UNIVERSITI PUTRA MALAYSIA

INVESTIGATION OF CHARACTERISTICS OF KENAF/PLA FILAMENT FOR ANKLE FOOT ORTHOSIS USING FUSED DEPOSITION MODELLING

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By

FARAH SYAZWANI BINTI SHAHAR

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Chair: Prof. Ir. Ts. Mohamed Thariq Bin Haji Hameed Sultan, PhD, PEng, CEng, PTech
Faculty: Engineering

Additive manufacturing had been taking a lot of attraction for the past several years and had been implemented in various fields including the Prosthetics and Orthotics industry. One of the applications is the Ankle-Foot Orthosis (AFO), which has an increase in demand in the recent years. However, most of the current materials used to manufacture AFO were made from plastics, which are non-biodegradable, wastes many fabrication materials, and not cost-effective. Thus, this highlights the aim of this research, which is to develop a lightweight AFO using Kenaf/PLA composite and 3D printing technology. This research consists of two phases, which is the experimental phase, and the numerical phase (FEA simulation). The experimental phase of the research will start with the development of Kenaf/PLA filament with different level of extrusion temperature (160°C, 170°C, 180°C, 190°C, 200°C) and fiber loading (0 wt. %, 3 wt. %, 5 wt. %, 7 wt. %), followed by physical and thermal testing of the filament, then fabrication of Kenaf/PLA composite using Fused Deposition Modelling (FDM) printer, and finally, mechanical and physical testing of 3D printed Kenaf/PLA specimens. As for the numerical analysis phase, it consists of two types of analysis, which are the static structural analysis and explicit dynamic analysis. In static structural analysis, the study will be specifically on three extreme gait stages, which are heel strike, mid-stance, and heel rise. As for explicit dynamic analysis, only the selected AFO composites material and PLA AFO will be studied and compared. The results of this research are consist of the effect of extrusion temperature on the physical structure of filament and the smoothness of the extrusion process, physical and thermal analysis of the filament extruded at the selected temperature, mechanical and physical properties of 3D printed Kenaf/PLA, as well as the comparison of strength between neat PLA AFO and the selected variation of Kenaf/PLA AFO. The result shows filament extruded at 170°C has the best physical structure and ease of extrusion process. The thermal analysis of the selected filament shows a reduction of temperature points in filament composites compared to a neat PLA. Based on the FEA simulation of static structural analysis, it was also found 3 wt.

% Kenaf/PLA AFO shows better total deformation, equivalent stress, and equivalent strain compared to PLA AFO and AFO made from other variation of Kenaf/PLA. Meanwhile, the explicit dynamic simulation result shows that 3D printed Kenaf/PLA AFO could retain the strength shown by neat PLA AFO. In addition, since the fabrication of the plaster mold was skipped and the design of AFO could be optimized digitally, material waste was reduced significantly.

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

PENYIASATAN CIRI-CIRI FILAMEN KENAF/PLA BAGI ORTOSIS KAKI BUKU LALI DIPERBUAT MENGGUNAKAN PEMODELAN PEMENDAPAN BERCANTUM

Oleh

FARAH SYAZWANI BINTI SHAHAR

Disember 2021

Pengerusi: Prof. Ir. Ts. Mohamed Thariq Bin Haji Hameed Sultan, PhD, PEng, CEng, PTech
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Sejak kebelakangan ini, Pembuatan Bahan Tambahan telah mendapat banyak daya tarikan dalam pelbagai jenis industri dan telah dilaksanakan di dalam industri-industri yang berbeza termasuk industri Prostetik dan Ortotik. Salah satu aplikasinya adalah Ortosis Kaki Buku Lali (AFO), yang mengalami peningkatan permintaan sejak beberapa tahun ini. Objektif utama penyelidikan ini adalah untuk membuat AFO ringan menggunakan teknologi pencetakan 3D dan komposit Kenaf/PLA. Penyelidikan ini terdiri daripada dua fasa, iaitu fasa eksperimen, dan fasa numerik (simulasi FEA). Fasa penyelidikan melalui eksperimen akan dimulakan dengan pembentukan filamen Kenaf/PLA dengan tahap suhu penyemperitan (160°C, 170°C, 180°C, 190°C, 200°C) dan pemuatan serat (0 wt. %, 3 wt. %, 5 wt. %, 7 wt. %) yang berbeza, diikuti dengan ujian fizikal dan termal pada filamen, kemudian fabrikasi spesimen komposit Kenaf/PLA menggunakan pencetak Pemodelan Pemendapan Bercantum (FDM), dan akhirnya, ujian mekanikal dan fizikal terhadap Kenaf/PLA spesimen yang telah dicetak menggunakan pencetak 3D. Dalam fasa numerik pula, ia terdiri daripada dua jenis analisis, iaitu analisis struktur statik dan analisis dinamik eksplisit. Dalam analisis struktur statik, kajian ini akan dilakukan pada tiga posisi jalan paling ekstrem, iaitu peringkat pemukulan tumit kaki, berdiri tegak dan penaikan tumit kaki. Bagi analisis dinamik eksplisit pula, hanya bahan komposit AFO terpilih dan AFO PLA yang akan dikaji dan dibandingkan. Hasil penyelidikan ini akan terdiri daripada kesan pengaruh suhu penyemperitan pada struktur fizikal filamen dan kelancaran proses penyemperitan, analisis fizikal dan termal filamen yang diekstrusi pada suhu terpilih, sifat mekanik dan fizikal Kenaf/PLA yang dicetak menggunakan pencetak 3D, serta perbandingan kekuatan antara PLA AFO dan variasi Kenaf/PLA AFO yang dipilih. Hasil kajian menunjukkan bahawa filamen yang diekstrusi pada suhu 170 ° C mempunyai struktur fizikal yang terbaik dan mempunyai proses penyemperitan yang terbaik. Analisis termal filamen yang dipilih menunjukkan pengurangan kadar suhu pada komposit filamen berbanding

dengan PLA. Berdasarkan simulasi analisis struktur static, didapati juga 3 wt. % Kenaf/PLA AFO menunjukkan Ubah Bentuk Keseluruhan, Tekanan Setara, dan Regangan Setara yang lebih baik berbanding AFO PLA dan AFO yang dibuat daripada variasi Kenaf/PLA yang lain. Hasil simulasi dinamik pula menunjukkan bahawa Kenaf/PLA AFO dicetak menggunakan pencetak 3D dapat mengekalkan kekuatan yang ditunjukkan oleh AFO PLA. Tambahan pula, oleh kerana proses pembuatan acuan plaster tidak diperlukan dan reka bentuk AFO boleh diubahsuai secara digital, pembuangan sisa bahan fabrikasi dapat dikurangkan.

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LIST OF ABBREVIATIONS

3D	3 Dimensional
ABS	Acrylonitrile butadiene styrene
AFO	Ankle-Foot Orthosis
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
DMLS	Direct Metal Laser Sintering
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
FFF	Fused Filament Fabrication
MJF	Multi Jet Fusion
PA 12	Polyamide 12
PETG	polyethylene terephthalate glycol
PLA	Polylactic Acid
PLS	Posterior Leaf Spring
PP	Polypropylene
PU	Polyurethane
SAFO	Solid Ankle-Foot Orthosis
SLS	Selective Laser Sintering
STL	Standard Tessellation Language
UTS	Ultimate Tensile Strength
UV	Ultra Violet

wt. %	Weightage %

CHAPTER 1

INTRODUCTION

In this chapter, discussions will be on the introduction towards this research. This chapter is divided into six sections which consist of Research Background, Research Motivations, Problem Statement, Objectives, Scopes, and Thesis Overview.

1.1 Introduction

Ankle-Foot Orthosis (AFO) is a device, which acts as a support around the ankle and foot area to fix muscle or nerve disorders such foot drop, sprain, or fracture (Choo & Chang, 2021). Typically, an AFO was designed with an L shape appearance as shown in Figure 1.1. The footplate will keep the foot stable throughout the gait cycle, thus requiring the AFO device to have characteristics such as strong, durable, and light (Choo & Chang, 2021).

Figure 1.1: Ankle-Foot Orthosis (AFO)

Throughout the years, AFO has been developed gradually with the advancement of technologies and material science. AFO has long been known and used since the ancient era until the current era. The materials of the AFO have been developed from a simple bark (Elliott Smith, 1908; J T W, 1936), followed by metal and leather (Banga, Kalra, Belokar, & Kumar, 2015), plastics (Shamp, 1983), and carbon fiber (Klasson, 1995). These materials were mainly used in the conventional manufacturing of AFO. The progress in AFO development ensures that the characteristics required by an AFO device could be achieved and current device could be further refined.

Conventional manufacturing of AFO can be divided into two methods, which are thermoforming polymer sheets and hand laying carbon fiber sheets (Munguia & Dalgarno, 2013). However, the basic processes for both methods are quite similar. There are mainly four stages in conventional manufacturing. It starts with cast rectification, followed by sheet placement on mold, edge cutting and finally accessories add on. This manufacturing process may take around 2 to 3 weeks to complete a fully functional AFO (DE Editors, 2017a). This slow manufacturing process promotes the use of Additive manufacturing in AFO fabrication.

Additive manufacturing is a process that uses the printing technology to print out 3D objects layer by layer controlled by the computer process (TWI Global, 2022). There are three main stages in this manufacturing process, which are 3D model and STL creation, printing process, and finally, the polishing and accessory add on stage. Currently, there are three types of additive manufacturing technology that are available in the market, which are material extrusion, laser sintering, and binder jetting (3D Printing Industry, 2017).

AFO mostly uses the material extrusion and laser sintering printing technology for its manufacturing process as shown in Table 1.1.

Table 1.1: Recent researches on 3D printing

Year	Authors	Materials	Additive Manufacturing (AM) Technologies
2016	Walbran et al. (Walbran, Turner, & McDaid, 2016)	1. Nylon 2. PLA 3. PETG	1. SLS 2. FDM
2017	Cha et al. (Cha et al., 2017)	1. PU	1. FDM
2017	Deckers et al. (Deckers et al., 2018)	1. PA	1. SLS
2018	Aydin and Kucuk (Aydin & Kucuk, 2018)	1. ABS	1. FDM
2019	Vasiliauskaite et al. (Vasiliauskaite et al., 2019)	1. PA	1. SLS

The implementation of Additive Manufacturing into AFO manufacturing had significantly reduced the manufacturing period from weeks to a few days. In addition, complex and form-fitting design of AFO could be easily achieved in additive manufacturing compared to conventional manufacturing, which needs highly skilled worker to achieve the same result. Figure 1.2 shows the types of manufacturing process and technology that are currently available in the manufacturing industry.

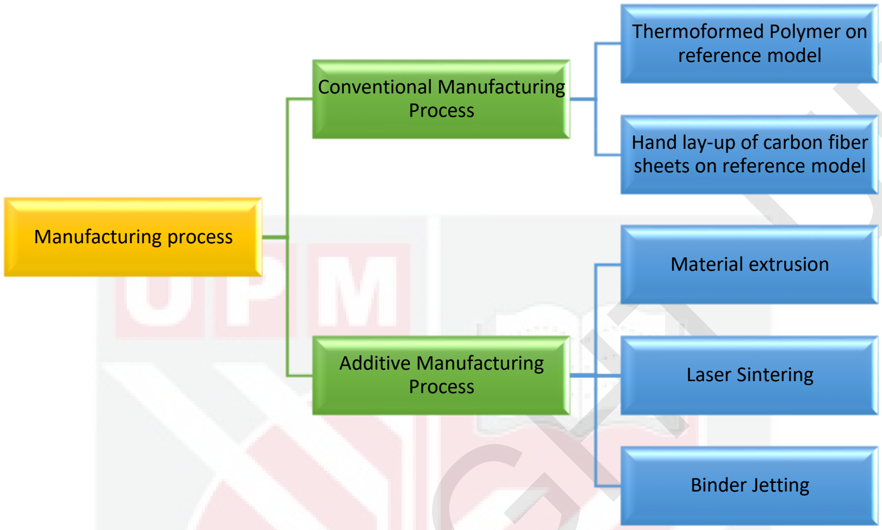

Figure 1.2: Types of manufacturing process and technologies in manufacturing industry

However, the use of plastics in additive manufacturing still could not reduce the amount of material waste during the disposal stage of the AFO device. The cumulative of such wastes causes an influx in landfill. Thus, this fact leads to the motivation of this research project, which is to use a natural filament that could resemble the strength of the printed pure plastics AFO and biodegrade after a period.

Therefore, in this research kenaf was selected as the main material to produce a natural filament. There are several factors, which induce the possibility of using kenaf for this research, such as shown in Figure 1.3.

Figure 1.3: Factors that induce the use of Kenaf in this research

1.2 Research Background

Ankle-Foot Orthosis (AFO) is a device, which is used to correct or enhance the function of the ankle-foot region. From the current market trend in Malaysia, there is an increase of demand for this device. However, due to the long procurement process of getting a good and functional AFO, many patients could not obtain this device within a short amount of time (The Royal Children's Hospital Melbourne, 2020). Thus, most users gave up completely while waiting or do not bother in getting one. Usually it took around a few weeks to obtain a complete functioning AFO.

AFO manufacturing also involves several complicated fabrication process. The conventional manufacturing process of an AFO requires skilled orthotists starting from the cast rectification phase up to assembling parts phase. Due to the amount of details and hands-on skill needed during its manufacturing, highly skilled orthotists are very significant. However, the amount of skilled orthotists is very limited (Ridgewell, Clarke, Anderson, & Dillon, 2021; Ridgewell, Dillon, O'Connor, Anderson, & Clarke, 2016).

Manufacturing an AFO requires several processes which involves the uses of non-biodegradable materials. One of such cases is the creation of plaster mould which corresponds to the measurements and shape of the patient's lower limbs. This mould will then be used to create a positive model which will be used as a reference to place thermoformed polymer sheets around the positive model. Both plaster mould and positive model will then be discarded after one-time usage. Thus, overtime it will provide towards the
increase of landfills in Malaysia.

Manufacturing an AFO also requires several processes, which involves the uses of non-biodegradable materials. One of such cases is the creation of plaster mold, which corresponds to the measurements, and shape of the patient's lower limbs (Munguia & Dalgarno, 2013). This mold will then be used to create a positive model, which will be used as a reference to place thermoformed polymer sheets around the positive model. Both plaster mold and positive model will then be discarded after one-time usage causing material wastes. Thus, overtime it will provide towards the increase of landfills.

The current procurement of AFO is also quite expensive (Rinella Prosthetics & Orthotics, 2020). Due to the high cost of this device, most patients could not afford a suitable AFO for themselves. Thus, end up not using this device when recommended by the doctors. It is especially much more expensive when the AFO are custom made for the patients compared to the off the shelf AFO.

1.3 Problem Statement

Currently, there is a gradual growth in the AFO market (Dataintelo, 2020). However, the manufacturing speed of AFO could not keep up with the ever-increasing demand for an AFO. Furthermore, current AFOs although light, were actually quite expensive due to the manufacturing method and the price of the material itself, whereas cheaper materials such as aluminum, steel, and leathers are usually heavy (Jiménez, Salgado, Sanchez, & del Castillo Granados, 2019). Another problem with the current AFO manufacturing process is that it needs highly skilled orthotists to fabricate a custom fit orthosis and these may takes a few days due to the small amount of orthotists available in Malaysia. Furthermore, a highly complex design of an orthosis may take several days to weeks to be completely fabricated. Therefore, this research mainly studies on developing a composite, which could be printed using a 3D printer to produce a lightweight, and cheap AFO, as well as increasing the speed of AFO manufacturing process. Furthermore, with the addition of natural fiber composite as its main material, the biodegrability of the orthosis could be secured.

In 3D printing, the role of a filament is extremely significant in determining the quality of the printed specimens. A low quality filament will print a specimen with low mechanical properties, whereas a good quality filament will print a specimen with better mechanical properties. These filament qualities were mostly affected by the extrusion process parameter such as extrusion temperature. However, there was limited research, which discusses on the effect of different extrusion temperature on the quality of the filament. Therefore, it was not clear what kind of condition the filament will be extruded, whether it is full of air gaps within the filament itself, or the physical surface of the filament will be smooth enough to be used as a 3D printing material. The presence of air gaps within the 3D printing filament and the physical surface condition of the filament will severely affect the quality of the printed composite specimens. Different types of filament will have different optimum temperature that can be used during 3D printing. Thus, this study will include investigation on several extrusion temperatures and its effect on the morphological surface of the extruded filament, as well as the filament's optimum temperatures for bed temperature, nozzle temperature, and the degradation temperature suitable for 3D printing set-up.

Most of the studies that are available currently use traditional manufacturing method such as hand lay-up or thermoforming. Therefore, there are large archives on the physical and mechanical properties of a Kenaf/PLA composite. However, there was limited research that had specifically studied on the physical and mechanical properties of the specimen that had used additive manufacturing method. It is important to understand the basic properties of the printed specimens in order to be used as an AFO material. There are several requirements that a good AFO must fulfill, which is the AFO must be strong to bear weight and resist impact, durable for a long period of time, lightweight and able to absorb smell and sweat to ensure comfortability. In order to fulfill these requirements, the material used to fabricate the AFO needed to undergo several physical and mechanical testing.

In the gait cycle, there are three significant stages that should be put into consideration when designing an AFO, which was heel strike, mid-stance, and heel rise. Since there was limited amount of FEA study that was conducted on AFO, it was hard to find specific data on the effect of the different amount of fiber loading on the strength of AFOs at these three different gait stages. Thus, causing the evaluation of the AFO composites ability to withstand failure becomes harder. A highly deformed AFO will severely affect the safety of the user, thus knowing the total deformation of the proposed material is extremely important. Another problem that could occur is that fracture failure could occur at certain points on the AFO after enduring repetitive load on the AFO. Knowing where this fracture could occur could help in enhancing the strength of the part with high equivalent stress and equivalent strain. Therefore, an FEA study of the 3D printed AFO composite is necessary to find the AFO's deformation, equivalent stress, and equivalent strain to predict the AFO performance at static position.

Predicting failure during static is completely different when the AFO was subjected under a dynamic condition. There are instances where failure will occur during dynamic conditions but performs very well during static conditions. Since AFO's function is to operate normally in daily activities, it is inevitable that the AFO will be subjected to high impact forces such as jumping or hopping. Thus, it is also necessary to perform an FEA simulation of AFO under free-falling condition, which could help in predicting failures that could occur during dynamic conditions.

1.4 Objectives

The main objective of the current research is to develop a lightweight AFO using Kenaf/PLA composites via 3D printing technology and use the proposed material to print out a 3D model of the AFO prototype. In order to fulfil the main objective of this research, several objectives were specified as follows:

i. To evaluate the effects of extrusion temperature on the morphological structure and thermal properties of the Kenaf/PLA filament after extrusion process
ii. To examine the physical and mechanical properties of the printed Kenaf/PLA composites
iii. To analyze FEA Static analysis of PLA and different variations of Kenaf/PLA AFO composite in terms of deformation, equivalent stress and equivalent strain during heel strike, mid-stance, and heel rise position
iv. Assess and compare the simulation of the selected Kenaf/PLA AFO and PLA AFO using explicit dynamic analysis through free-fall drop test

1.5 Scopes and limitations

This research focused on the development of natural filament for 3D Printing. The natural fiber used in this research was limited to Kenaf powders with size particles lower than 250 µm. The study will involve two stages of extrusion, where the first extrusion was via twin-screw extruder to get the Kenaf/PLA pellets and the second extrusion via mini desktop filament extruder to obtain a continuous filament of 1.75 mm in diameter. The filament was mainly made of Kenaf powder and Polylactic Acid (PLA) pellets with the variation of 3% wt., 5% wt., and 7% wt. of kenaf powder. SEM analysis, TGA and DSC will only be conducted on the filament of the selected extrusion temperature, which was extruded by the mini desktop filament extruder. Mechanical test such as tensile, fatigue, Izod impact, and physical test such as density, water absorption, thickness swelling, will only be conducted on the printed composites. The data obtained from the mechanical test will be used in FEA simulation to simulate AFO at heel strike, mid-stance, and heel rise in the static structural analysis, as well as free-fall test in explicit dynamic analysis. Only PLA AFO and the selected Kenaf/PLA material will be used in the explicit dynamic analysis. All numerical analysis will be conducted using ANSYS 18.2 software, whereas all 3D models were created using CATIA P3 V5 R18. Finally, only PLA AFO and the selected Kenaf/PLA AFO will be used to print out a small-scale version of the AFO prototype.

Good processing of materials will result in good product quality. While processing a filament for 3D printing, there are several challenges that could occur. One of the greatest limitations is the filament for 3D printing must meet stringent quality requirements. The quality requirements of the filament are strictly defined filament diameter (1.75 mm based on standard printer) and a homogenous core of the line. Any inconsistency in the filament diameter or deviation will affect the quality of the print significantly. The print may deteriorate and clogged due to the buildup at the printer's nozzle. The accuracy of the filament's diameter is usually around ±0.02 mm.

Another limitation is the production of air bubbles during filament extrusion. Improper mixing or inhomogeneous blending of the filler and matrix may have caused these air bubbles. The presence of air bubbles in the filament will produce more void within the specimen. In addition, the air bubbles present in the filament will cause the filament to easily snap during printing. Therefore, it is important to handle the raw materials properly. The moistures must be completely removed before the start of the extrusion process.

3D printing composites could be tedious without the proper setup and planning. Many problems could occur during the printing process that could compromise the quality of 3D printing a composite model. The strength of the printed specimen will be reduced significantly, and it could become significantly brittle.

In 3D printing composite, the state of the raw material used to produce the 3D print filament has a significant effect towards subsequent printing process. The fibers and polymers must be completely dry and free from any type of moisture. If it is possible, it is important to ensure that fresh fibers are being used in the filament production since it has not yet degrade and the specimens printed from these materials will have the highest mechanical strength.

1.6 Thesis Overview

In this thesis, detailed discussions of the research are spread across several chapters. There are five major chapters in this thesis, which starts with the introduction of the research project, followed by the literature reviews that are related to this research, the methodology aspects of the project, results and discussion, and finally the concluding remarks for this research respectively.

Currently, the first chapter starts by discussing a brief insight into the research background and motivations that drives this research. Then, several issues were discussed in problem statement section to support the necessity of this research. Finally, the objectives and scopes for this project will highlight the focus and limitations of this research.

After the introduction chapter, Chapter 2 will highlight on the fundamental theories related to Ankle-Foot Orthosis, current related researches that has been done, insight into Kenaf fiber and composites, and finally the technological gap for AFO manufacturing.

Chapter 3 briefly explains the methodological part of this project. This chapter highlights the research flow of this project, the materials and equipment used, as well as the procedures and standards used for this research.

Followed right after Chapter 3 is Chapter 4, which mainly consist of the results and discussion aspects of this project. This chapter will show the results obtained from tests that had been conducted and discusses the impact of this results towards the prototype.

Finally, Chapter 5 will conclude the findings of this research. This chapter will conclude whether the project has reached its objectives, and summarized the whole project. This chapter also discusses on the limitations and challenges while conducting this research as well as future recommendations for this research.

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