakan FDM. Kajian ini menganalisis kesan persediaan parameter proses pencetakan terhadap sifat mekanikal dan fizikal komposit polimer bertetulang gentian semulajadi (NFRPC) iaitu gentian kelapa sawit (SPF)/PLA dan gentian nanas (PALF)/PLA. Parameter proses pencetakan optimum untuk kedua-dua komposit SPF/PLA dan PALF/PLA ditentukan berdasarkan keputusan sifat mekanikal dan fizikal. Perkaitan antara parameter proses pencetakan dengan sifat mekanikal dan fizikal komposit SPF/PLA dan PALF/PLA juga ditentukan dalam kajian ini. Penyediaan komposit filamen dimulakan dengan memotong, mengisar dan mengayak gentian. Kemudian, proses diteruskan dengan mencampurkan gentian dengan PLA. Akhirnya, komposit dihancurkan dan diproses menjadi filamen komposit sebelum proses percetakan sampel untuk analisis sifat mekanikal dan fizikal. Reka bentuk eksperimen yang digunakan dalam kajian ini adalah kaedah Taguchi dengan tiga peringkat parameter proses pencetakan iaitu ketebalan lapisan, kelajuan cetakan dan ketumpatan isian. Jumlah sampel yang dicetak untuk setiap filamen komposit ialah 90 sampel. Keputusan menunjukkan bahawa bagi komposit SPF/PLA, parameter proses pencetakan optimum ialah ketebalan lapisan 0.1 mm, kelajuan cetakan 25 mm/s dan ketumpatan isian 100% untuk kualiti mekanikal dan fizikal yang baik. Daripada semua parameter, ketumpatan isian mempunyai korelasi linear positif dengan semua sifat dan ketebalan lapisan mempunyai korelasi linear negatif dengan semua sifat. Oleh itu, ketumpatan isian disimpulkan mempunyai kesan yang lebih besar ke atas sifat tegangan berbanding parameter lain dengan r antara 0.703 dan 0.773. Bagi komposit PALF/PLA, parameter proses pencetakan optimum ialah ketebalan lapisan 0.1 mm, kelajuan cetakan 25 mm/s dan ketumpatan isian 100% untuk sifat mekanikal dan fizikal yang baik. Daripada kesemua parameter tersebut, ketumpatan infill juga mempunyai korelasi linear positif yang kuat dengan sifat tegangan dengan nilai r antara 0.931 dan 0.951 dan ketebalan lapisan mempunyai korelasi linear positif dengan kekasaran permukaan dengan nilai r 0.628. Parameter lain mempunyai pelbagai korelasi dengan sifat. Oleh itu, ketumpatan isian disimpulkan mempunyai kesan besar terhadap sifat mekanikal dan ketebalan lapisan mempunyai kesan yang tinggi terhadap sifat kekasaran permukaan. Kesimpulannya, kedua-dua SPF/PLA dan PALF/PLA mempunyai parameter proses pencetakan optimum yang sama untuk ciri mekanikal dan fizikal yang baik. Malah, setiap sifat untuk kedua-dua bahan mempunyai kolerasi yang berbeza dengan parameter proses percetakan.

ACKNOWLEDGEMENTS

All praise and thank is due to Almighty Allah SWT, the one, the only and the most merciful creator. To Him, we belong and to Him, we will return. All praises to Allah, I have managed to complete my thesis. I would like to express my gratitude towards every one that has been fully and partially involved in giving me a helping hand during my journey to complete this thesis.

First and foremost, my deepest appreciation to my supervisor, Dr. Noryani Binti Muhammad for her unwavering support, for guiding and her advice. Her encouragement and valuable feedback have been helping me lot towards the direction of my research. I also would like to express my deepest appreciation to my co-supervisor, Dr. Mastura Binti Mohammad Taha, for her assistance in guiding me towards the study of the FDM machine and study on the filament composites. Her expertise and dedication have been a great help to the success of this study.

Huge gratitude to the Ministry of Education Malaysia for supporting this research by the grant (Grant No.: FRGS/1/2022/STG06/UTEM/02/1) and to Universiti Teknikal Malaysia Melaka specifically Faculty of Technology and Mechanical Engineering and Faculty of Industrial and Manufacturing Technology and Engineering for the facility of the laboratory that has been employed during the experimental work.

I am deeply grateful towards my teammates specifically Hazliza Aida Binti Che Hamid and Mohd Hakim Bin Mohd Nasir who have been with me throughout this research project. Their collaboration, valuable discussions, and assistance have been greatly contributed to overcoming challenges and achieving meaningful results. I would like to express my gratitude towards everyone from the DSAM Laboratory for their technical support, resources, and valuable opinion in my experimental study for the research.

I would like to express my special thanks to my beloved family, especially my beloved mother, Latifah Binti Mohamad and my siblings for their encouragement and unwavering support throughout this journey. Additionally, I am also thankful towards my partner for his continuous support, love and emotional support throughout this journey. I want to express my deepest appreciation towards my Sakura Girls and my RE Family too for providing unending support and encouragement for me during this tough journey. Finally, I would like to express my gratitude to everyone that involved during this whole study. All of your contributions have been a great support towards the completion of this study.

Thank you for all the support and guidance that have been given towards me throughout this journey.

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LIST OF ABBREVIATION

ABS	-	Acrylonitrile butadiene styrene
AM	-	Additive manufacturing
ASTM	-	American Society for Testing and Materials
CAD	-	Computer-aided design
DOE	-	Design of experiment
FDM	-	Fused Deposition Modelling
FFF	-	Fused Filament Fabrication
NF	-	Natural fibre
NFRPC	-	Natural fibre reinforced polymer composite
PALF	-	Pineapple leaf fibre
PC	-	Polycarbonate
PLA	-	Polylactic acid
PP	-	Polypropylene
SEM	-	Scanning Electron Microscopy
SNR	-	Signal to Noise Ratio
SPF	-	Sugar palm fibre
3D	-	Three-dimensional

LIST OF SYMBOLS

wt%	-	Weight percent
˚C	-	Celcius
µm	-	Micrometre
cm	-	Centimetre
mm	-	Millimetre
mm/s	-	Millimetre per second
rpm	-	Revolution per minute
%	-	Percent
MPa	-	Megapascal
GPa	-	Gigapascal
Ra	-	Average surface roughness
r	-	Correlation coefficient

LIST OF APPENDICES

LIST OF PUBLICATIONS

Nurul Nadia, M., Noryani, M., Mastura, M.T., Muhammad Alif Zuhair, A.M., Muhammad Naim, Y.Z. (2024). The Development of Pineapple Leaf Fibre/Polylactic Acid Composites Filament. In: Salim, M.A., Khashi'ie, N.S., Chew, K.W., Photong, C. (eds) Proceedings of the 9th International Conference and Exhibition on Sustainable Energy and Advanced Materials. ICE-SEAM 2023. Lecture Notes in Mechanical Engineering. Springer, Singapore.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Three-dimensional (3D) printing is a frequently employed method in additive manufacturing that involves producing an object layer by layer in three-dimensional form out of material. Fused deposition modelling (FDM) is a material extrusion-based subclass of additive manufacturing technology. FDM is one of the most widely used techniques for small-scale additive manufacturing (AM) and being preferred than other 3D printing technology because of its affordability and ease of handling that utilised polymers for manufacturing final products, prototypes, or samples (Wojtyła et al., 2017; Rahim et al., 2019; Deb et al., 2021). The printability of FDM refers to the filament's ability to be continuously extruded and deposited via the heated nozzle to produce a part that is equivalent to its computer-aided design (CAD) model. FDM working principle is printing layer by layer of material from the filament with a diameter size of 1.75 mm. Common materials that are also used in traditional processing technologies, like plastic, metal, sand, wax, and gyps, are mostly used in AM. Rapid prototyping development is accompanied by worries about 3D printing's environmental impact. Given the increasing popularity of this subject, researchers are starting to pay more interest to the detrimental effects of waste and carbon footprints. In order to further the concept of "eco-friendly" materials, biodegradable, recyclable, and compostable materials have been developed (Danut Mazurchevici et al., 2020).

Nowadays, polylactic acid (PLA) is being used in additive manufacturing due to its superior processing ability, bio-derived origin, and desirable mechanical characteristics. It has been demonstrated that 3D printed composites' mechanical, thermal, and physical characteristics are enhanced when PLA is reinforced with bio-derived materials (Muthe et al., 2022). Recently, natural fibres (NF) have been integrated as reinforcement materials in FDM filaments. A high-quality natural fibre-filled thermoplastic composite necessitates thorough mixing of the biofiller with the polymeric matrix, like other additives such as coupling and toughening agents (Mazzanti et al., 2019).

In general, natural fibre composites are categorised into three types of resources that are minerals, plants, and animals. Out of these three types of natural fibres, plant-based fibres are used mostly in product design purposes as reinforcement materials for polymer-based goods since they are abundantly available and require minimal processing to be extracted (Mastura et al., 2022). Human-made fibres produced by chemical reactions are known as synthetic fibres, and they are further divided into organic and inorganic categories according to their content. Some of the synthetic fibres utilised in structural applications are carbon, glass, basalt, and aramid fibres (Ahmad et al., 2021). The substitution of synthetic and carbon fibre with NF, which has been studied by numerous scientists and researchers, is one of the options stated that would enhance the quality of the environment and the new product (Aida et al., 2021).

The printability of PLA composite filament can be influenced by the presence of NF since it can increase brittleness of the composites and lead to interior nozzle rupture. Additionally, various printing process variables like temperature, layer thickness, infill density, printing speed and others depend on the material and the wide range of NF properties makes it challenging for FDM to determine the material's printability. The nozzle also works as a melting compartment in where the thermoplastic is heated to an appropriate density to be ejected (Ferretti et al., 2021). Process parameter optimisation is regarded as a significant alternative to enhancing the quality of the finished components (Attoye et al., 2019). It has been discovered that each of these variables affects the product's structural and mechanical characteristics (Rouf et al., 2022).

A study states that the raster-to-raster air gap, building orientation, raster angle, layer thickness, and infill percentage are the FDM printing process variables that are anticipated to have the greatest influence on mechanical attributes. The study also discovered that the tensile strength increased along with the infill density and the tensile characteristics are greatly affected by the interaction between the nozzle temperature and the infill pattern (Rouf et al., 2022). The way these variables interact is crucial while considering the mechanical characteristics (Popescu et al., 2018).

The quality of the surface finish is vital for affordability and total prototype time reduction as well as to enhanced functionality and attractiveness. One of the main drawbacks of FDM is that, in comparison to other methods, the printed part's surface is disproportionately rough since the AM process uses a layered manufacturing approach (Alsoufi et al., 2017). A study on the physical properties of the FDM printed parts shows that the morphological structure, quality and finishing of the surface are significantly impacted by the printing parameters of infill density and layer thickness. Variability in layer height and infill density caused changes in the FDM manufactured parts of surface roughness (Sammaiah et al., 2020). Previous research also discovered that the thickness of the layer is closely correlated with the surface roughness; as layer thickness rises, so does the surface roughness (Shirmohammadi et al., 2021).

FDM has gained prominence not only due to its cost-effectiveness but also because of its compatibility with a wide range of thermoplastic materials. Among these, PLA stands out as the most widely used material in FDM owing to its ease of printing, low warping tendency, and good dimensional accuracy. As a biodegradable polymer derived from renewable resources such as corn starch or bamboo, PLA aligns well with sustainability goals while still offering competitive mechanical properties for prototyping and functional applications. However, despite its advantages, PLA exhibits limitations such as brittleness and relatively low thermal resistance, which can restrict its use in load-bearing or high-temperature environments. These shortcomings have encouraged research into reinforcing PLA with natural fibres to enhance its mechanical strength, toughness, and thermal stability while maintaining its biodegradability and printability within the FDM process.

Therefore, in this study, the effect on the mechanical and physical properties of the sugar palm fibre (SPF) and pineapple leaf fibre (PALF) reinforced with PLA were being analysed with different printing process parameter setup which are layer thickness, printing speed and infill density. The mechanical properties included in this study are flexural and tensile properties with physical properties which are surface roughness and surface morphological. All the properties of SPF/PLA and PALF/PLA are analysed to finalise the optimum printing process parameters in FDM 3D printing applications. Finally, the strength of the correlation between the printing process parameter with the mechanical and physical properties are also determine and being analysed in this study using Pearson Correlation Coefficient.

1.2 Problem Statement

The FDM technology utilises the material extrusion concept, that involves melting or softening materials to form multiple layers of material to create three-dimensional printed items. The use of an extrusion machine to create the composite filament internally in natural fibre polymer composites has brought environmentally safe materials to the attention of researchers in the expanding field of study on FDM materials. Since the addition of fibres to the polymer matrix modifies all characteristics of the polymer, the printing process parameter needs to be reset (Wojtyła et al., 2017).

In addition, the fibres in polymers would make the materials more brittle and less sturdy (Kamran et al., 2016). This means that instead of the filament being deposited, it would probably break and melt inside the nozzle. In nature, the addition of fibres for reinforcing causes the polymer's viscosity to rise, and an excessive amount of fibres may impede the polymer's flow. The issues with the even dispersion of natural fibres in the matrix are brought to light. For instance, a 3D printer's nozzle may experience non-homogenous composite flow, this could cause uneven printing or blockage (Lee et al., 2021).

Figure 1.1 shows on the main issues that concerning of FDM 3D printing. The first issue is the fabrication of the composite filaments. The variety properties and structure of the fibres do give an impact towards the filament and impacted the printing process. The suitable extrusion temperature and speed to fabricate the composites filament is important in the determination of the strength and structure of the composites filament. Previous study shows the variety of shape of fibres included wood, bamboo and cork had difference in their structure and thus different strength of properties (Mazur et al., 2022). It is a crucial process to ensure the diameter of the filament is 1.75 mm to avoid a blockage during the printing.

From Figure 1.1, the other concern in FDM 3D printing is the printing process parameter including the nozzle and bed temperature, layer thickness, printing speed and infill density. An appropriate printing setting is important to provide a good quality of printed parts with better performance in mechanical and physical properties. Better mechanical attributes and part quality can derive from selecting these parameters effectively, but weaker mechanical strength and quality can emerge from choosing them erroneously. As a result, process variable optimisation becomes essential. While process variables are optimised, 3D printed goods with the desired properties can be manufactured (Alafaghani et al., 2017; Jaisingh Sheoran et al., 2020).